Available online at www.sciencedirect.com

SCIENCE DIRECT®

Global and Planetary Change 47 (2005) 221–231

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Climate variability, vegetation productivity and people at risk

Cristina Milesi[a,b,*], Hirofumi Hashimoto[c], Steven W. Running[a], Ramakrishna R. Nemani[b]

[a]*Numerical Terradynamic Simulation Group, Dept. of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT 59812, USA*
[b]*NASA Ames Research Center, Moffett Field, CA 94035, USA*
[c]*Graduate School of Agricultural and Life Sciences, University of Tokyo, 1-1-1 Yayoi, Bunkyoku, Tokyo 113, Japan*

Received 23 February 2004; accepted 29 October 2004

Abstract

Human domination of ecosystems has been pervasive over the last century, with nearly half of Earth's surface transformed by human actions. It is widely accepted that humans appropriate up to 50% of global net primary production (NPP), the energy base of all the trophic levels on the land surface. Yet, despite the important role of vegetation productivity for defining Earth habitability, the covariation of NPP and human population distribution has not been analyzed in depth. We used recently available satellite-based NPP estimates, along with gridded population at 0.5° resolution, first, to identify the global distribution of human population with reference to average NPP and to the various climatic constraints (temperature, water and cloud cover) that limit NPP, second, to analyze recent trends in global NPP in relation to population trends, and third, to identify populations that are vulnerable to changes in NPP due to interannual variability in climate. Our results indicate that over half of the global human population is presently living in areas with above the average NPP of 490 g C m^{-2} $year^{-1}$. By 1998, nearly 56% of global population lived in regions where water availability strongly influences NPP. Per capita NPP declined over much of Africa between 1982 and 1998, in spite of the estimated increases in NPP over the same period. On average, NPP over 40% of the total vegetated land surface has shown significant correlations with ENSO-induced climate variability affecting over 2.8 billion people.
© 2004 Elsevier B.V. All rights reserved.

Keywords: remote sensing; vegetation; productivity; ENSO; human population

1. Introduction

During the 20th century, a fourfold growth in human population to 6 billion people and remarkable increases in fossil fuel and industrial emissions, land cover changes, and agricultural activities have resulted in several changes in the Earth system, including changes in climate, hydrologic cycling, biodiversity and general degradation in environmental quality (Chapin et al., 2000; IPCC, 2001; WRI, 2003). A number of global efforts have been characterizing these changes at regular intervals (UNEP, 2002; WRI,

* Corresponding author. Tel.: +1 650 604 6431; fax: +1 650 604 6569.
E-mail address: milesi@ntsg.umt.edu (C. Milesi).

0921-8181/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2004.10.020

2003). Although incorporating socially relevant changes in this characterization could help in understanding the relevance of the biophysical changes in terms of Earth habitability, this joint analysis is often limited by the different spatial scales at which social and biophysical variables are being measured and made available at the global scale (Rindfuss and Stern, 1998; Tobler et al., 1995). The availability of global gridded population data, with recently improved and updated data sets such as the Gridded Population of the World (CIESIN, IFPRI and WRI, 2003) and LandScan (Dobson et al., 2000) provide a starting point towards a spatially explicit incorporation of a human dimension in the interpretation of the changes the biosphere is undergoing.

One of the biophysical variables that serves as a good indicator of the climatic, ecological, geochemical, and human influences on the biosphere but that has not yet been analyzed in relation to the distribution of human population is terrestrial net primary productivity (NPP), the net amount of carbon fixed by plants over time. Terrestrial NPP has direct relevance to humankind since it not only satisfies our immediate needs for renewable food, fuel, and shelter, but also provides the energy to sustain the life of the other organisms we depend on and controls a number of ecosystem services (Field, 2001; Daily, 1997). For example, terrestrial NPP integrates the annual carbon flux from the atmosphere to the land and, together with marine NPP, is the main driver of seasonal fluctuations in atmospheric CO_2 concentration (Keeling et al., 1996). Terrestrial NPP is an indicator of the vegetation contribution to the regulation of the water cycle, and relates to soil moisture and surface air humidity, reduced risk of floods, landslides, and soil erosion. Terrestrial NPP is also an indicator of the role played by vegetation in the regulation of nutrient cycling in limiting groundwater pollution and maintaining soil fertility (Daily, 1997).

According to Nemani et al. (2003), during the years 1982–1999, the combination of changes in climate and, possibly, land management practices (including nitrogen applications, irrigation, and reforestation) have resulted in an increase in NPP over large regions, globally averaging 6%. In particular, climate had a positive effect on NPP by becoming warmer in regions where vegetation growth is limited mostly by cold temperatures, wetter where it is principally limited by suboptimal precipitation, and less cloudy where available radiation, rather than low precipitation and/or cold temperatures, is the limiting climatic factor. The same study also indicates that the increase in terrestrial NPP was characterized by strong interannual variability, averaging 9% over the two decades, but with extremes of 20–30%. How did this long-term and interannual changes in terrestrial NPP compare with the recent growth in global human population and what can we infer about the effects of these changes on Earth's habitability?

Although a more complete answer to this question would require the analysis of several other socio-economic factors, we propose to take a first look at the potential sensitivity of the global population to climate-induced variability in vegetation productivity by analyzing the following points: (1) how was population distributed with respect to NPP and to the various climatic constraints (temperature, water and cloud cover) that limit vegetation productivity? (2) How did recent trends in global NPP compare to population trends? (3) How was the population distributed in relation to the geographic distribution and intensity of the interannual variability in terrestrial NPP?

2. Materials and methods

2.1. Population data

A digital representation of the global human population distribution (Fig. 1a) was obtained from the LandScan 1998 data set (Dobson et al., 2000). The layer was resampled from the original 30-by-30 arc second (corresponding to approximately 1-by-1 km grid cells) to 0.5° spatial resolution to match the resolution of the NPP data. The resampled grid cells cover an area on the land surface of approximately 56-by-56 km at the equator and 56-by-19 km at 70° N. The total population for the year 1998 estimated at 0.5° resolution was 5920 million people (comparable to the 5900 million people reported by the World Resource Institute).

To our knowledge, there was no global population distribution data set with a resolution comparable to LandScan for the early 1980s. The only available population maps for this period were representing

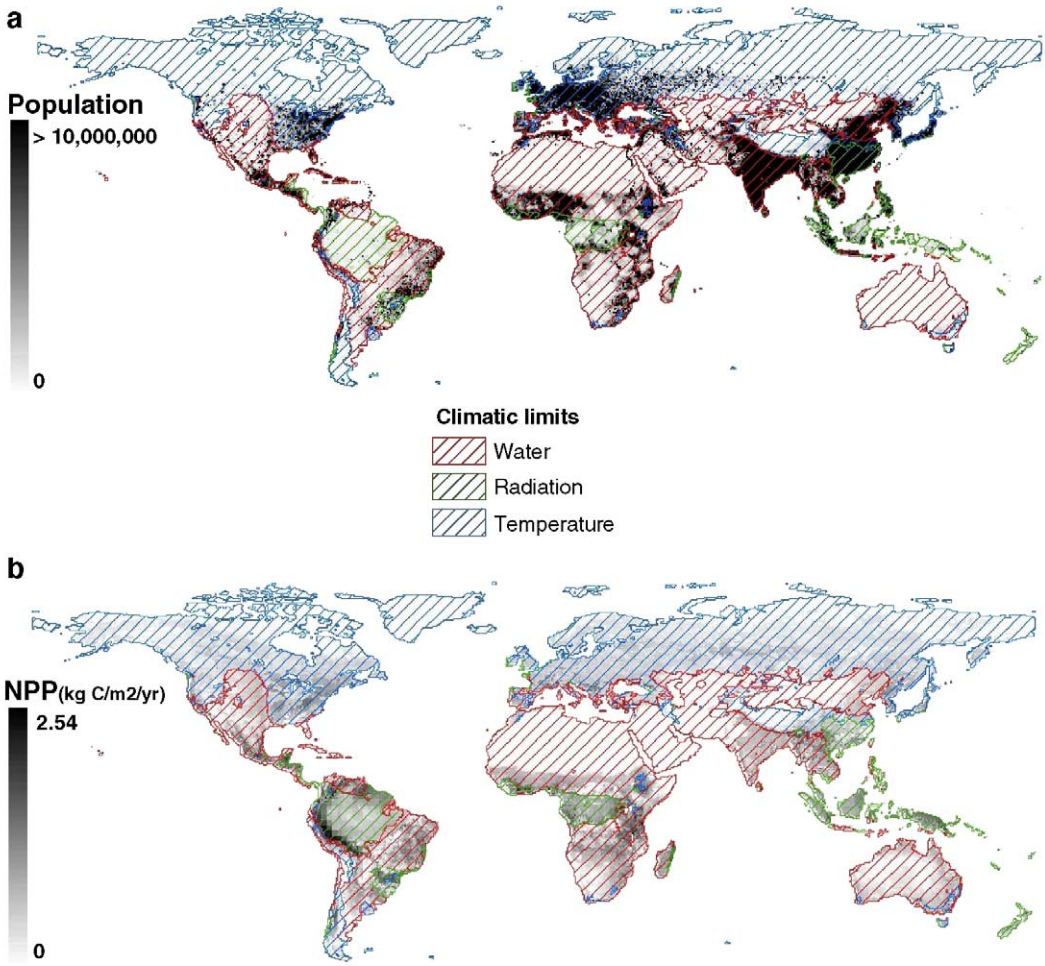

Fig. 1. (a) 1998 population derived from LandScan 1998. (b) 1982–1999 average NPP at 0.5° by 0.5° spatial resolution. A map of the climatic limits on NPP is superimposed on both maps.

country population totals. For this reason, we created a 0.5° gridded population map for the year 1982 using the 1998 resampled LandScan grid and national or, for the largest countries, subnational 1982–1998 population growth rates. The population growth rates were calculated from census data reported at the national and subnational level in the Populstat database (Lahmeyer, 2003). With the aid of a country mask and, for large countries, subnational administrative borders, the national or subnational 1982–1998 population growth was subtracted from the 1998 LandScan population of each grid cell falling within the specific administrative unit. Although overestimating the total population for the year 1982 (4702 million people versus the 4582 million people reported by the World Resource Institute), this approach provides a reasonable approximation of the spatial distribution of population growth at the scale of analysis of this study.

2.2. NPP data

We used monthly global 0.5° NPP data from 1982 to 1999 estimated by Nemani et al. (2003). The NPP data were estimated using a production efficiency model (Running et al., 2000) driven by satellite

greenness data calculated from monthly AVHRR (Advanced Very High Resolution Radiometer) NDVI (Normalized Difference Vegetation Index). Two independently processed global NDVI data sets were used: the Pathfinder AVHRR Land (PAL; James and Kalluri, 1994), and the Global Inventory Monitoring and Modeling System (GIMMS; Zhou et al., 2001). For this study, we used NPP estimates calculated as an arithmetic average of the two data sets (Fig. 1b).

2.3. Dominant climatic controls on NPP

Dominant climatic controls on NPP were defined by Nemani et al. (2003) using long-term (1960–1990; Leemans and Cramer, 1991) monthly climate data of maximum/minimum temperatures, cloudiness, and rainfall, and developing scaling factors (0–1) to indicate the reduction in growing potential from its maximum in each month. In most regions, precipitation, radiation, and temperature co-limit and interact in controlling yearly NPP. The Indian Monsoon region, for example, can be limited by water during the dry season and radiation during the overcast wet season. However, in general, one of the three factors has a prevailing influence in diminishing NPP from its potential (it is precipitation in the case of the Indian Monsoon), and identifying the dominant limiting factor for every pixel results in the aggregation of spatially contiguous grid cells into large regions, generally analogous to the temperate (temperature-limited), inter-tropical (water-limited) and tropical-equatorial (radiation-limited) regions, offering a more physically-based alternative to a characterization of the population distribution based on latitudinal bands.

2.4. Population distribution with respect to average terrestrial NPP

In order to minimize the effects of interannual variability in vegetation productivity, we calculated a reference NPP for the late 1990s as the average of the 1996–1999 annual NPP. The relationship between the 1998 population and the reference NPP was analyzed by means of joint frequency distributions calculated for the occupied land areas and total land areas, both as global totals and disaggregated by climatic zones.

The spatial distribution of the changes in NPP over the period 1982–1999 was derived by mapping the significant (P-value <0.001) 18-year trend in vegetation productivity. For each pixel, the yearly trend was calculated by fitting a linear regression through the annual NPP data. A percent change in per capita NPP was also mapped to compare the effect of the long-term changes in local NPP with local population changes.

Due to the coarse spatial resolution of the analysis presented here, several types of land covers and topography are included in most of the 0.5° by 0.5° grid cells so that the NPP of each grid cell is an averaged estimate. Other sources of uncertainty affecting the joint frequency distributions are due to the resampling of the 1998 population data set and the methodology used to estimate the 1982 population layer. Therefore, as the results of the joint frequency distributions are likely to slightly change at a different spatial resolution, the relative differences in NPP between the populated and the total land areas, as well as the differences in productivity under the different climatic constraints should be deemed more important than the absolute values of NPP.

2.5. Population distribution with respect to interannual variability of terrestrial NPP

While the overall increase in NPP recorded during the period 1982–1999 can be attributed both to long-term changes in climate that helped easing constrains on plant growth and to changes in land management, the strong interannual fluctuations are dominated by year-to-year climatic variability. On a global scale, the major coupled ocean–atmosphere forcing mechanism on interannual climatic variability is exerted by the ENSO (El Niño-Southern Oscillation) phenomenon (Philander, 1990). The Southern Oscillation, representing the atmospheric component of the ENSO, is determined by the difference in atmospheric pressure between Indonesia/North Australia (Darwin) and the southeast Pacific (Tahiti). El Niño is used to refer to the warming of the surface waters of the eastern equatorial Pacific that occurs at irregular intervals of 2–7 years. During an El Niño, sea level pressure tends to be lower in the eastern Pacific and higher in the western Pacific. La Niña is the counterpart of El Niño and is characterized by cooler than normal sea surface

temperatures across much of the equatorial eastern and central Pacific. During La Niña, sea level pressure patterns across the eastern and central Pacific are reversed with respect to the ones observed during El Niño. The teleconnections between climate patterns arising during ENSO events and NPP can be identified through statistical temporal correlations with climatic indexes. The Multivariate ENSO Index (MEI) captures the coupled oceanic-atmospheric character of ENSO as the first unrotated principal component of the main variables observed over the tropical Pacific, namely sea-level pressure, the east–west and north–south components of the surface wind, sea surface temperature, surface air temperature, and total amount of cloudiness (Wolter and Timlin, 1988). Negative values of MEI indicate a cool ENSO event (La Niña) while positive values signify a warm ENSO event (El Niño conditions).

To map the spatial distribution and intensity of the teleconnections between ENSO-induced climate variability and NPP, we linearly regressed, by grid value, the time series of detrended monthly NPP data upon the monthly standardized MEI values for the period 1982–1999. To account for the lagged response of NPP to ENSO, we performed the regression with a 6-month time lead in the climatic index. The 1991 Pinatubo eruption dictated the exclusion of the NPP and MEI data for the months between mid-1990 and mid-1993.

To address the question of how the population was distributed in relation to the geographic distribution and intensity of the interannual variability in terrestrial vegetation productivity, we isolated the grid cells displaying significant correlations (P-value <0.05), and overlaid the human population layer on the regression results.

3. Results

3.1. Distribution of population with respect to average NPP and dominant climatic limits to NPP

The statistics on the distribution of the population and the land area as a function of NPP are summarized in Table 1. While these values are likely to change with the use of higher resolution data, they provide a framework to define average present conditions and set a reference for monitoring changes. The statistics indicate that the global human population tends to live in areas characterized by average to above-average values of vegetation productivity. While the populated areas and the total land area have the same mean NPP, the median person lives at higher than average NPP (590 g C m^{-2} $year^{-1}$ versus a global mean of 490 g C m^{-2} $year^{-1}$). The median land pixel has an NPP of 460 g C m^{-2} $year^{-1}$. Large land areas (51.6 million km^2 or 35% of the total) are bare or very sparsely vegetated, with an NPP of less than 50 g C m^{-2} $year^{-1}$, and thinly populated (212 million people, on average 4 people km^{-2}). On the other hand, a surface of 2.4 million km^2 possesses very high vegetation productivity (NPP greater than 1500 g C m^{-2} $year^{-1}$). These high productivity areas are inhabited by 89 million people (on average 36 people km^{-2}).

Table 1
Distribution of 1996–1999 average NPP (g C m^{-2} $year^{-1}$) and 1998 population over populated areas and total land area

Populated land					Total land			
NPP (g C m^{-2} $year^{-1}$)	Global	Water	Radiation	Temperature	Global	Water	Radiation	Temperature
Minimum	0	0	0	0	0	0	0	0
First quartile	420	440	470	390	250	280	550	70
Median	590	630	600	490	460	550	780	270
Third quartile	770	780	880	640	750	800	1090	440
Maximum	2550	2490	2550	2170	2550	2490	2550	2170
Mean	490	490	870	380	490	570	890	340
Standard deviation	400	410	450	270	380	380	450	260
Population								
1998 Population (10^6)	5900	3300	1100	1500				
1998 Population density (people km^{-2})	40	50	71	22				

The dominant climatic limits on NPP superimposed on both maps in Fig. 1 show that temperature is the climatic limiting factor at high latitudes, from the poles to 40–30°, depending on the longitude, affecting 45% of the total (vegetated and ice covered/barren) land surface. Suboptimal levels of precipitation constrain vegetation growth over an additional 45% of the land area, in the tropical and subtropical areas and much further north than that in both North America and Asia. Regions where vegetation growth responds predominantly to a reduction in cloudiness (i.e., an increase in radiation) are mostly confined to equatorial areas and to southeastern China, amounting to 10% of the total land surface. Table 1 also reports that, while the largest percentage of the global population in 1998 was living in water-limited regions (56% of the total), the highest density (more than 70 people km^{-2}) is found in the radiation-constrained areas, which are also characterized by the highest rates of vegetation productivity. Here, the mean NPP of the populated grid cells is 870 g C m^{-2} $year^{-1}$, followed by the water-limited and the temperature-limited areas. While the mean NPP of the populated areas in each of the climatic regions is generally not higher than the mean land NPP, the median person of the water- and temperature-limited areas lives in areas characterized by a higher NPP than the median land grid cell under the same constraining climatic factor.

3.2. 1982–1999 trends in population versus trends in NPP

Fig. 2 maps the distribution of the 1982–1999 changes in NPP and in population, and the combined relative effect of these changes on per capita NPP. Fig. 3 summarizes the changes in NPP and population by dominant climatic limits.

During the years 1982–1998, the world population increased globally by 26%. Population growth presented strong spatial heterogeneity, with the strongest growth in water-limited areas (34%), which, including most of India and southeastern China, also hosts the largest population. In radiation-limited regions, population grew by 26% whereas the smallest growth (12%) was recorded for temperature-limited regions, where, during the analyzed period, many countries had very limited population growth. Only a few regions show a net decrease in population over the analyzed period, and are mostly represented by eastern European countries and an area of eastern China, the latter being possibly due census counts inconsistencies.

While overall population has risen linearly, NPP has increased with large interannual fluctuations and with a lower pace. The largest increase has been observed over the radiation-limited areas (11%), followed by temperature- (5%) and, lastly, water-limited areas (3%), with a global average of 6%. Wide regions in all continents have recorded net decreases in NPP, although less significant than the increases (Nemani et al., 2003).

The per capita change in NPP for the period 1982–1999 (Fig. 2), calculated as the ratio between the changes in NPP and the changes in population, indicates that for 47% of the vegetated pixels the combined demographic and vegetation productivity dynamics resulted in a decrease in per capita NPP. For only 7% of the vegetated pixels the increase in vegetation productivity surpassed population growth. This was possible only where population growth was very limited or negative. In all the grid cells where NPP per capita decreased, population increased and NPP either decreased or increased too little to compensate for population growth. This effect was most evident in the water-limited regions (Fig. 3), where rates of population growth were the highest and were accompanied by the smallest positive trends in NPP.

3.3. Population sensitivity to interannual variability in NPP

The monthly NPP regressed upon the monthly MEI values shifted with a 6-month lag, filtered to show only the grid cells where the P-value ≤ 0.05, is displayed in Fig. 4. The regression depicts the 18-year average effect of ENSO-related climatic variability on NPP through altered patterns in precipitation, temperature and/or radiation availability.

Significant correlations between MEI and NPP are found over a total of 64 million km^2 (63% of the total vegetated surface). This result is consistent with the analysis of the teleconnections of climate to the terrestrial carbon flux reported by Potter et al. (2003). The changes in NPP per unit variation in MEI top 50 g C m^{-2} $year^{-1}$. The total surface showing

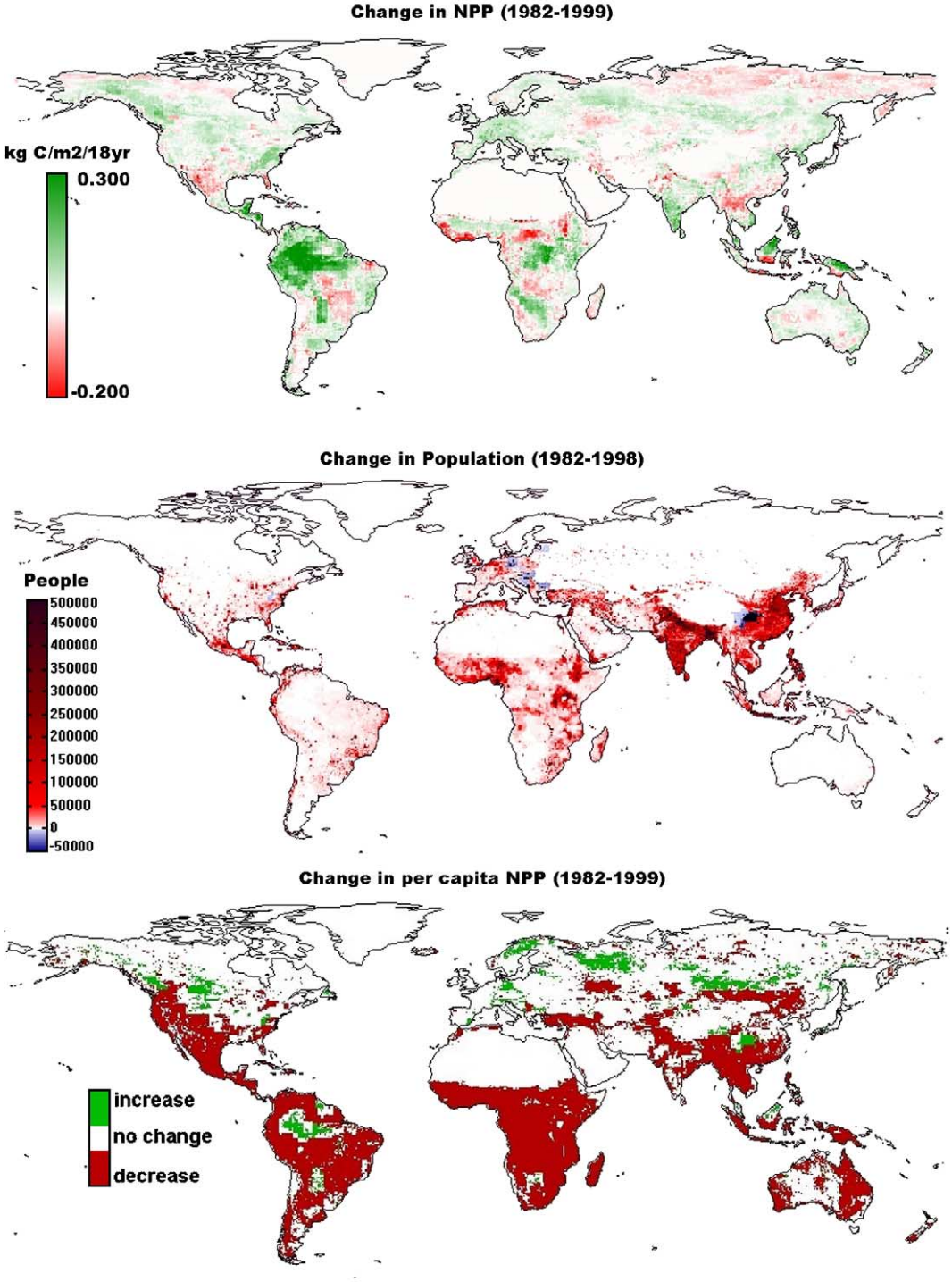

Fig. 2. Spatial distribution of the changes in total NPP, population and per capita NPP observed during the period 1982–1999.

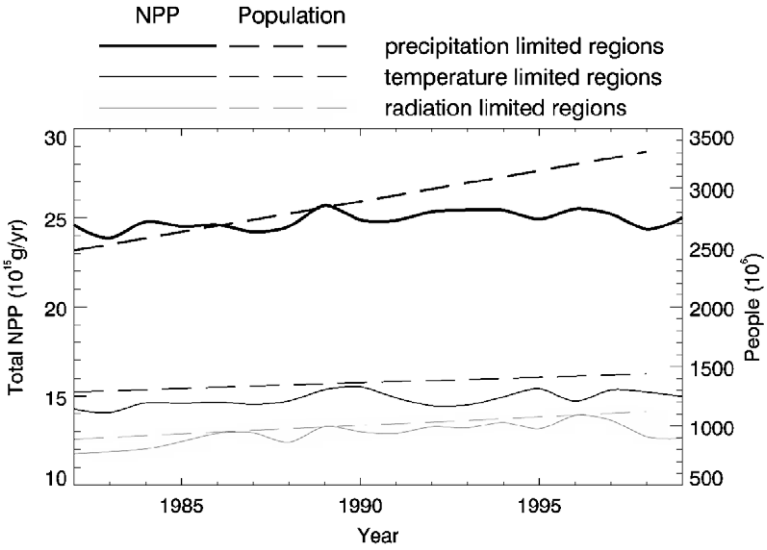

Fig. 3. Times series of population (dashed line) and NPP (continuous line) for the period 1982–1999 by climatic constraints on NPP.

significant correlations with MEI is populated by a total of 3350 million people. Negative correlations between MEI and NPP represent by far the prevailing pattern, interesting 78% (50 million km^2) of the surface showing significant teleconnections and 2800 million people. The strongest decreases in NPP per unit variation in MEI are found in Central America, Venezuela, Guyana, Suriname and large portions of both the dominantly radiation-limited and precipitation-limited regions of Brazil, large portions of the sub-Saharan regions of Africa (with the exception of most of Angola, Zambia, Tanzania, Kenya and South Africa), east-central India and most of Southeast Asia and Southeastern Australia.

Positive variations per unit variations in MEI are stronger in western Canada and western United States, Peru, central Argentina, some portions of eastern Africa (mainly in Ethiopia and Kenya).

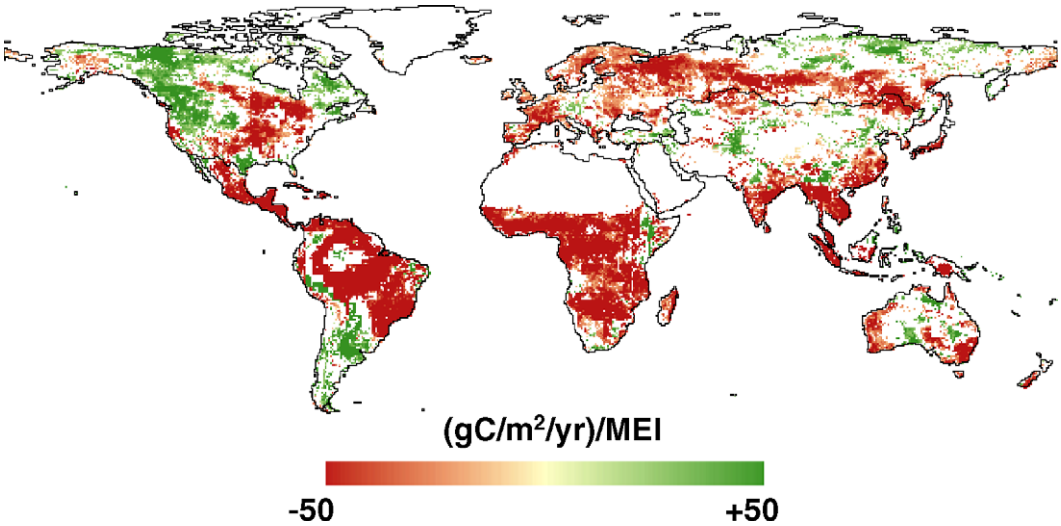

Fig. 4. Variations in NPP per unit variations of MEI.

For more than 90% of the area displaying significant correlations between NPP and MEI, the relative variation in NPP per year is generally within ±10% of the average 1982–1999 NPP. Greater relative variations in NPP per unit variation in MEI take place in areas with progressively lower NPP.

Analyzing the spatial extent of the MEI–NPP relationship by climatic limits, it appears that 47% of the total affected area falls within water-limited regions, followed by 35% in the temperature-limited areas and 18% in the radiation-limited areas. Of the total population living in the affected areas, 53% is in the water-limited areas, followed by 23% in temperature- and 24% in radiation-limited areas.

4. Discussion and conclusions

The distribution of population as a function of NPP indicates that humans are localized in areas with average to above-average NPP. Because of the several ecosystem services associated with NPP, such as access to water and high soil fertility, many of these regions have been civilized for thousands of years. Some of the above-average productivity areas would probably show even higher NPP if less densely populated. The conversion of forests or grasslands into croplands and urban areas tends to lower the NPP (Houghton, 1999). It is noteworthy to observe that the regions of the world with the highest NPP, such as the tropical rainforests (radiation-limited areas) are still relatively sparsely populated. The fact that in these regions, the median land grid cell has a higher NPP than the median populated grid cell (Table 1) could indeed indicate that an increased human presence could decrease NPP. In less productive regions, on the other hand, the conversion of non-forested land into cropland has increased the NPP above the potential levels with the aid of irrigation and fertilization (DeFries, 2002). Examples can be found in some of the water-limited regions of China and India, which rely heavily on irrigation for 40% and 24% of their respective croplands (FAOSTAT, FAO Statistical Databases, available online at http://apps.fao.org). Humans, therefore, by increasing NPP above potential levels where it is low and reducing it below potential levels where it is high, create an intermediate productivity environment where they localize and maximize their activities.

Although the changes in NPP observed during the period 1982–1999 probably helped mitigate the effects of increased human activities that took place during the same period, on a per capita basis they had little or no effect, as in most of the regions population growth was by far larger than the increase in vegetation productivity, especially in the water-limited regions (Fig. 3). Among these, it is noteworthy that the African continent, which also has among the poorest populations, appears to have benefited the least form changes in NPP per capita over the period 1982–1999.

The moderate increase in NPP observed during the past two decades has come with a strong interannual variability (Fig. 4), which in most of the years surpassed in magnitude the global average increase in NPP. While it is too early to say whether the increasing trend in NPP will continue in the future, it is highly probable that the interannual variability will remain strong or even intensify (IPCC, 2001), and will potentially continue to affect the regions currently inhabited by more than half of the global human population. As more than half of the total population living in regions with significant MEI–NPP correlations is found in water-limited areas, which also had the fastest population growth in 1982–1998 period, we can expect that the number of people at risk to ENSO-related variability in vegetation productivity will continue to grow. The regions with the strongest variations in NPP associated to ENSO-related climatic variability were characterized by below average vegetation productivity, mostly grasslands and savanna, a characteristic that probably made the local population even more sensitive to climatic fluctuations.

Decreases in NPP, mostly caused by droughts and wildfires, were the most frequent result of this variability. The analysis presented in this paper identifies *potentially* sensitive populations to ENSO events because it defines the regions where NPP has displayed significant correlations with MEI over an 18-year period. How these decreases impact societies is highly variable and depends also on a number of other predisposing factors, such as government policies, human diseases, dependence on regional water and power supply, conflicts, unfavorable

markets, lack of credit, unavailable storage and shipping facilities, and many others (Glantz, 2001a). The decreases in NPP resulting from ENSO teleconnections observed over most of the African continent, which also showed widespread decreases in NPP per capita over the period 1982–1999, indicate that here populations may have a higher potential sensitivity to future intensifications of interannual climatic variability. Even where the variability was associated with an increase in NPP, this may not have been always a positive event since it could have come along with floods. Heavy rains during ENSO events have also been associated with the outbreaks of waterborne and vector transmitted diseases (Epstein, 1999; Linthicum et al., 1999).

In conclusion, recent increases in global NPP appear to have been very modest when analyzed from the perspective of population growth, especially in those regions with larger population bases and higher demographic growth rates. These are also the regions that, on average, appear to have stronger ENSO teleconnections and that could be more severely at risk of an intensification of climatic variability, independently of whether this variability will result in a long-term net increase in global NPP.

The analysis presented in this study makes use of a global NPP data set calculated at 0.5° spatial resolution, but standard yearly NPP data from the Earth Observing System at 1-km resolution will vastly enhance the detail of this analysis and the potential for future monitoring (Running et al., 2000; Running et al., 2004). Incorporating population data, already available as a gridded data set at 1-km resolution, and other socioeconomic information into the regular monitoring of global NPP could improve our understanding of the effects of global environmental change on Earth sustainability. The standard translation of NPP into variables holding more tangible economic and societal meaning, such as crop yield and timber production, would further enhance the monitoring.

It is important to keep monitoring the geographical distribution of socioeconomic variables also as we continue to improve our ability of seasonal or annual forecasting of climatic teleconnections and their effect on NPP. Incorporating socioeconomic information into the monitoring process, the vulnerable portion of the population (i.e., likely to be exposed and adversely affected (Cutter, 1996)), could also be identified, translating the scientific results into information that could be highly valuable to government and societies (Glantz, 2001b). For many regions of the world, where the climatological network is sparse and data require manual collection rather than being distributed online, it is otherwise difficult to estimate the spatial impact of climatic variability. Even when climate data are available to be analyzed in real-time, an integrated ecological measure such as NPP is a better parameter than precipitation or temperature alone.

Acknowledgements

This work was funded in part by NASA's Earth System Science Fellowship Program and various grants from NASA's Earth Science Enterprise. We acknowledge the additional support provided by START of IHDP/IGBP/WCRP for inviting C. Milesi to the International Young Scientists' Global Change Conference (16–20 November, 2003, Trieste, Italy) and sponsoring this special issue. We are grateful to three anonymous reviewers for their valuable comments and suggestions. We are also indebted to Faith Ann Heinsch, Carol Brewer, Eric Edlund, Sarah Halvorson and Steve Siebert at the University of Montana for their input on earlier drafts.

References

Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI); and World Resources Institute (WRI), 2000. Gridded Population of the World (GPW), Version 2.

Chapin III, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Díaz, S., 2000. Consequences of changing biodiversity. Nature 405, 234–242.

Cutter, S.L., 1996. Vulnerability to environmental hazards. Prog. Hum. Geogr. 20 (4), 529–539.

Daily, G., 1997. Nature's services: societal dependence on natural ecosystems. Island Press, Washington.

DeFries, R.S., 2002. Past and future sensitivity of primary production to human modification of the landscape. Geophys. Res. Lett. 29 (7), 36-1–36-4.

Dobson, J.E., Bright, E.A., Coleman, P.R., Durfee, R.C., Worley, B.A., 2000. Landscan: a global population database for estimating population at risk. Photogramm. Eng. Remote Sensing 66 (7), 849–857.

Epstein, P., 1999. Climate and health. Science 285, 347.

Field, C.B., 2001. Sharing the garden. Science 294, 2490–2491.

Glantz, M.H., 2001. Currents of change: Impacts of El Niño and La Niña on climate and society. Cambridge University Press, Cambridge.

Glantz, M.H., 2001. Once Burned, Twice Shy? Lessons learned from the 1997–98 El Niño. UN University Press, Tokyo, Japan. 294 pp.

Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. Tellus, B 51 (2), 298–313.

IPCC, 2001. Climate change 2001: impacts, adaptation and vulnerability—contribution of working group II to the Third Assessment Report of IPCC. Cambridge University Press, Cambridge, UK.

James, M.E., Kalluri, S.N.V., 1994. The Pathfinder AVHRR land data set: an improved coarse resolution data set for terrestrial monitoring. Int. J. Remote Sens. 15 (17), 3347–3364.

Keeling, C.D., Chin, J.F.S., Whorf, T.P., 1996. Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. Nature 382, 146–149.

Lahmeyer, J., Populstat: historical demography of all countries, their divisions and towns, available online at: http://www.library.uu.nl/wesp/populstat/populframe.html. (Last update: 2003.03.10; verified 2004.06.03).

Leemans, R., Cramer, W.P., 1991. The IIASA database for mean monthly values of temperature, precipitation and cloudiness of a global terrestrial grid. IIASA research report, vol. RR-91-18. International Institute of Applied Systems Analyses, Laxenburg.

Linthicum, K., Anyamba, A., Tucker, C., Kelley, P., Myers, M., Peters, C., 1999. Climate and satellite indicators to forecast Rift Valley fever epidemics. Science 285, 397–400.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R.B., Running, S.W., 2003. Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. Science 300, 1560–1563.

Philander, S.G., 1990. El Niño, La Niña, and the Southern Oscillation. International Geophysics series, vol. 46. Academic Press, San Diego, CA.

Potter, C., Klooster, S., Steinbach, M., Tan, P., Kumar, V., Shekhar, S., Nemani, R., Myneni, R., 2003. Global teleconnections of climate to terrestrial carbon flux. J. Geophys. Res. 1081 (D17), 4556, doi:10.1029/2002JD002979.

Rindfuss, R.R., Stern, P.C., 1998. Linking remote sensing and social sciences: the need and the challenges. In: Liverman, D., Moran, E.F., Rindfuss, R.R., Stern, P.C. (Eds.), People and Pixels: Linking Remote Sensing and Social Science. National Academy Press, Washington, DC, pp. 1–27.

Running, S.W., Thornton, P.E., Nemani, R., Glassy, J.M., 2000. Global terrestrial gross and net primary productivity from the Earth Observing System. In: Sala, O., Jackson, R., Mooney, H. (Eds.), Methods in Ecosystem Science. Springer-Verlag, New York, pp. 44–57.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M., Hashimoto, H., 2004. A continuous satellite-derived measure of global terrestrial primary production. Bioscience 54 (6), 547–560.

Tobler, W., Deichmann, U., Gottsegen, J., Maloy, K., 1995. The Global Demography Project. Technical Report TR-95-6. National Center for Geographic Information and Analysis, Department of Geography. University of California, Santa Barbara, CA.

UNEP, 2002. Global Environment Outlook 3. Earthscan Publications, London.

Wolter, K., Timlin, M.S., 1988. Measuring the strength of ENSO events—how does 1997/98 rank? Weather 53, 315–324.

WRI, 2003. World Resources 2002–2004: decisions for the Earth: balance, voice, and power. World Resource Institute, Washington, DC. Also available online at: http://pubs.wri.org/.

Zhou, L., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N.V., Myneni, R.B., 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981–1999. J. Geophys. Res. 106 (D17), 20069–20083.