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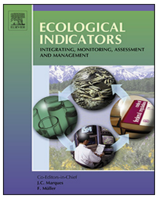

Spatiotemporal changes and drivers of global land vegetation oxygen production between 2001 and 2010

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ABSTRACT

Oxygen is a sensitive indicator of atmospheric compositional changes, and also a primary requirement for human life. Values for the normalized difference vegetation index (NDVI), temperature, and radiation are input into the C-FIX model in this study in order to simulate global net ecosystem productivity (NEP). According to carbon–oxygen equilibrium theory, NEP is further converted into oxygen production by land vegetation around the world. Thus, an in-depth analysis of spatiotemporal changes in the oxygen production of land vegetation globally is presented in this study alongside a discussion of relevant mechanisms of change. The results of this research show that global annual average oxygen production between 2001 and 2010 had a significant increasing trend, amounting to 194×10^{10} t, at a rate of 0.78×10^{9} t/a. Data show that the most obvious increases in oxygen production occurred in Asia, Europe, and North America, while changes in Africa, South America, and Oceania were insignificant. Global maximum oxygen production was seen in South America, encompassing roughly 30% of the global total, while between 2001 and 2010, the distribution of production by global land vegetation can be characterized by a gradual decrease from the equator to the poles. Production on approximately 12.0% of global landmass increased significantly (mainly in eastern Siberia, eastern Europe, and in the western part of North America), while a significant decrease was observed on approximately 5.43% of global landmass (mainly in western Siberia, central Africa, and the southern part of South America). At the same time, changes in carbon dioxide (CO_2) concentration and vegetation resulted in an overall increase in global oxygen production, while climate change led to a decrease. Moreover, the increase of CO_2 concentration is the main factor for the significant increase in the total oxygen production of land vegetation in the world, accounting for 70.0%, while the conversion of cultivated land and grassland into forested land led to significant global decreases. The main contributions of this study are thus to reveal the spatial distribution of, and variation in, global oxygen production by vegetation over the last decade, and to clarify the factors that have influenced these changes.

1. Introduction

Climate warming-related changes in atmospheric carbon dioxide (CO_2) content have attracted worldwide attention. However, another change in atmospheric chemical composition, a gradual reduction in oxygen (O_2), has been largely ignored, even though it directly threatens all life on Earth. Measurement data suggest that the oxygen content of the lower atmosphere has gradually decreased over time, at a rate of 2 ppm/year (Santilli, 2000), while in some heavily polluted cities and industrial regions where population density is relatively large, oxygen content is around 15.0% or lower (Santilli, 2000; Lenton, 2003). A lowered atmospheric oxygen content (i.e. less than 19.5%) creates symptoms of anoxia, a direct cause of cell hypoxia which leads to chronic pain and diseases (Semenza, 2001; Jacobsen, 2008).

The majority of atmospheric oxygen is the result of photosynthesis by algae in oceans and green plants on land (Kasting and Siefert, 2002; Schäfer, 2004). In recent years, however, because of intensifying human activity, great changes in land use and land cover (LUCC) have taken place around the world (Foley et al., 2005; Grimm et al., 2008; Friedl et al., 2010). Forested area, for example, decreased by 1,500,000 km^2 between 2000 and 2012 (Hansen et al., 2013), being mainly converted into either cultivated land or grassland (Zak et al., 2008; Tsegaye et al., 2010). Changes in both the area and quality of vegetation affect photosynthetic intensity as well as global oxygen

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production, while temperature changes influence enzyme activity during this process. The 5th Report of the Intergovernmental Panel on Climate Change (IPCC) noted that, from the mid-19th century onwards, when observations started, global average temperature has risen by about 0.8 °C. The period between 1983 and 2012 probably experienced the highest temperatures seen over the last 1400 years, and levels are expected to further increase (IPCC, 2013). At the same time, CO_2 is a key resource for photosynthesis and the concentration of this gas in the atmosphere continues to increase; atmospheric CO_2 concentration has increased by nearly 30.0% since the early stages of the Industrial Revolution, and the annual average increase per year over the last ten years has been between 1 ppmv and 3 ppmv (Tao et al., 2001). Thus, in the context of increasing global LUCC intensity and speed, as well as continuously increasing temperature and CO_2 concentration, evaluating changes in global oxygen production remains a key scientific problem worthy of further discussion, not least because this gas is essential to all organisms on Earth. The ever increasing levels of global environmental pollution weaken the strength and intensity of solar radiation; as illumination intensity influences photosynthesis via photochemical reactions, the issue of global oxygen production is even more significant and urgent.

The photosynthesis of green plants both produces organic matter ($C_6H_{12}O_6$) and oxygen and consumes a part of them via respiration. Three basic measures of the carbon (C) cycle, gross primary productivity (GPP), net primary productivity (NPP), and net ecosystem productivity (NEP), have been defined in the literature (Tao et al., 2001), and according to the principles of photosynthesis and respiration, a proportional relationship exists between the organic C (OC) and oxygen absorbed and released by vegetation. This means that the amount of oxygen produced by vegetation can be estimated via the volume of OC, an approach referred to as the carbon–oxygen equilibrium method. A review of relevant literature reveals that a number of previous researchers have estimated oxygen production using GPP (Zhang et al., 2007; Chen and Lu, 2009), while others have utilized NPP (Peng, 2003; Ma et al., 2011). The first of these measures, GPP, incorporates the initial OC produced via photosynthesis without taking into account the amount consumed by vegetation respiration, while the second, NPP, considers the OC that remains after accounting for plant autotrophic respiration. However, as NPP does not take into account the OC consumed via plant heterotrophic respiration, results based on these different measures can be different from one another. Distinct from the GPP and NPP, the NEP takes into account OC that remains after both autotrophic and heterotrophic respiration (Zhang et al., 2014; Liu et al., 2015); in other words, this measure refers to net photosynthetic production after respiration. It is clear, therefore, that estimates based on NEP represent net oxygen production and so more directly evaluate both the change and content of this gas in the atmosphere. Surprisingly, however, no research to date has been conducted to evaluate the global oxygen production of vegetation based on the NEP.

The aim of the study is to simulate the global annual oxygen production of vegetation between 2001 and 2010 using the photosynthetic light energy utilization (C-FIX) model. This was achieved by simulating the global NEP of land vegetation, and then converting these values into oxygen production based on photosynthesis and respiration equations. The goal of this research is therefore to explore spatiotemporal changes in the global oxygen production of vegetation, as well as the factors that have influenced variation. The main contribution of this study is to reveal the oxygen content of the atmosphere produced by land plant photosynthesis over the last ten years, as well as to discuss its variation, and reveal the factors that contribute to change. The results of this study thus provide a quantitative baseline for research on global atmospheric oxygen content changes as well as environmental assessment.

2. Data

The data sources as well as the steps taken to process the three major parameters of the C-FIX model are discussed in this section. The three parameters that comprise this model are the normalized difference vegetation index (NDVI), daily average temperature, and daily average radiation.

2.1. The NDVI

The NDVI, the most appropriate indicator for vegetation growth status and coverage, is equivalent to an index change in biomass, which is calculated as follows (Running et al., 2000):

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

where *NIR* and *Red* denote the reflectance values of the near-infrared and red bands, respectively. As this index is calculated based on these two bands, it also relies on an atmospheric correction; thus, when there are no clouds or snow, as well as a relatively low aerosol content, NDVI values are very precise. This index reflects vegetation status, but is also affected by the plant canopy background factors, including soils, humid ground, snow, dead leaves, and surface roughness. For example, if a surface is very bright or dark, such as the case for snow, desert oases, or inland water bodies, NDVI values are not stable; thus, to minimize calculation error, NDVI data was processed in this study according to the steps. In cases where the NDVI is negative, the land surface is covered by clouds, water, or snow, but if the index is zero, then the land surface is covered by construction land, rock, or barren land in place of vegetation. However, if the NDVI is positive, then the land surface is covered with vegetation; this coverage increases with the increase of the index values. As the aim of this study is to evaluate vegetation oxygen production, negative NDVI values are inconsistent with simulation conditions; thus, during calculations, oxygen production is marked as zero in areas where the NDVI is negative.

NDVI was obtained from the NASA MOD13A2 product via the Terra satellite platform at a spatial resolution of 1 km × 1 km and a temporal resolution of 16 days, and 6690 images were collected to cover the global regions (https://ladsweb. nascom. nasa.gov). The NDVI data used in this study covered the period between January 1st, 2001, and December 31st, 2010, and a total of 66,900 images were collected. Image format conversion and mosaics were conducted using ERDAS9.2, with resolution reset as 0.5° using MATLAB. Global regional image cutting, superposition, and meaning were performed using ArcGIS; during these steps, if two images were available for a given month, then the average of the two was used; the final data set comprised a total of 120 grid image layers of monthly NDVI values between 2001 and 2010 at a spatial resolution of 0.5° × 0.5°. In particular, each of the 0.5° × 0.5° grids included 3080 grids that had a spatial resolution of 1 km × 1 km such that resolution increased to 0.5° from 1 km. An average value of the 3080 child grids was chosen as the NDVI for the parent grid.

2.2. Daily average temperature

The C-FIX model provides a daily simulation that requires temperature input. However, because of the extensive calculations required by this study, monthly rather than daily average values were used. Monthly average temperatures for the period between 2001 and 2010 were extracted from the Climate Research Institute (CRU) (University of East Anglia, Norwich, UK) CRU-TS3.2.4.1 data set, in the form of global regional values downloaded from the website (http://www.cru.uea.ac.uk/cru/data) using a program created using FORTRAN. These data were then converted into a grid format using the "To Raster" tool in the Spatial Analyst Tools model within ArcGIS. A total of 120 image layers for monthly average gridded temperature data between 2001 and 2010