Climate driven increases in global terrestrial net primary production from 1982 to 1999

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Recent climatic changes have enhanced plant growth in northern mid and high latitudes. However, a comprehensive analysis of the impact of global climatic changes on vegetation productivity has not before been expressed in the context of variable limiting factors to plant growth. We present a global investigation of vegetation responses to climatic changes by analyzing 18 years (1982-1999) of both climatic data and satellite observations of vegetation activity. Our results indicate that global changes in climate have eased several critical climatic constraints to plant growth, such that net primary production increased 6% (3.4 Pg C/18 yr) globally. The largest increase was in tropical ecosystems. Amazon rainforests accounted for 42% of the global NPP increase, owing mainly to decreased cloud cover and the resulting increase in solar radiation.

Between 1980 and 2000 the Earth experienced dramatic environmental changes (1). It had two of the warmest decades in the instrumental record (1980s and 1990s), had three intense and persistent El Niño events (1982-1983, 1987-1988 and 1997-1998), and saw significant changes in tropical cloudiness (2) and monsoon dynamics (3). Meanwhile, atmospheric CO_2 levels increased by 9% (337 to 369 ppm) and human population increased by 37% (4.45×10^9 to 6.08×10^9). Changes in terrestrial net primary production (NPP) integrate these and other climatic, ecological, geochemical, and human influences on the biosphere. Several regional studies have reported increases in NPP (4-10), but a globally comprehensive analysis of the impacts of climatic changes on NPP is lacking. For the northern mid and high latitudes, these studies suggest that multiple mechanisms (e.g., nitrogen deposition, CO_2 fertilization, forest regrowth and climatic changes) have promoted increases in NPP, while increases in the tropics have been primarily attributed to CO_2 fertilization. Here we analyzed nearly two decades of recent

global climatic data and satellite observations of vegetative activity and show that climatic changes have eased multiple climatic constraints to plant growth, increasing NPP over large regions of the Earth.

Temperature, radiation, and water interact to impose complex and varying limitations on vegetation activity in different parts of the world (11). In order to provide a comprehensive interpretation of climate change impacts on plant growth, we first constructed a map of the relative contributions of climatic controls on global vegetation. We used long-term monthly climate statistics to build simple bioclimatic indices (12). From these indices, we estimated that water availability most strongly limits vegetation growth over 40% of the Earth's vegetated surface, temperature limits 33%, and radiation 27% (Fig.1A). These factors tend to be co-limiting. For example, cold winter temperatures and cloudy summers limit high latitude Eurasian vegetation, while cold winters and dry summers limit vegetation in western North America. Tropical areas are never limited by low temperatures, but may have either a sustained dry season, or nearly perpetual cloud cover that limits solar radiation (13).

We have estimated the trends in these growth limiting climate factors from 1982 to 1999 using daily reanalysis data from the National Center for Environmental Prediction (NCEP) (14). The observed trends were confirmed with independent data sets of ground and satellite based observations (Fig S1-S3) (12). Air temperatures that regulate the growing season dynamics have increased over temperature-limited regions of North America and northwest Europe (Fig. 1B) promoting earlier plant growth (7) and additional carbon sequestration (15). Changing monsoon dynamics produced wetter rainfall regimes, and associated reductions in vapor pressure deficit (VPD) in water-limited ecosystems of Australia, Africa and the Indian sub-continent (Fig. 1C) (3).

Significantly increasing incident solar radiation was evident over radiation-limited regions of Western Europe and the equatorial tropics (2, 16) (Fig. 1D).

Most of the observed climatic changes have been in the direction of reducing climatic constraints to plant growth. To quantify this effect, we used a biome specific production efficiency model (PEM) (12, 17) that combines monthly estimates of satellite-derived vegetation properties with daily NCEP climate data to estimate monthly and annual NPP at 0.5° x 0.5° resolution. The satellite-derived vegetation properties used were: the fraction of absorbed photosynthetically active radiation (FPAR) and leaf area index (LAI) derived from remotely sensed Normalized Difference Vegetation Index (NDVI) and a biome map (18, 19). The PEM that we used is similar in logic to other PEMs (8, 13, 20) but has parameters derived from field studies and a global ecosystem process model (17, 21). To account for differences in satellite data processing, we used two independent datasets of LAI and FPAR derived from Global Inventory Monitoring and Modelling Studies (GIMMS) (22) and Pathfinder AVHRR Land (PAL) (23) NDVI data sets (12)

From 1982 to 1999, modelled NPP increased the most (6.5%) in water and radiation limited regions followed by temperature and radiation limited regions (5.7%), and temperature and water limited regions (5.4%). NPP increased significantly (p<0.01) over 25% of the global vegetated area, with a mean rate of 6.3 $gC/m^2/y$, and decreased significantly over only 7%, with a mean rate of 4.2 $gC/m^2/y$ (Fig. 2).

To isolate the role of climate from other mechanisms that could enhance carbon sequestration such as CO_2 fertilization, nitrogen deposition and forest re-growth, and to remove spurious trends in satellite data due to residual sensor calibration effects, we alternately estimated NPP by assuming *constant vegetation* (1982-1999 monthly average

FPAR and LAI) but changing climate and by assuming *constant climate* (average daily climate from 1982-1999) with changing vegetation. Changes in climate (with constant vegetation) directly contributed nearly 40% of the total increase in NPP from 1982 to 1996 (Table S2). Changes in vegetation (with constant climate) over the same period contributed about 60% of total NPP increase, possibly as a result of climate-vegetation feedbacks, changes in land use and growth stimulation from other mechanisms. Over parts of North America, Western Europe, the Amazon, south and central Africa, Australia and the Indian sub-continent, changing climate alone produced persistent NPP increases (Fig. S8).

Globally, NPP increased (Fig. 3) by 6.17%, 3.42 PgC/18yr (p<0.001), between 1982 and 1999. Ecosystems in all tropical regions and those in the high latitudes of the Northern Hemisphere accounted for 80% of the increase. Although terrestrial NPP only accounts for part of the biosphere-atmosphere carbon exchange, interannual variations of NPP are negatively correlated with global increases in atmospheric CO_2 growth rate (r = 0.70, p<0.001). NPP anomalies attributable to climate alone (calculated with constant vegetation) explained nearly the same amount of variation in the NPP-CO_2 relationship (r = 0.71, p<0.001), indicating that climatic variability over land exerts a strong control over the variation in atmospheric CO_2 (Fig. S9).

NPP responded differentially with respect to latitude to major climatic events such as El Niño and volcanic eruptions (Fig. 4). Globally, NPP declined during all three major El Niño events with corresponding increases in global CO_2 growth rate (24). El Niño events dominate tropical NPP variability, which has the highest association with global CO_2 growth rate (r = 0.75, p<0.001). This response is likely due to NPP and soil respiration being more tightly coupled in tropical climates compared to ecosystems in other latitudes. Soil carbon residence times range from less than four years in hot, wet

tropical areas to greater than 1000 years in cold boreal or dry desert conditions (25). A strong decline in NPP following the Mt. Pinatubo eruption (1991) was evident only at the high latitudes of the Northern Hemisphere. Cooler temperatures resulting from this eruption decreased the growing season length there (15), but cooling, in association with favourable radiation regimes for photosynthesis (26), promoted plant growth in low latitude ecosystems by reducing evaporative demand and respiration losses.

An increase in NPP of only 0.2% per ppm increase in CO_2, could explain all of the estimated global NPP increase of 6.17%/18yr and is within the range of experimental evidence (27). However, NPP increased by more than 1%/yr in Amazonia alone, which accounts for 42% of the global NPP increase between 1982 and 1999. This result cannot be explained solely by CO_2 fertilization. We suggest that increases in solar radiation, owing to declining cloud cover in these predominantly radiation-limited forests, is the most likely explanation for the increased tropical NPP (28, 29). Since there is no evidence of trends in rainfall or streamflows (30) concurrent with these declines in cloud cover in this region, it is likely that rainfall patterns have changed.

Quantifying trends in NPP, as we have sought to do here, is necessary, but not sufficient for understanding land surface net ecosystem exchange of CO_2. The same climatic changes that have caused decadal-scale increases in NPP can also change above and below ground carbon allocation, decomposition rates, disturbance regimes and other processes that cycle carbon between terrestrial ecosystems and the atmosphere. Atmospheric CO_2 inversion models show that northern mid-latitude ecosystems have recently been consistently large carbon sinks, and the tropics are either neutral or small sources, albeit with high uncertainty (1). Our satellite-based estimates of NPP, on the

other hand, show significant growth stimulation in both the tropics and the northern high latitude ecosystems. Assuming that carbon emissions, including those from biomass burning and land use changes, are properly accounted for in the atmospheric inversions, this spatial discrepancy means that respiration as well as NPP is a major driver of terrestrial carbon sink dynamics. Global climate models project, in response to increasing greenhouse gases, an intensified hydrologic cycle altering the patterns of temperature, humidity, cloud cover and rainfall (1). Our ability to predict the future of terrestrial ecosystems is contingent upon how well we can interpret such changes in the context of multiple limiting factors to biogeochemical cycling.

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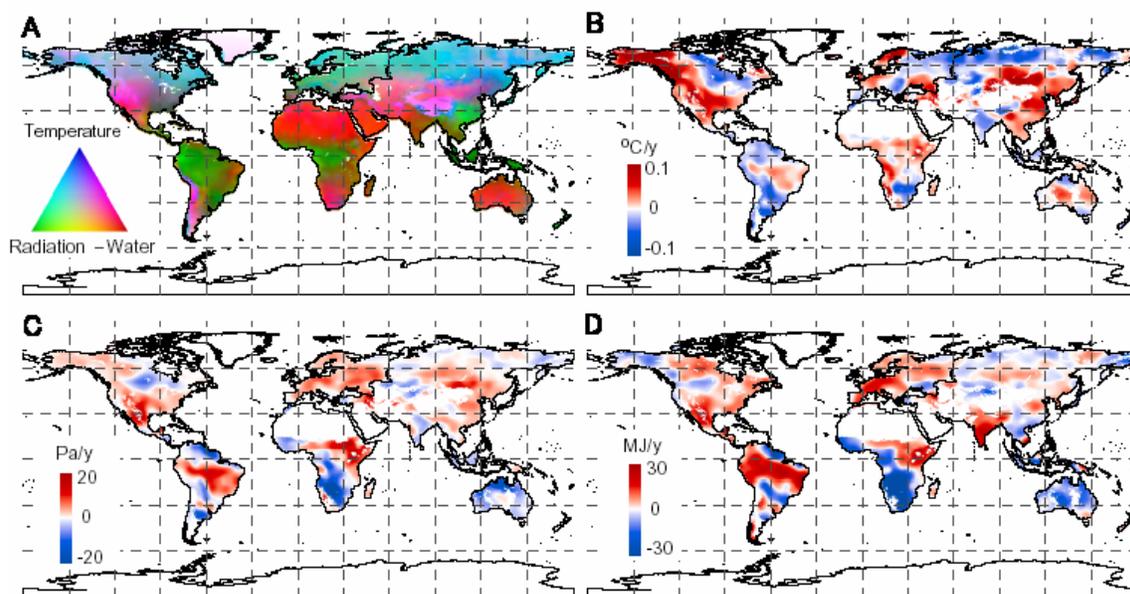31.   K. Wolter, M. S. Timlin, *Weather* **53**, 315-324 (1998).

Figure 1: Geographic distribution of potential climatic constraints to plant growth derived from long-term climate statistics (A), and recent climatic changes, estimated from reanalysis data from 1982 to 1999, over the growing season of average temperature (B), of vapor pressure deficit, reductions in VPD are indicative of increased water availability (C), and of solar radiation (D). Growing season is defined as those months with 1982-1999 average air temperatures above zero ^{o}C.
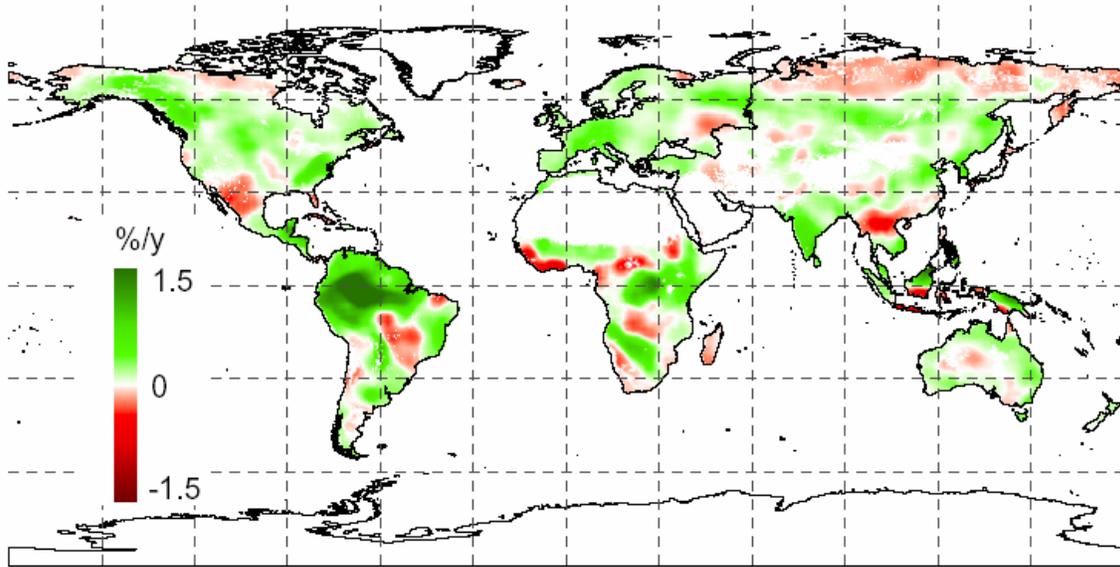
Fig. 2: Spatial distribution of linear trends in estimated NPP from 1982 to 1999. NPP was calculated using mean FPAR and LAI derived from GIMMS and PAL data sets.
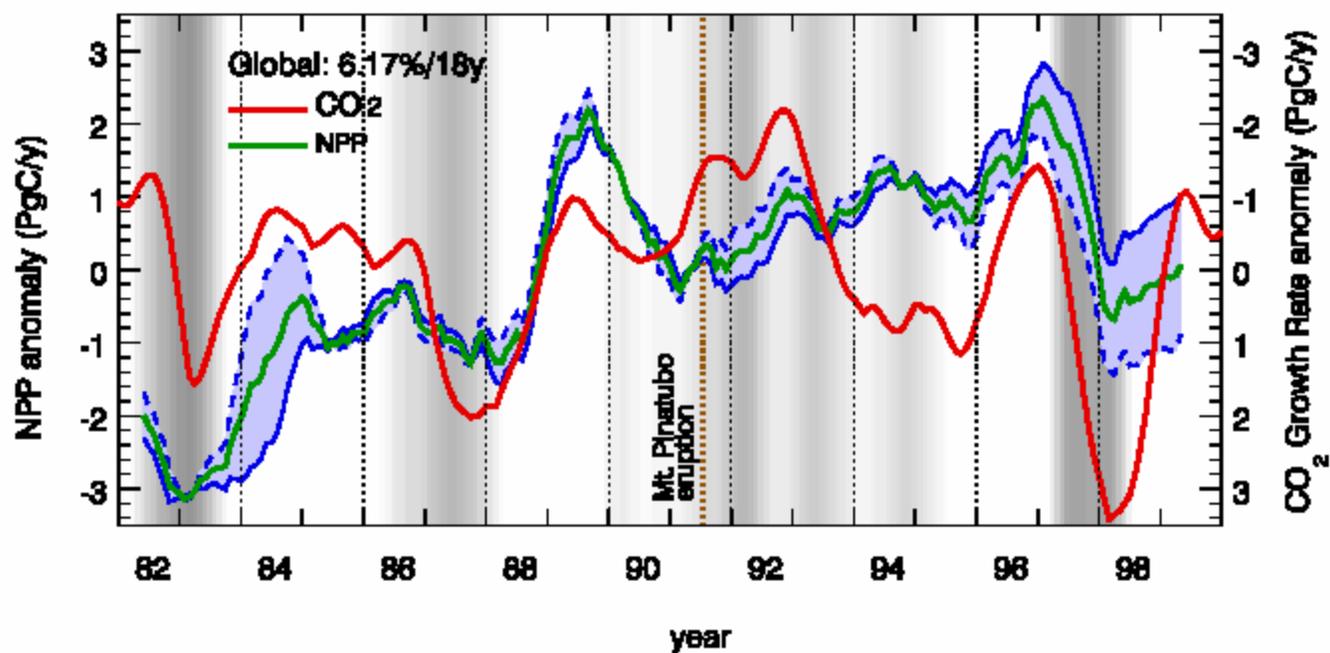
Fig. 3: Interannual variations from 1982 to 1999 in global NPP in relation to atmospheric CO_2 growth rate. Trends in global NPP anomalies are shown for GIMMS (solid blue), PAL (dashed blue) and their average in green. CO_2 growth rate (inverted) is shown in red. Growth rates in ppm were converted to Pg of carbon using a conversion factor of 2.12 Pg per ppm (24)). Mean NPP was 54.5 PgC/yr. Mean CO_2 growth rate was 3.2 Pg C/yr. A multivariate ENSO index (MEI (31)) is shown in grey scale, where darker shades represent higher MEI values.
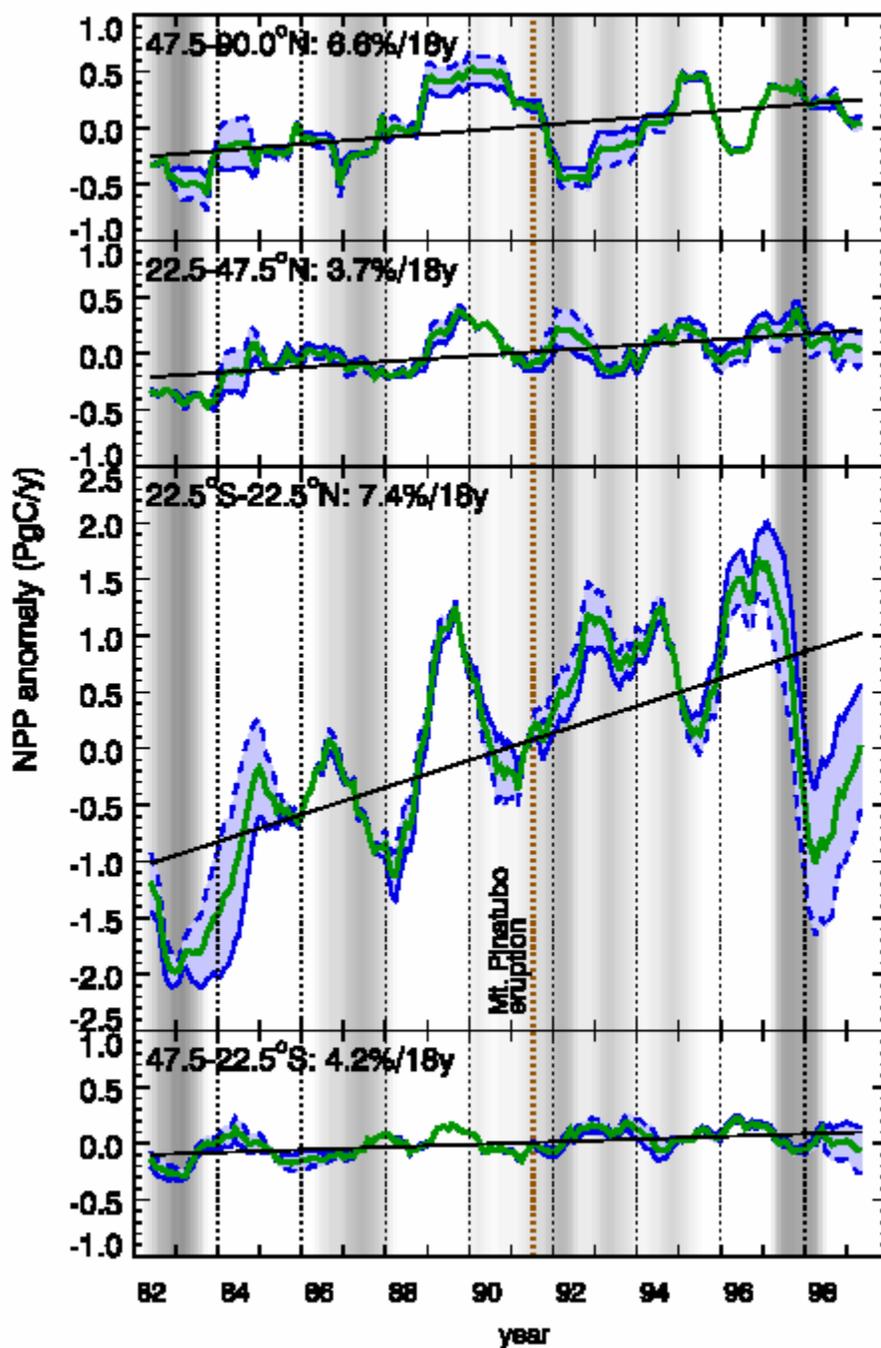
Fig. 4: Interannual variations in NPP distributed by latitudinal zones. Zonal NPP anomalies in each zone are shown for GIMMS (solid blue), PAL (dashed blue), and their average in green.