Comparative analysis of NPP changes in global tropical forests from 2001 to 2013

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Abstract. Net primary production (NPP) is the difference between total photosynthesis (gross primary production, GPP) and total plant respiration in an ecosystem. NPP is a key component of the terrestrial carbon cycle and is important in global climate research. Tropical forests, distributed mainly in Central Africa, Central and South America, and Southeast Asia, are among the most important ecosystems on earth. They are very important to analyses of the global carbon budget and to the projection of future climatic changes. In this study, we analyzed and compared the temporal and spatial changes of NPP within the three dominant areas of tropical forest from 2001 to 2013 by using data from the Moderate Resolution Imaging Spectroradiometer (MODIS). We found that Central and South America has the highest annual mean NPP, statistically, while the average NPP shows an increasing trend both in Central and South America and Central Africa but a decreasing trend in Southeast Asia.

1. Introduction

Net primary productivity (NPP) is the rate at which all plants in an ecosystem produce net useful chemical energy. It is equal to the difference between the rate at which the plants in an ecosystem produce useful chemical energy (gross primary production, GPP) and the rate at which they use some of that energy during respiration. NPP is a fundamental ecological variable, not only because it measures energy input to the biosphere and terrestrial carbon dioxide assimilation, but also because of its significance in indicating the environmental health of an ecosystem and the status of a wide range of ecological processes.

Tropical forests are disproportionately important in the global carbon budget, representing an estimated 59% of the global carbon pool in forests [1], 20% of global terrestrial carbon stocks, and 30% of global terrestrial NPP, despite accounting for less than 7% of global dry-land surface [2]. In addition, tropical forest regions have experienced significant environmental changes in past decades, such as extreme weather events, changes in surface radiation budgets due to cloud cover changes [3, 4], and changes in global atmospheric CO₂ concentration [2, 5]. In response to these environmental challenges, tropical ecosystems may have experienced changes in their carbon budgets. To date, scientific understanding of the responses of tropical ecosystems to environmental changes is still incomplete [5], and so an improved understanding of current variations of the tropical forest NPP is critically needed.

Although the spatial variation of tropical carbon processes has been studied by many scientists, and tropical forest NPP has been assessed using multiple approaches (from plot-scale extrapolations to satellite- and model-derived estimates, among others), all large-scale NPP estimates are modeled (either explicitly or implicitly). While field-based estimates may be considered more robust in that they are based on actual small-scale measurements of plant growth, the limits of spatial and temporal coverage mean that NPP estimates cannot be adequately validated or calibrated in tropical forests [6].

Geoinformatics, including remote sensing, is an approach with many practical applications including analyses across time and space [7]. Remote sensing has been used to monitor GPP and NPP dynamics at regional and global scales [8, 9]. The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument produces one of the most reliable data sources at a global scale. This dataset provides operational, near-real-time calculation of global GPP at a 250 m spatial resolution with daily coverage [9]. The resulting data products have been validated as being able to capture spatial and temporal GPP and NPP patterns across various biomes and climate regimes, and the data are consistent with ground flux tower-based GPP and field-observed NPP estimations [10, 11]. The
availability of MODIS GPP and NPP data provides a unique opportunity for examining spatial patterns within the global NPP/GPP ratio [12].

In order to better understand the spatial and temporal dynamics of NPP in global tropical forests in the context of climate change, we used MODIS data to analyze changes in NPP within the three main distribution areas of tropical forests, Central Africa, Central and South America, and Southeast Asia, from 2001 to 2013.

2. Data and methods

2.1 Study area

In order to analyze the distribution and variation of tropical forest NPP, we focused on forests between the Tropics of Cancer and Capricorn, as shown in Figure 1. Considering that forest area may differ from year to year, we used MODIS land-cover data for each year from 2001 to 2013 to determine the specific boundaries of the study area.

Figure 1. Study area: tropical forest regions extracted from MODIS land-cover data are shown in green.

2.2 Data

In this study, we used the MODIS land cover product (MCD12Q1), NPP product (MOD17A3), and vegetation continuous fields product (MOD44B). Each dataset covers the entire study area and is available from 2001 to 2013.

The MCD12Q1 product identifies a suite of land-cover types by mapping global land cover using spectral and temporal information derived from satellite imagery. It is produced using a supervised classification algorithm that is calibrated using a database of high-quality land cover training sites. This product supplies global maps of land cover at annual time steps and 500 m spatial resolution, consisting of five land cover data of different classification systems including the International Geosphere Biosphere Programme (IGBP) scheme [13, 14, 15, 16], which we used in this study to delineate the study region for global tropical forests.

The MOD17A3 product provides continuous estimates of GPP/NPP across Earth’s entire vegetated land surface, supplying global maps of NPP at annual time steps and 1 km spatial resolution. A simple light-use efficiency model (MOD17) is at the core of the GPP component of the algorithm, as described in [17, 18]. Since the MODIS instrument was placed in orbit in 1999, there have been multiple updates of its land products [19]. In this study, we used version 55 of the NPP product, which corrects previous problems with cloud-contaminated MODIS LAI-FPAR inputs to the MOD17 algorithm. Therefore its accuracy has been assessed and uncertainties in the product are well-established via independent measurements made in a systematic and statistically robust way that represents global conditions.

The MOD44B Vegetation Continuous Fields (VCF) product is a sub-pixel-level representation of surface vegetation cover estimates globally. This product provides a continuous, quantitative portrayal of land surface cover with improved spatial detail at annual time steps and 250 m spatial resolution. The VCF product has three components of ground cover: percent tree cover, percent non-tree vegetation and percent bare [20, 21, 22, 23, 24]. The three components are each stored in separate layers so they can be used independently to look at a particular type of ground cover or collectively to look at the entire surface [25]. In this study, we used the percent tree cover layer of the version 51 VCF product, which has improved training data and data mining software which resulted in much
greater accuracy in the final product without human intervention.

In order to obtain the spatial and temporal variation of global tropical forest NPP, we followed four steps. Firstly, the three MODIS datasets for the study area from 2001 to 2013 were downloaded and mosaicked; secondly, the annual study areas were extracted from the land cover type dataset; thirdly, NPP and VCF data were clipped according the study area; finally, spatial and temporal variations of NPP and VCF were analyzed and compared for the three major tropical forest regions.

3. Results and discussion

3.1 Spatial and temporal variation of NPP within Central and South America

This study area includes the enormous catchments of the Amazon and Orinoco rivers and extends into Central America [26]. The average NPP of this region shows an overall downward trend (Figure 2) with a change-trend slope of around -2.0 g∙C∙m^{-2}∙a^{-1}, meaning that the total NPP in this region collectively declined (on average) about that amount annually from 2001 to 2013. The forest area in this region also shows an overall decreasing trend (Figure 2) with a change-trend slope of around -0.11 million ha∙a^{-1}. We suggest that the reduction in forest area has partly influenced the reduction in collective NPP.

Tree cover can indicate the growth status of forests. While the land-cover type can only show whether one pixel is forest or not, tree cover reflects what percentage of the pixel is covered by canopy. The western region of the study area has experienced the most dramatic decrease in NPP from 2001-2013, in contrast to the stable or increasing trend in the eastern region. However, changes in tree cover over the same period (Figure 3) seem to show no clear geographic correlation. For example, along southeast edge of the region, tree cover has decreased while NPP has increased. In addition, the areas with the most severe decline in NPP show stable or rising tree cover.

![Figure 2](image.png)

**Figure 2.** Distribution map (a) showing the slope of NPP change trend in the Central and South America study region. Figures on the right show change curves of NPP (b) and forest area (c) for the same region.
3.2 Spatial and temporal variation of NPP within Central Africa

This study area is located in the central two-thirds of Africa, including the basins of the Congo, Niger, and Zambezi rivers [26]. The average NPP of this study region shows an upward trend (Figure 4) with a change-trend slope of around 9.98 g·C·m⁻²·a⁻¹, meaning that the total NPP in this region has increased, on average, 9.98 g·C·m⁻² annually from 2001 to 2013. The total forest area in this study region is declining (Figure 4) with a change-trend slope of around -0.41 million ha·a⁻¹. Most parts of the study area have experienced an increase in NPP from 2001 to 2013 (Figure 4), in contrast to the reduction in tree cover seen over much of the area (Figure 5). In the west-central area, there is an especially strong decline in tree cover with a relatively slight decline in NPP. However, in the central area, the NPP shows an upward tendency despite a decline in the tree cover.

![Figure 3](image1.png)

**Figure 3.** Distribution map showing the slope of tree-cover change trend in the Central and South America study region.

![Figure 4](image2.png)

**Figure 4.** Distribution map (a) showing the slope of NPP change trend in the Central Africa study region. Figures on the right show change curves of NPP (b) and forest area (c) in the same region.
3.3 Spatial and temporal variation of NPP within Southeast Asia

This study area covers portions of India and Southeast Asia, including Myanmar (Burma), Thailand, and Malaysia along with islands including those in the Malay Archipelago, particularly Sumatra, Borneo, New Guinea, and those of the Philippines. These areas all have significant rainforest regions, as do parts of northern Australia and islands of the West Indies [26]. The average NPP of this study region shows a downward trend (Figure 6) around $-14.75 \text{ g} \cdot \text{C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$, meaning that the total NPP in this region declined, on average, about $14.75 \text{ g} \cdot \text{C} \cdot \text{m}^{-2}$ annually from 2001 to 2013. The total forest area in this region shows a clear upward trend.

Many areas, including the Malay Peninsula, Sumatra, Borneo, Celebes, and northwestern New Guinea, show significant decline in NPP from 2001 to 2013. With the exception of Sumatra, most of these areas also show an increase in tree cover during the same period (Figure 7). We suggest that deforestation plays a minor role in NPP change in this area, and instead that forest degradation may have more to do with the declining NPP.

Figure 6. Distribution map (a) showing the slope of NPP change trend in the Southeast Asia study region. Figures on the right show change curves of NPP (b) and forest area (c) in the same region.
3.4 Comparing NPP changes between the three major tropical forest regions

The Central and South America study region has the largest physical area (543.00 million ha), followed by Southeast Asia (223.19 million ha) and the Congo (175.71 million ha). The total forest area in the three regions did not significantly change over the study period. The Southeast Asia study region shows a dramatic decline in NPP, along with having the lowest average NPP (about 1046.99 g·C·m⁻²). The Central and South America study region shows a relatively stable NPP, and has the largest average NPP (about 1067.45 g·C·m⁻²). The Central Africa study region is unique in showing an upward NPP tendency, with an average NPP of about 1053.48 g·C·m⁻². As for percent tree cover, the Central and South America study region has the highest coverage, followed by the Central Africa study region and the Southeast Asia study region. It is apparent that there is no obvious relationship between the inter-annual variation of NPP and tree cover in these study regions, which suggests that NPP is influenced by many other biochemical and meteorological factors.

Comparing the changes in NPP and tree cover (Figures 9 and 10), we observed that in all three study regions, areas with severe fluctuations in NPP have relatively small variations in tree cover. Under most conditions, the most dramatic reduction in tree cover appears along the edges of tropical forest areas, while central parts of these areas show only a slight change. In comparison, changes in NPP tend to be less fragmented. In general, the different slopes change gently from one level to another across a wide extent of the study areas. We suggest that the differences in distribution between NPP and tree cover may reflect the connection of tree cover to human activities and of NPP to other biogeographic and biochemical conditions.
4. Conclusion
From 2001-2013, the Central and South America study region had the highest forest area and tree cover, with a relatively steady NPP. The Central Africa study region had the lowest forest area and second-highest tree cover, and was the only region with an upward NPP trend. The Southeast Asia study region had the second highest forest area and the lowest tree cover, with the largest decrease in NPP. Areas with severe fluctuations in NPP generally had relatively small variations in tree cover, while sections with severe reduction in tree cover tended to also show a decline in NPP. Moreover, compared to changes in tree cover, the change of NPP is more continuous, which we suggest is due to the influence of human activities on tree cover while changes in NPP are mainly connected to other biogeographic and biochemical conditions. However, the mechanisms behind these dynamics require further exploration.

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