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The supply and demand of net primary production in the Sahel

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Abstract

Net primary production (NPP) is the principal source of energy for ecosystems and, by extension, human populations that depend on them. The relationship between the supply and demand of NPP is important for the assessment of socio-ecological vulnerability. We present an analysis of the supply and demand of NPP in the Sahel using NPP estimates from the MODIS sensor and agri-environmental data from FAOSTAT. This synergistic approach allows for a spatially explicit estimation of human impact on ecosystems. We estimated the annual amount of NPP required to derive food, fuel and feed between 2000 and 2010 for 22 countries in sub-Saharan Africa. When comparing annual estimates of supply and demand of NPP, we found that demand increased from 0.44 PgC to 1.13 PgC, representing 19% and 41%, respectively, of available supply due to a 31% increase in the human population between 2000 and 2010. The demand for NPP has been increasing at an annual rate of 2.2% but NPP supply was near-constant with an inter-annual variability of approximately 1.7%. Overall, there were statistically significant ($p < 0.05$) increases in the NPP of cropland (+6.0%), woodland (+6.1%) and grassland/savanna (+9.4%), and a decrease in the NPP of forests (−0.7%). On the demand side, the largest increase was for food (20.4%) followed by feed (16.7%) and fuel (5.5%). The supply-demand balance of NPP is a potentially important tool from the standpoint of sustainable development, and as an indicator of stresses on the environment stemming from increased consumption of biomass.

S Online supplementary data available from stacks.iop.org/ERL/9/094003/mmedia

Keywords: Drylands, sustainability, NPP, Sahel, climate change, vulnerability

1. Introduction

Net primary production (NPP) represents the amount of atmospheric carbon that is fixed by vegetation during photosynthesis and accumulates as biomass. It represents the availability of carbon in the form of plant material for consumption as food, fuel and feed. NPP has been linked to crop yield (Tao *et al* 2005), biomass energy potential (Field *et al* 2008), forest production (Baisden 2006), and grazing resources (Leriche *et al* 2001). In sub-Saharan Africa NPP resulting from extensive agriculture and dry woodlands plays an important role in maintaining food security and providing household energy. However, these resources are under pressure from high population growth, which increases demand for NPP, and climate change, which impacts supply (IPCC 2014). The 'supply' of NPP is defined here as the annual amount of carbon stored in the ecosystem as plant tissue.

Semi-arid regions are particularly vulnerable to fluctuations in the supply of NPP due to its natural scarcity. In these regions, increased human activities are often driven by the demand for food, fuel and feed, which brings about changes that alter the spatial patterns of NPP such as cropland expansion, pasture creation, and fuelwood extraction. For example, large increases in demand for NPP lead to increased

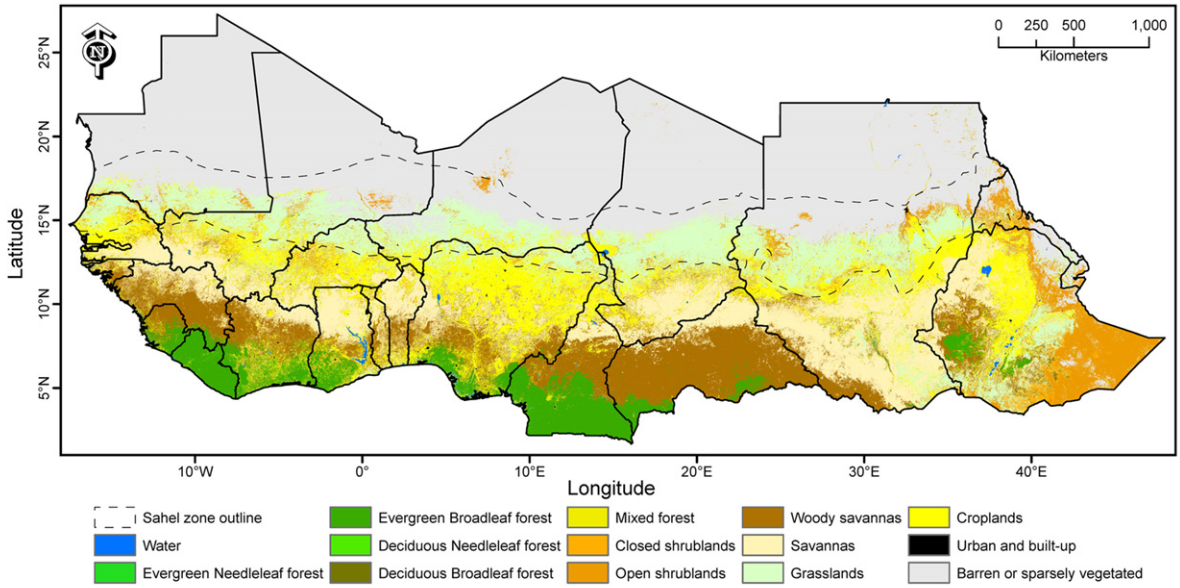

Figure 1. IGBP classification of the study area according to the MODIS Land Cover Type Product (MCD12Q1). The dashed line represents rainfall isohyets between 100 and 600 mm that delineate the Sahelian zone.

pasture stocking rates (Vargas *et al* 2009) resulting in soil compaction and vegetation defoliation (Hiernaux *et al* 1999). Additionally, crop yields, particularly in parts of sub-Saharan Africa, have been declining (Aune *et al* 2005, Chianu *et al* 2006) due to, among other things, reduction in soil fertility caused by continuous cropping to meet demand (Samaké *et al* 2005).

We use the terms 'demand' and 'consumption' to denote two different, but closely related, things. Demand for NPP is defined as the annual amount of carbon required to derive the food, fuel and feed necessary for human survival, and which also includes carbon lost during harvest and handling. The term 'consumption' refers to the actual amount of NPP that is extracted from the ecosystem as reported in the statistical database of the Food and Agriculture Organization of the United Nations (FAOSTAT).

Field estimation of NPP involves harvesting vegetation and calculating the annual growth of wood, the mass of foliage at peak leaf display, and the difference in the mass of tissue harvested at the beginning and end of the growing season (Schlesinger 1997). NPP varies spatially due to both environmental and anthropogenic factors and, because fieldwork is both labor and cost intensive, it would be exorbitantly expensive to conduct measurements over large extents. In this regard, data from satellite remote sensing platforms provide useful tools for quantifying the availability of NPP at regional scales.

We chose the Sahel region of Africa as an example of a complex, semi-arid, human-environment system where the supply-demand balance of NPP is in a constant flux. The Sahel has been subject to numerous droughts in the late 20th and early 21st centuries. Severe, region-wide, drought-induced famines occurred in 1972–1973 and 1984–1985 (Sen 1983, Ibrahim 1988), and there were localized food shortages in 1990, 2002 and 2004. Recently, food production deficits were reported by several Sahelian countries in 2011/2012 and it is presently estimated that over 11 million people across the region are food insecure (United Nations 2013). A combination of unfavorable climatic conditions (Gonzalez *et al* 2012) and anthropogenic pressure (Sop and Oldeland 2011, Hassan *et al* 2009) have caused declines in crop yield (Thornton *et al* 2008) and the diversity of Sahelian woody plant species (Wezel 2005).

The objectives of this paper are to quantify for the period 2000–2010: (1) the amount of NPP required to derive food, fuel and feed, (2) the fluctuations in the supply NPP, and (3) the percent of NPP demand relative to supply across the region. The chosen study period coincides with the availability of two open-access datasets (1) a continuous, high-resolution, satellite-derived NPP dataset, and (2) a high resolution population distribution dataset covering three time slices: 2000, 2005, and 2010.

2. Materials and methods

2.1. Study area

The study area covers the portion of the African continent between 5° and 25° north latitude with a focus on the Sahel, which is bounded by the 100 mm and 600 mm rainfall isohyets (figure 1). Northern parts of the area that border the Sahara Desert have a mean annual rainfall of less than 100 mm. To south of the Sahel are the humid savannas of the Sudano-Guinean zone that receive ample rainfall, between 600–1000 mm, enabling high vegetation productivity. Most of the region has one growing season, the start and length of which varies with latitude. The growing season in northern parts of the of the study area begins in July and ends in October; in the southern parts (<10°N) the season starts around April and lasts until November (Vrieling *et al* 2013).

2.2. NPP supply

We obtained the latest Collection 5.1 annual MODIS NPP data from 2000 to 2010 from the NASA Earth Observation System repository at the University of Montana (www.ntsg.umt.edu/). The MOD17 light use efficiency model (Heinsch *et al* 2003) calculates NPP as the difference between gross primary production (parameters within parentheses in equation (1)) and autotrophic respiration including growth and maintenance components:

$$\mathrm{NPP_{Supply}} = \left(\mathrm{PAR*FPAR*}\varepsilon_{\max}\mathrm{*VPD*}T_{\min}\right) - \mathrm{Ra} \quad (1)$$

where $\mathrm{NPP_{Supply}}$ is the NPP available in the ecosystem regardless of land use type; PAR is incoming photosynthetically active radiation; FPAR is the fraction of incident PAR absorbed by the vegetation canopy; $\varepsilon_{\max}$ represents maximum light use efficiency under hypothetical biome-specific ideal conditions according to Monteith (1972); VPD and $T_{\min}$ are environmental scalars that constrain light use efficiency and stand for vapor pressure deficit and minimum temperature, respectively; Ra (autotrophic respiration) represents maintenance and growth respiration of leaves, fine roots and woody tissue. Further descriptions of the MOD17 model are detailed in Running *et al* (2004), Zhao *et al* (2005) and Zhao and Running (2010).

In order to delineate the land cover classes that source NPP for food, fuel, and feed, we obtained the latest Collection 5.1 of the MODIS Land Cover Type Product (MCD12C1) (Friedl *et al* 2010) from NASA's Land Processes Distributed Active Archive (LPDAAC) (https://lpdaac.usgs.gov). We used the International Geosphere Biosphere Program (IGBP) classification system and aggregated the 14 land cover classes within the study area into four land cover groupings (table 1S, supplementary information) based on ecophysiological similarities and their shared NPP sourcing capacity. For example, grasslands (<10% tree cover) and savannas (10–30% tree cover) were grouped together because both categories are predominantly composed of herbaceous cover that serve as grazing habitat for the region's livestock population. Similarly croplands and cropland/natural vegetation mosaics were grouped together into one category. We calculated $\mathrm{NPP_{Supply}}$ trends for the region based on regression slopes resulting from ordinary least squares versus time. We then isolated areas that displayed significance ($p < 0.05$) and intersected them with reclassified grids of the land cover groupings. This procedure resulted in grids of statistically significant $\mathrm{NPP_{Supply}}$ change for each land cover grouping. We also calculated annual $\mathrm{NPP_{Supply}}$ anomalies for the 2000–2010 time period by subtracting the decadal average from each yearly total.

2.3. Population density

Gridded population data for the years 2000, 2005 and 2010 were downloaded from the WorldPop Project (http://worldpop.org.uk/). The dataset is derived by using high resolution census data as a dependent variable in a Random Forest model along with a suite of independent variables that include land use and land cover, digital elevation, night-time lights, mean annual precipitation and mean annual temperature. Detailed descriptions of the population model are presented in Tatem *et al* (2007) and Linard *et al* (2011). We interpolated between 2000–2005 and 2005–2010 using annual population growth data from United Nations Statistical Database (UNSTAT 2014) to obtain continuous annual coverage between 2000 and 2010.

2.4. NPP demand

The Sahelian growing season coincides with the summer rains; crops are generally planted between May and July and harvested from October to November (USDA 1994). The NPP of croplands during the growing season represents the annual provision crops that are produced in the region. Sorghum, millet and maize, which together constitute 50% of Sahelian crop distribution (Leff *et al* 2004) are important both for human consumption and as fodder for livestock. Sahelian pastoralists depend on grassland and savanna productivity as forage for their livestock herds. Presently, 80% of the crop calories produced in the region are used for food, 10% for animal feed, and the remaining 10% for other uses (Cassidy *et al* 2013). In most parts of the Sahel, energy demand is met by woodfuels, and NPP provides biomass for energy in the form of fuelwood and charcoal.

We calculate demand for NPP ($\mathrm{NPP_{Demand}}$) as the annual amount (in grams of carbon) of terrestrial carbon necessary to derive food, fuel and feed requirement in each country and account for carbon lost due to burning and harvest losses. Approximately 90% of the food produced in the region is consumed domestically (Gollin 2009, Barrett 2013), leaving 10% for other use. Therefore we constrained $\mathrm{NPP_{Demand}}$ within each country in the region by using domestic production data from FAOSTAT (http://faostat3.fao.org/) (FAOSTAT 2013).

$$\begin{aligned}\mathrm{NPP_{Demand}} = \; & \mathrm{NPP_{food}} + \mathrm{NPP_{fuel}} + \mathrm{NPP_{feed}} \\ & + \mathrm{NPP_{burned}} + \mathrm{NPP_{residues}} \end{aligned} \quad (2)$$

where $\mathrm{NPP_{food}}$ is the NPP required to produce domestically consumed food items which includes meats sourced from six types of domestic animals (cattle, goats, sheep, pigs, camels, chickens) and two non-meat animal products (eggs and milk) (table 2S, supplementary information). Also included were 27 types of regionally important primary crops (table 3S, supplementary information). These crops represent 95% of all those that are domestically consumed by most of the countries in the study area (FAOSTAT 2013). A conceptual flowchart of the demand module is depicted in figure 1S in the supplementary information.

$\mathrm{NPP_{fuel}}$ represents fuelwood and charcoal extracted from the region's dry woodlands. Woodfuel requirement ranges from 55% in Senegal (Pires 2003) to over 90% in Chad (van der Plas and Abdel-Hamid 2005), but on average it is around 80% across the study area. $\mathrm{NPP_{feed}}$ is the total amount of feed required to sustain the region's livestock population. This was calculated by converting the total number of heads of the six Sahelian domestic animal species to their equivalent Tropical

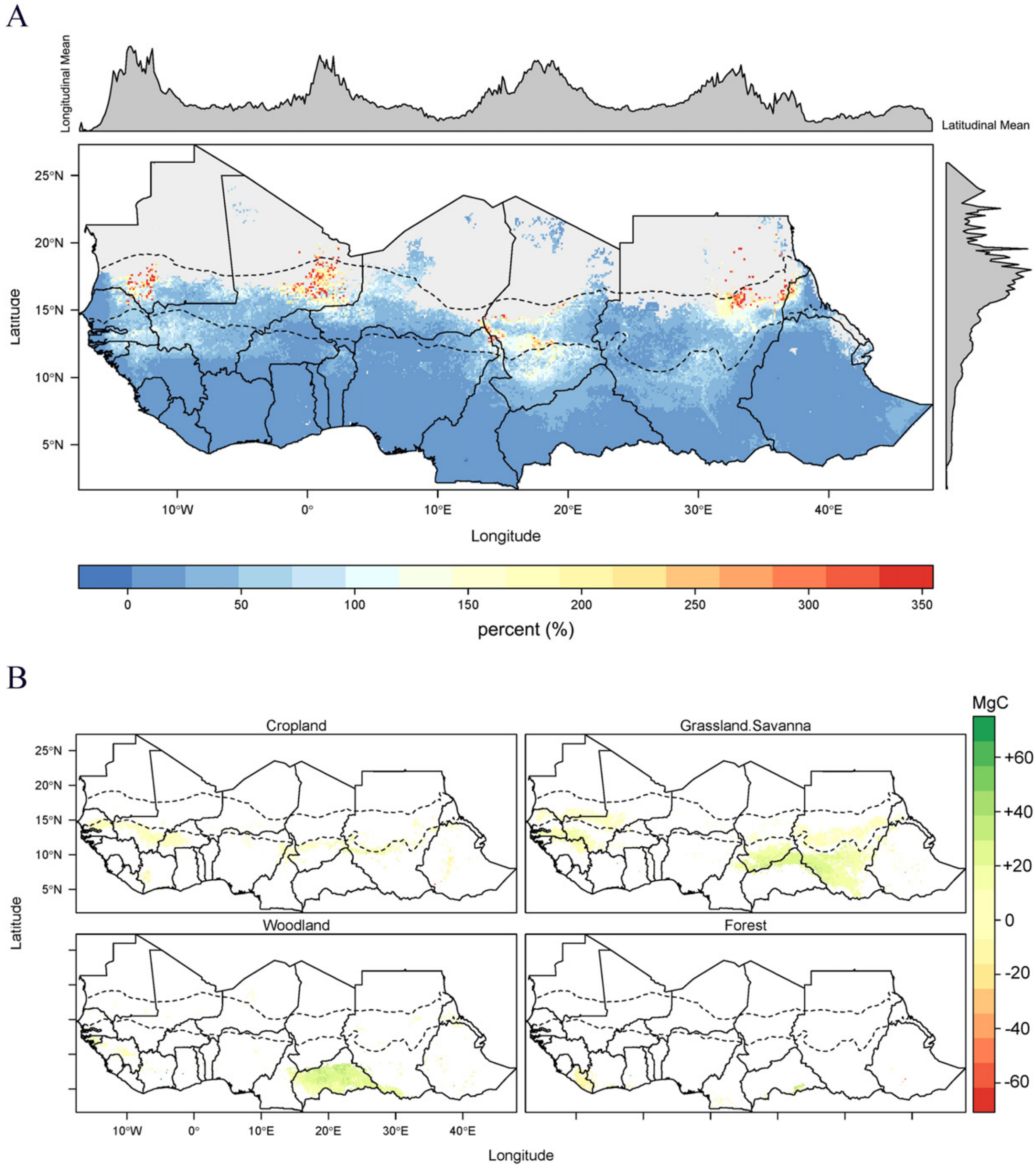

Figure 2. (A) Coefficient of variation of NPP 2000–2010. The dashed line represents rainfall isohyets between 100 and 600 mm that delineate the Sahelian zone. There are well-defined clusters of high NPP variability (>100%) in the Sahelian zone notably in southern Mauritania, northeast Mali, central and eastern Chad and northeastern Sudan. The gray coloration within each countries national borders signify areas with no data. (B) Significant trends ($p < 0.05$) in NPP_{Supply} for the four land cover groupings in the study area between 2000 and 2010.

Livestock Units (TLU), then multiplying by the annual feed requirement for each TLU (table 4S, supplementary information). Domestic human-driven NPP loss resulting from biomass burning of forest resources for land clearing is represented by NPP_{burned}. Agricultural byproducts are represented by $NPP_{residues}$ and were calculated by applying harvest factors provided in literature (table 5S, supplementary information).

Urban and rural consumption ratios vary due to differences in diet, lifestyle and wealth (Popkin 1999). We separated urban and rural areas by masking the urban extent of the WorldPop grids using data from the Global Rural-Urban Mapping Project (CIESIN *et al* 2011). We derived per capita NPP_{Demand} by dividing total consumption with each country's population, and used the WorldPop data as a spatial surrogate to apply the per capita NPP_{Demand} to grid cells. Consumption patterns of NPP in sub-Saharan Africa can differ considerably and depend on several factors such as income and product availability. We applied ratio factors for urban and rural consumption to national sums of each component of NPP_{Demand} based on figures from the literature (Reardon 1993, Teklu 1996, Marufu *et al* 1997, Hartter and

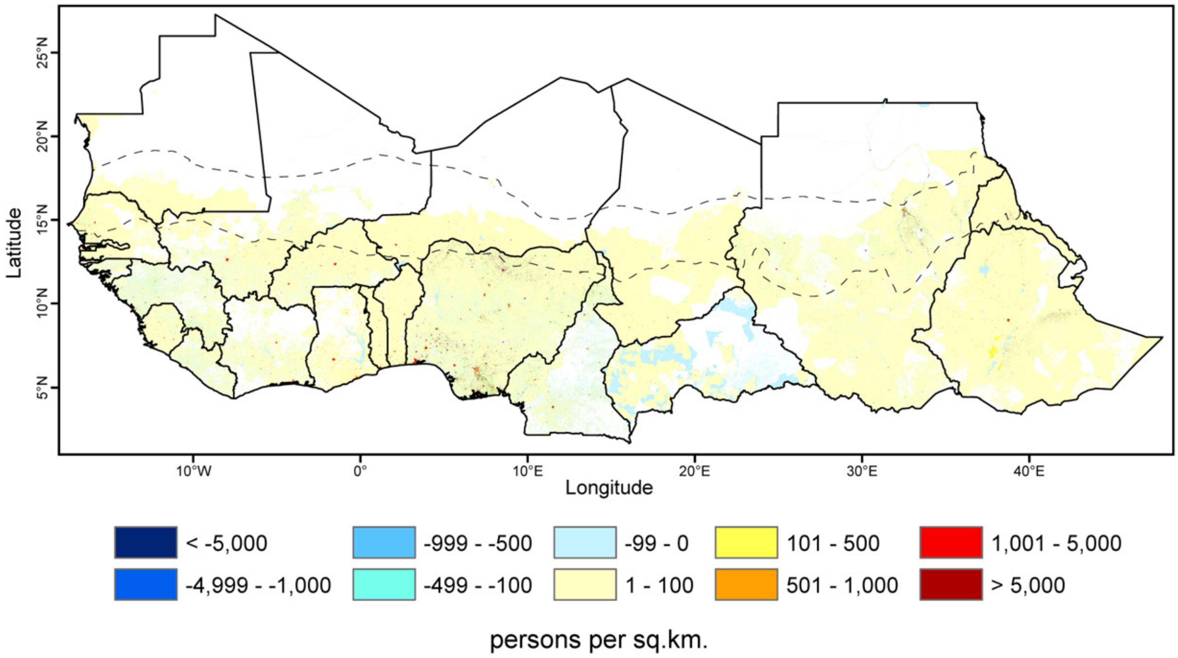

Figure 3. Difference in population density (persons per km^2) between 2000 and 2010 according to WorldPop data. There is a general increase of 1–100 persons per sq. km across much of the region with large increases of up to, and greater than, 5000 persons per sq. km in and around the major urban centers. Several countries exhibit large patches of decrease in population density, most notably in the Central African Republic. Areas with difference values of less than 1 were masked out.

Table 1. Statistically significant ($p < 0.05$) NPP_{Supply} trends based on regression slopes of ordinary least squares regression versus time (2000 and 2010).

Country	Cropland NPP	Woodland NPP	Forest NPP	Grassland/Savanna NPP	Total NPP
Benin	−0.37%	4.80%	—	8.09%	4.17%
Burkina Faso	8.68%	8.17%	—	8.47%	8.44%
Cameroon	7.57%	4.00%	−0.98%	6.86%	4.36%
Central African Republic	8.50%	5.45%	4.15%	9.87%	6.99%
Chad	14.86%	12.85%	—	17.87%	15.19%
Djibouti	—	—	—	10.78%	10.78%
Eritrea	16.14%	10.05%	—	10.69%	12.29%
Ethiopia	1.87%	5.13%	−1.28%	5.32%	2.76%
Gambia	9.47%	—	—	10.37%	9.92%
Ghana	1.17%	12.42%	−0.84%	8.27%	5.26%
Guinea	1.94%	3.48%	−2.00%	4.59%	2.00%
Guinea Bissau	4.35%	14.18%	—	19.87%	12.80%
Ivory Coast	−1.93%	1.17%	−1.80%	14.83%	3.07%
Liberia	−1.84%	—	−1.97%	—	−1.90%
Mali	12.53%	9.96%	—	9.05%	10.51%
Mauritania	17.54%	19.26%	—	12.39%	16.40%
Niger	−6.70%	−20.82%	—	−6.97%	−11.50%
Nigeria	3.36%	−5.08%	−0.16%	4.01	0.53%
Senegal	16.36%	17.84%	—	14.44%	16.21%
Sierra Leone	0.61%	2.62%	−1.47%	—	0.59%
Sudan	11.74%	5.36%	—	9.48%	8.86%
Togo	0.53%	5.46%	—	9.70%	5.23%

Boston 2008) and national household consumption surveys (ISTEEBU 2001, Maziya-Dixon *et al* 2004, Tafere and Worku 2012, GSS 2008, Food Security Technical Secretariat 2010, NSO 2012). Grids of urban and rural consumption were then merged to produce a single grid of NPP_{Demand} for each year.

3. Results

3.1. NPP supply

Mean total NPP_{Supply} based on 2000–2010 MODIS data is 2.41 PgC with an inter-annual variability of approximately 0.04 PgC (1.7%). The dry Sahelian zone exhibited high

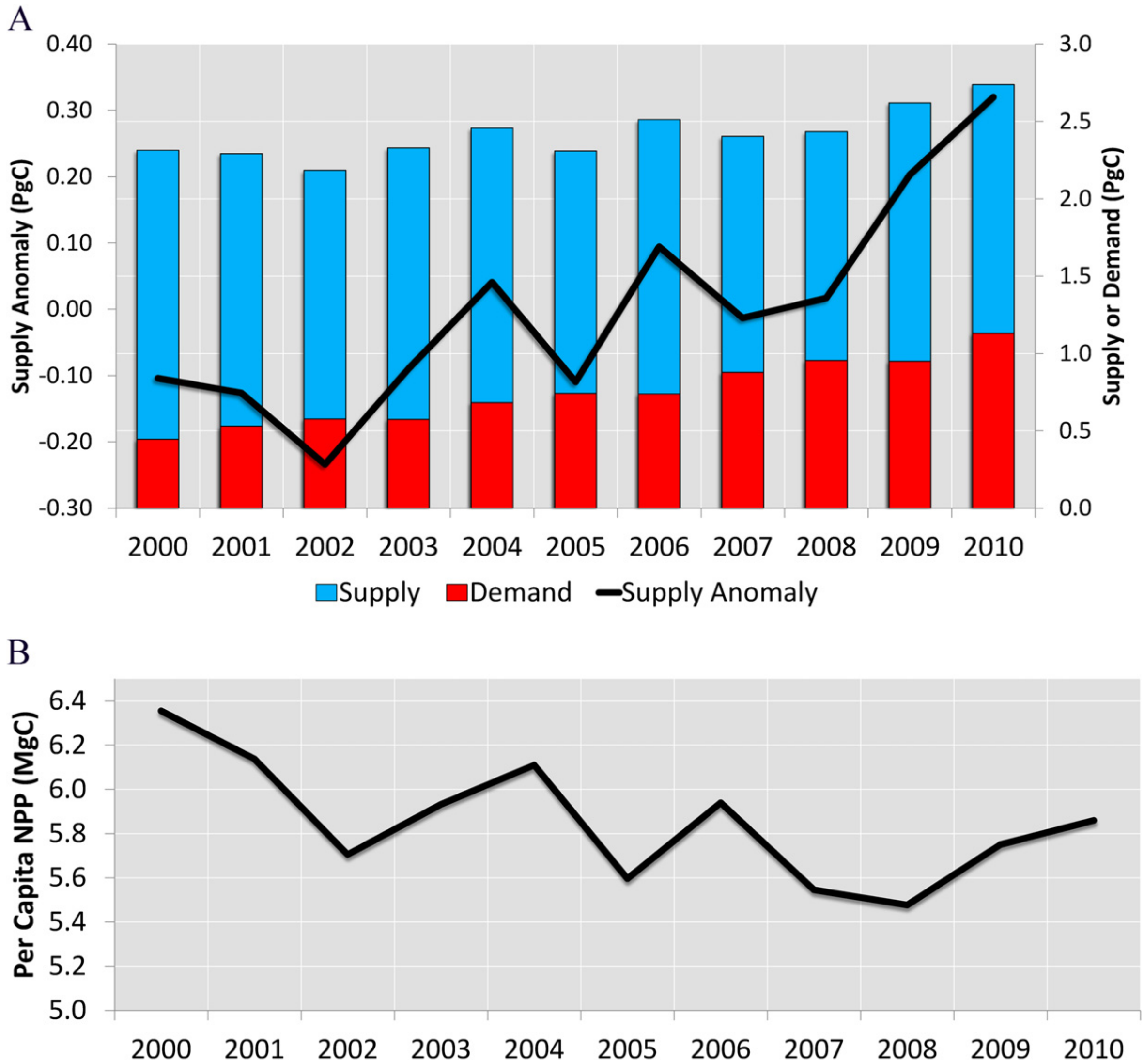

Figure 4. (A) Total NPP_{Supply}, NPP_{Demand}, and NPP_{Supply} anomalies in the study area between 2000 and 2010. NPP_{Supply} anomalies were computed as differences of NPP_{Supply} from annual mean using the 11-year record. (B) Per capita NPP from 2000 to 2010. The total amount of NPP that is available to the region's population experienced abrupt declines in 2002 and 2005 (see section 3.1).

coefficients of variation values in south-central Mauritania, northeast Mali, central Chad and around the Khartoum metropolitan area in Sudan (red colors in figure 2(A)). The years 2002 and 2005 had the lowest total regional NPP_{Supply} values with anomalies of −0.23 and −0.11 PgC, respectively (figure 4(A)). The trend in NPP_{Supply} between 2000 and 2010 for each of the 22 countries is given in table 1. There were significant ($p < 0.05$) region-wide increases in the NPP_{Supply} of cropland (+6.0%), woodland (+6.1%) and grassland/savanna (+9.4%) and a decrease in forest NPP_{Supply} (−0.7%). NPP_{Supply} in individual countries varied considerably; some such as Niger demonstrated large NPP_{Supply} decreases in cropland (−6.7%), woodland (−20.8%) and grassland/savanna (−6.9%), while others such as Senegal had relatively substantial increases in the NPP_{Supply} of cropland (+16.3%), woodland (+17.8%) and grassland/savanna (+14.4%) (figure 2(B)). In 2002, the total region-wide NPP_{Supply} dropped −9.7% below the decadal average due to droughts in Ethiopia, Eritrea, parts of Sudan, Senegal, Mali and Mauritania.

3.2. Population density

Between 2000 and 2010 the population of the region grew from 367 million to 471 million at an average rate of 2.8% per year, and is projected to increase to nearly one billion by 2050 (United Nations 2011). The increase was highest in Eritrea (43.2%) and lowest in Central African Republic (18.9%). Most of the growth took place around and between existing settlements, creating networks that link different urban centers (figure 3).

3.3. NPP demand

The total regional NPP_{Demand} between 2000 and 2010 ranged from 0.44 PgC to 1.13 PgC, representing between 19% and 41%, respectively, of NPP_{Supply} (figure 4(A)). Overall,

Table 2. Variability in the demand for food, fuel, feed and total demand between 2000 and 2010. Food includes crop- and meat-derived products; fuel is the household energy requirement in the form of woodfuel and charcoal; feed is the amount of NPP required to sustain the region's livestock population. Total demand includes the above as well as crop residues and burnt biomass. Total population refers to the percent change in a country's aggregated population (i.e. total persons) between 2000 and 2010 according to the WorldPop data.

Country	Food	Fuel	Feed	Total demand	Total population
Benin	9.81%	2.68%	12.79%	8.61%	35.78%
Burkina Faso	34.43%	27.03%	22.03%	28.04%	33.96%
Cameroon	34.27%	12.32%	−2.63%	24.84%	25.01%
Central African Republic	13.92%	11.11%	21.85%	18.92%	18.88%
Chad	16.76%	13.62%	18.57%	19.88%	36.55%
Djibouti	−1.49%	5.92%	−3.63%	−1.24%	19.03%
Eritrea	19.62%	−23.16%	1.72%	1.37%	21.45%
Ethiopia	39.59%	9.67%	28.64%	27.22%	43.24%
Gambia	18.04%	9.06%	14.09%	18.19%	26.49%
Ghana	19.93%	19.42%	18.62%	20.57%	33.23%
Guinea	14.81%	5.06%	29.16%	17.70%	27.27%
Guinea Bissau	9.13%	4.66%	10.54%	9.66%	19.63%
Ivory Coast	2.14%	4.26%	13.32%	2.07%	22.08%
Liberia	2.65%	20.81%	23.18%	12.93%	40.29%
Mali	38.77%	7.45%	26.02%	31.34%	36.08%
Mauritania	13.52%	14.54%	5.03%	6.73%	30.91%
Niger	46.03%	−44.03%	22.37%	28.41%	42.03%
Nigeria	11.67%	6.68%	13.22%	11.42%	28.08%
Senegal	17.78%	4.76%	8.60%	12.30%	30.80%
Sierra Leone	54.34%	2.15%	48.50%	25.41%	41.64%
Sudan	18.35%	13.50%	14.44%	15.07%	27.39%
Togo	14.50%	−7.64%	21.14%	11.01%	25.74%

NPP_{Demand} increased 22% between 2000 and 2010 with the highest increase being for food (20.4%) followed by feed (16.7%) and fuel (5.5%) (table 2). We found large decreases in demand for woodfuel in the Sahelian countries of Eritrea (−23.1%) and Niger (−44%), which could be the result of initiatives promoting alternative fuels such as liquefied petroleum gas (LPG), provision of efficient cookstoves, and rural fuelwood markets aimed at sustainable forest management (Foley 1997, Habtetsion and Tsighe 2007, Rives *et al* 2013). Per capita NPP dropped in 2002 and 2005 (figure 4(B)) due to shortages in NPP_{Supply} caused by climatic variability (see section 4). The difference in NPP_{Demand} between 2000 and 2010 (figure 5(A)) generally followed the difference in population with the areas in and around urban centers displaying the highest values. However, significant trends in percent NPP_{Demand} relative to NPP_{Supply} (figure 5(B)) were confined mostly to the south of the Sahelian zone. Sizeable parts of the study area have experienced large increases (>200%) of percent NPP_{Demand}.

4. Discussion

At the present time around 41% of Sahelian NPP_{Supply} is consumed by humans. The low regional inter-annual variability of NPP, at 1.7%, is representative of the global trend over the past 35 years (Running 2012) suggesting that the supply of NPP is at a near constant level. On the other hand, both population and NPP_{Demand} are increasing at similar annual rates of 2.8% and 2.2%, respectively. This supply-demand relationship is sensitive to systemic shocks such as droughts or pest invasions that might lower the regional NPP_{Supply}. For example, there were two years, 2002 and 2005, that exhibited large negative NPP_{Supply} anomalies. The year 2002 was marked with a severe drought in Ethiopia and parts of Sudan that caused food and water deficit to over 12 million people (Balogun *et al* 2013) as well as localized food shortages in West Africa. In 2004, the largest desert locust (*Schistocerca gregaria*) invasion in 17 years, resulting from heavy rains the preceding year that created ideal breeding conditions, reduced the regional NPP_{Supply} until the 2005 growing season (Ceccato *et al* 2006). These incidents illustrate the vulnerability of the regional NPP_{Supply} to fluctuations in climate that can lead to declines in the availability of NPP for human consumption.

The spatial pattern of significant trends in the NPP_{Supply} of the four land cover groupings that source food, fuel and feed to the region exhibited non-uniform patterns (figure 2(B)): cropland exhibited modest increases just south of the 600 mm rainfall isohyet; woodland exhibited increases that were mostly confined to the Central African Republic (CAR); grassland/savanna displayed no change in the Sahelian zone but increases south of the 600 mm rainfall isohyet, particularly in CAR, southern Chad and Sudan; forest displayed decreases everywhere except in CAR.

The overall increase in the demand for NPP_{fuel} (table 2) generally triggers more fuelwood extraction unless there is a

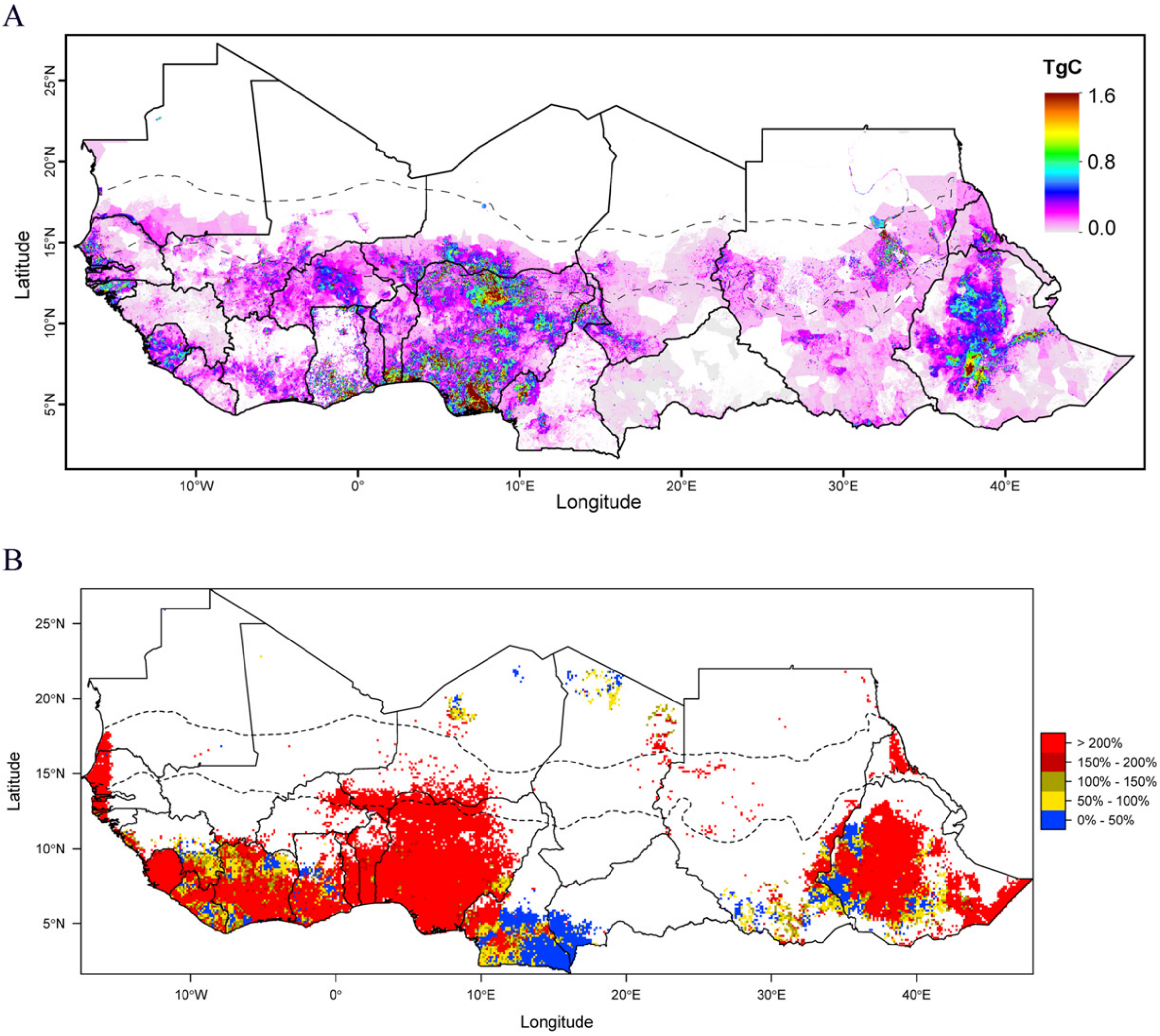

Figure 5. (A) Difference in NPP_{Demand} over the region between 2000 and 2010 in areas that exhibited changes in population density of greater than one person per km^2 during the same time frame. (B) Percent of NPP_{Demand} relative to NPP_{Supply} between 2000–2010. Only areas with a statistical significance of $p < 0.05$ are shown here. Large areas, most notably in West Africa and Ethiopia, experience NPP_{Demand} that is much larger than available supply.

major shift towards efficient cooking stoves or alternative household fuels such as LPG. For example, in Eritrea, a combination of factors, all taking place during the study period, may have contributed to the decrease in the demand for woodfuel. By the end of 2004, the country's Ministry of Energy and Mines had installed 27 000 efficient stoves in rural households through its Improved Stove Dissemination Program (Habtetsion and Tsighe 2007). An additional 10 120 stoves were planned for 2005 and 5000 stoves every year thereafter (Bode 2005, Habtetsion and Tsighe 2007), though statistics about the implementation of those plans are not available. Additionally, the Eritrean government had invested heavily in promotion of LPG as an alternative household energy source to the extent that LPG became cheaper than woodfuels for the purposes of cooking (Habtetsion and Tsighe 2007).

This paper revealed that the Sahelian NPP supply and demand nexus is driven by the geographic distribution of population density and climatic variability, and projections for the future are alarming. A combination of increasing temperatures and changes in the precipitation regime will likely decrease the NPP_{Supply} of important crops in the region as well as increase the prevalence of pest infestations (IPCC 2014). Forecasts of Sahelian rainfall for the next four decades are inconsistent (Ben Mohamed 2011), and the best-case scenarios predict that the region will receive more rainfall, which should cause an increase in NPP_{Supply}. However, the impact of higher temperatures may counteract this effect, producing a net reduction in NPP_{Supply} across the region (Delire et al 2008). Similarly, forecasts of reduced crop yields of up to −41% due to increased temperature have been consistent across various studies despite projected increases in rainfall (Jones and Thornton 2003, Wolfram and David 2010, Sultan et al 2013). These factors point to a complex system in a delicate balance between human requirement on the one hand, and the ecosystem's capacity to satisfy it on the other.

4.1. Uncertainties and limitations

Uncertainties in the estimates of NPP_{Supply} stem from MOD17's implementation of water stress control through atmospheric VPD. Mu *et al* (2007) demonstrated that VPD underestimates water stress and overestimates NPP_{Supply} in Sahelian conditions. Pan *et al* (2006) have shown that correcting for soil water content improves MOD17 NPP estimates. Another source of uncertainty in NPP_{Supply} stems from the static biome-specific values of the maximum light use efficiency (ε_{max}, see section 2.2) that MODIS implements, which have been found to be considerably lower than field estimated values (Sjöström *et al* 2013).

We acknowledge the limitations presented by using data from FAOSTAT, which is sometimes challenged either due to shortage of resources to perform meticulous surveys or over-/under-reporting of national statistics by certain countries (Krausmann *et al* 2008). Despite these shortcomings, FAOSTAT represents the only available, widely used, resource that compiles, cross-checks and standardizes global agricultural data (Goudriaan *et al* 2001, Ciais *et al* 2005, Ramankutty *et al* 2008, Ma *et al* 2012). We, therefore, consider it acceptable for the purposes of this study.

A drawback to employing annual land cover groupings to represent exploitable resources is the complete dependence on the MODIS Land Cover Type Product. Although the latest version of the product (Collection 5.1) has undergone several refinements and possesses an overall accuracy of 75% (Friedl *et al* 2010), the amount of training data from the Sahel that the algorithm employs is considerably small ($n = 58$) and for one class (woody savanna) it is as low as a single site.

5. Conclusion

In this paper, we quantified the spatiotemporal variation of supply of NPP in relation to anthropogenic demand for a portion of sub-Saharan Africa using a combination of satellite remote sensing and socioeconomic data. We identified region-wide spatial patterns of annual NPP extraction to derive food, fuel and feed from the available supply.

This research adds to a series of studies on Sahelian vegetation dynamics with a focus on the relationship between anthropogenic exploitation and supply of NPP. The combination of rapidly increasing demand for food, fuel and feed driven by population growth makes the region vulnerable to climatic changes that may alter the per capita availability of NPP. Additionally, the region's location in a geographic transition zone between the arid Sahara desert and the high NPP Sudano-Guinean zone increases its sensitivity to fluctuations in rainfall. Investigating inter-annual variations of NPP supply and demand could help explain patterns of ecosystem change by identifying areas under anthropogenic pressure. Considering the current 2.2% annual increase in NPP_{Demand}, there is a risk that ecosystems may not be able to provide food, fuel and feed for the region's humans and livestock without a corresponding increase in NPP_{Supply}. If future droughts occur at similar climatic magnitudes as the ones that took place in the 1970s and 1980s the Sahel will be at risk of mega famines.

The integrated analysis of the supply and demand of NPP allows the identification of areas where demand for carbon exceeds available supply, either presently or in future scenarios. Hence, the methodology presented in this paper can be applied to other human-environment systems where the supply-demand balance of NPP approaches critical levels.

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