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Quantitative Assessment of the Human Appropriation of Net Primary Production (HANPP) in the Coastal Areas of Jiangsu, China

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Abstract: Global increases in population and consumption have raised concerns regarding the sustainability of the current and future use of natural resources. The human appropriation of net primary production (HANPP) provides a useful measure for determining human-derived alterations in the amount of biomass that is available in ecosystems each year. HANPP was calculated based on vegetation modelling, agricultural statistics, and remote sensing data on land use and land cover to assess the human impacts on ecosystems in the coastal areas of Jiangsu, China. The results showed that HANPP increased from 332 g·C/m^2/year in 2000 to 442 g·C/m^2/year in 2010, with an average annual increase of 2.9%. The proportion of appropriated net primary production increased from 50.3% to 71.0% of NPP$_{pot}$, mainly driven by HANPP$_{harv}$ (harvested NPP) with an increase from 45.2% to 61.3% of NPP$_{pot}$. Additionally, the spatial variation in average HANPP was striking among counties in the observed period with the lowest and highest values of 21.8% and 63.8% of NPP$_{pot}$, respectively. Further analysis showed that observed levels of HANPP are high due to a high level of biomass harvest from cropland and the increases in fertilizer use, farmland irrigation rate and population and economic growth explain the trends in HANPP in the coastal areas of Jiangsu.

Keywords: HANPP; NPP; spatial-temporal patterns; factors; coastal areas of Jiangsu

1. Introduction

Ecosystems are essential for human survival and development because they provide many types of services required by humans, e.g., food, fuel, and fiber. With the rapid development of economies and societies, huge impacts have been observed on the balance of ecosystems because of the over-consumption of natural resources [1]. Human appropriation of net primary production (HANPP) is the amount of net primary production (NPP) appropriated by humans in a specific area and is extensively used as an ecological indicator to measure human interventions in the biosphere. Extensive attention has been given to HANPP, which is now used as an indicator that links natural processes with socio-economic processes, and it is used to measure the limitations of ecological environments in relation to the population and economy [2–4]. However, most studies of HANPP have been conducted at global and national scales, and smaller scale studies are scarce. Smaller scale studies are necessary to better understand how HANPP can be used for land use policy and to demonstrate an important extension of HANPP.

The coastal areas of Jiangsu in China consist of three prefecture-level cities, namely Liangyungang, Yancheng and Nantong, which consists of three districts and 19 counties (Figure 1). The longitude and latitude of this region range from 118°24′ E to 121°01′ E and from 31°38′ N to 35°08′ N, with a total land area of 32,500 km^2. This region is located at the junction of three productive areas: the China Coast, the Yangtze River and the Longhai-Lanxin Railway, which is also the head of the new Eurasian continental bridge. The climate in this area is classified as an intersection of the warm temperate zone and the northern subtropical zone, with an annual temperature of approximately 13–15 °C and annual rainfall of approximately 850–1080 mm. The vegetation in this area is dominated by cultivated crops, and the natural vegetation, including evergreen coniferous forest, evergreen broadleaved forest, and coastal salt vegetation, is distributed sparsely. According to the data of the Second Land Census of China, the percentages of cropland, forestland, construction land, water areas (including tidal flats), and unused land are 55.4%, 0.8%, 18.5%, 23.0%, and 2.3%, respectively.

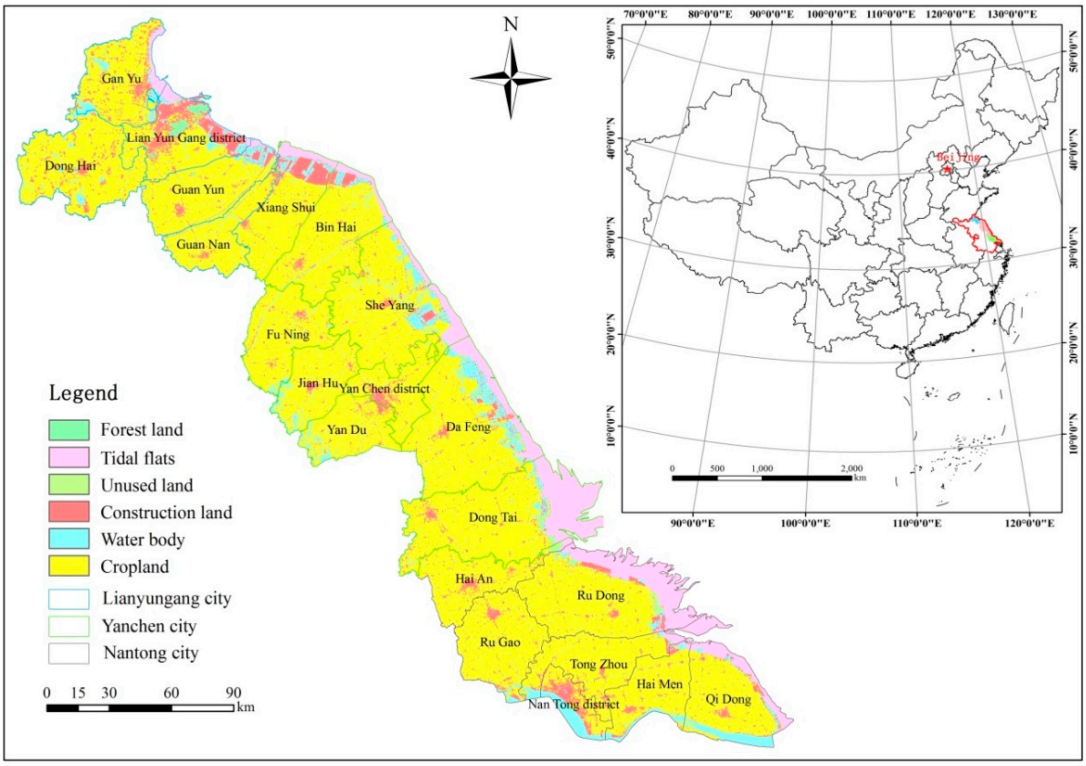


Figure 1. The location of the coastal areas of Jiangsu.

This area is a region of significant land use change; it is greatly affected by human activities and is also an ecologically fragile region where wetland resources and natural area reserves are densely distributed [5]. Driven by the coastal development strategy in China, the ever-increasing use of ecosystems by humans has increased the pressure on the ecological environments in the coastal areas of Jiangsu [6,7]. HANPP studies in China have rarely been reported [8] and are even lacking for the China Coast. The aims of this study were to estimate HANPP in the coastal areas of Jiangsu, to explore the temporal and spatial variation in HANPP, and to determine its driving forces in this area from 2000 to 2010. This study will be of value for revealing the intensity of human activities in terrestrial ecosystems and for providing important insights into sustainable development in the coastal areas of Jiangsu. Furthermore, this study is an attempt to extend HANPP research from global and national scales to a smaller scale.

2. Materials and Methods

2.1. Definition and Calculation of HANPP

Different studies use different definitions of HANPP, and these differences largely explain the range of reported results. Vitousek *et al.* calculated three estimated levels (low, intermediate, and high) of global HANPP according to the NPP used directly by humans and livestock, the entire NPP of human-dominated ecosystems and they further included NPP losses through land-conversions (by including a potential NPP estimate) [9]. Imhoff *et al.* estimated the appropriation of NPP during harvesting and processing of forests and agriculture without accounting for the NPP losses through land use changes calculated by subtracting actual NPP from potential NPP [10]. Haberl *et al.* [11] defined HANPP as the difference between the NPP of potential natural vegetation and the NPP remaining in ecosystems, and stated that HANPP is affected by two separate processes: (1) biomass harvesting and (2) land use and land cover changes. The Haberl method has become the standard for HANPP studies [12], and we chose to use the definition of HANPP outlined in Haberl, *et al.* [13]. Accordingly, HANPP can be calculated as follows.

$$\mathrm{HANPP} = \mathrm{HANPP}_{\mathrm{luc}} + \mathrm{HANPP}_{\mathrm{harv}},\ \mathrm{HANPP}_{\mathrm{luc}} = \mathrm{NPP}_{\mathrm{pot}} - \mathrm{NPP}_{\mathrm{act}} \quad (1)$$

To calculate HANPP, some variables must first be determined, which include the NPP of the natural vegetation ($\mathrm{NPP}_{\mathrm{pot}}$), the NPP of the currently prevailing vegetation ($\mathrm{NPP}_{\mathrm{act}}$), and the harvested NPP ($\mathrm{HANPP}_{\mathrm{harv}}$).

2.2. Estimation of HANPP$_{harv}$

More than one-half of the regions in the coastal areas of Jiangsu are covered by cultivated land, and the majority of harvests are related to agricultural activities. The wood harvest of the forestry industry was not considered in our study because the timber harvest data were unavailable and the proportion of the forestland in the study area was only approximately 0.8%. Thus, $\mathrm{HANPP}_{\mathrm{harv}}$ in our calculation focuses on biomass harvest from cropland.

We used crop yield data from the Jiangsu Agriculture Database (Statistics Bureau of Lianyungang, Yancheng and Nantong) to estimate the biomass harvested from croplands. Agricultural statistics were obtained for the period between 2000 and 2010. To analyze the spatial variability of HANPP, all harvest data were tabulated annually on a county scale (n = 21). Generally, only the edible portion of a crop was recorded in the agricultural harvest statistics. To incorporate information on the harvest residues, the reported production amounts were divided by the crop-specific ratios of the residue to economic yield, which were obtained from the literature [14–17]. The harvest data were converted from fresh weight to dry weight using a literature-derived fraction of dry matter [18,19].

To estimate the agricultural harvest, production data were analyzed for 12 crops grown in the coastal areas of Jiangsu. The studied crops were wheat, barley, broad bean, pea, rice, maize, soybean, potato, peanut, rapeseed, sesame, and cotton and they represent an average of 82.7% of the total harvested acreage of the crops in the coastal areas of Jiangsu. Since the remaining cropped areas (17.3%) were primarily planted with vegetables for which related data sets were unavailable, HANPP estimates were not performed for these areas. The amount of $\mathrm{HANPP}_{\mathrm{harv}}$ in the coastal areas of Jiangsu was calculated by summing C_{y} and C_{r} as follows:

$$HANPP_{harv} = C_y + C_r \quad (2)$$

$$C_y = \sum_{i=1}^{n} Y_i \times F_{\mathrm{id}} \times F_{\mathrm{icy}} \quad (3)$$

$$C_r = \sum_{i=1}^{n} Y_i \times F_{\mathrm{id}} \times R_{\mathrm{iry}} \times F_{\mathrm{icr}} \tag{4}$$

where C_y is the total amount of NPP in the economic yield, C_r is the total amount of NPP in the crop residues, Y_i is the economic yield, F_{id} is the dry matter fraction, F_{icy} and F_{icr} are the carbon fractions of the economic yield and residues, respectively, and R_{iry} is the ratio of the residue to the economic yield. The details of these parameters are listed in Table 1.

Table 1. Parameters used for estimating $\mathrm{HANPP_{harv}}$ in the coastal areas of Jiangsu.

Crops, Product	Residue: Economic Product Ratio R_{iry}	Dry Matter Fraction (%)	Carbon Fraction	
			F_{icy}	F_{icr}
Wheat, grain	1.38	87	0.39	0.49
Barley, grain	1.04	86.5	0.39	0.49
Broad bean, bean	1.17	87.5	0.40	0.45
Pea, bean	1.17	87.5	0.40	0.45
Rice, grain	1.04	88	0.38	0.42
Maize, grain	1.00	83.5	0.39	0.47
Soybean, bean	1.38	87.5	0.40	0.45
Potatoes, tuber	0.53	20	0.39	0.42
Peanut, tuber	1.26	88.5	0.38	0.38
Rapeseed, seed	2.85	90	0.42	0.45
Sesame, seed	2.01	85	0.40	0.45
Cotton, unginned	2.61	91	0.40	0.39

Source: References [11–16].

$\mathrm{HANPP_{harv}}$ in our calculation includes the crop harvest and its residues (the straws and stover of wheat, rice, cotton, *etc.*, and the leaves of potatoes and peanuts), whereas belowground NPP (with the exception of potatoes and peanuts), NPP losses during the growth period, and losses resulting from herbivory are not considered in the study. All of the results of this analysis are expressed in g C per year.

2.3. Estimation of NPP_{pot} and NPP_{act}

$\mathrm{NPP_{pot}}$ was generally derived by the regression analysis of NPP data with climate or other factors. As an empirical model, the Miami model [20] determines NPP for a particular location as the minimum of the temperature and precipitation regression functions. It is widely used for its simplicity and relative accuracy and sometimes used as a baseline for global NPP evaluation [21–25].

The parameters of the Miami model were calibrated by fitting the NPP observations with temperature and precipitation data in the early years before the 1970s and must be re-parameterized with new sets of productivity and climate change observations [25]. A new set of parameters was calibrated and optimized by Zaks, *et al.* in 2007 [25] based on the 3023 global NPP field observations and corresponding annual mean temperature and precipitation data. We chose the new calibrated Miami model to calculate $\mathrm{NPP_{pot}}$ in this study.

$\mathrm{NPP_{act}}$ in the coastal areas of Jiangsu from 2000 to 2010 was calculated using the Carnegie Ames Stanford Approach (CASA) model, which was proposed by Potter *et al.* in 1993 [26]. $\mathrm{NPP_{act}}$ calculated using the CASA model includes all biomass in the process of vegetation growth. The amount of NPP determined by absorbed photosynthetic active radiation (APAR) and light use efficiency (ε) was calculated as follows.

$$\mathrm{NPP}\,(x,t) = \mathrm{APAR}\,(x,t) \times \varepsilon\,(x,t) \tag{5}$$

$$\mathrm{APAR}\,(x,t) = \mathrm{SOL}\,(x,t) \times \mathrm{FPAR}\,(x,t) \times 0.5 \tag{6}$$

$$\varepsilon\,(x,t) = T_1\,(x,t) \times T_2\,(x,t) \times W\,(x,t) \times \varepsilon^* \tag{7}$$

where t is the time; x is the spatial position; SOL(x,t) is the total amount of solar radiation ($\mathrm{MJ/m^2}$); FPAR(x,t) is the fraction of photosynthetic active radiation, which was calculated using the method proposed by Los [27] that is based on the normalized difference vegetation index (NDVI) and the ratio vegetation index (SR); the constant 0.5 is the ratio of the amount of effective solar radiation absorbed by vegetation (wavelength range between 0.38 and 0.76 μm) to the total amount of solar radiation; $T_1(x,t)$ and $T_2(x,t)$ are the influence of temperature on the light use efficiency (*i.e.*, the temperature scale) and calculated following Potter and Field, *et al.* [26,28]; W(x,t) is the influence of water on the light use efficiency (*i.e.*, the water scale), calculated following Piao, *et al.* [29]; and ε* is the maximum light use efficiency, which was based on the results presented by Zhu *et al.* for typical vegetation in China [30].

The models are driven by NDVI, climate, and land use and land cover data. The monthly NDVI data were obtained from the MOD13Q1 16-day composite product that was downloaded from the Level 1 and Atmosphere Archive and Distribution System (LAADS) website (http://ladsweb.nascom.nasa.gov/data/). The climate data, including temperature, precipitation and solar radiation, were obtained by interpolation from meteorological station data that were downloaded from the China Meteorological Data Sharing Service System website (http://cdc.nmic.cn/home.do). The solar radiation data were calculated following Zhang, *et al.* [31], using ground water vapour pressure and sunshine percentage, and the land use and land cover data were interpreted from TM images from 2000 and 2010. All data were projected to Albers projection and resampled to a resolution of 250 m × 250 m.

2.4. Statistical Analysis

2.4.1. Trend Analysis

We used the following linear regression equation to analyse the HANPP trend.

$$k = \frac{n \times \sum_{i=1}^{n} i \times \overline{HANPP_i} - \sum_{i=1}^{n} i \sum_{j=1}^{n} \overline{HANPP_i}}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{8}$$

where k is the trend slope and n is the number of years.

F statistics were calculated as follows to test the significance of the trend, which reflects the confidence of the trend.

$$\mathrm{F} = \mathrm{U} \times \frac{n-2}{Q} \tag{9}$$

$$\mathrm{U} = \sum_{i=1}^{n} (\hat{y}_i - \overline{y})^2 \tag{10}$$

$$\mathrm{Q} = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{11}$$

where U is the sum of the squared errors, Q is the sum of the squares of the regression, y_i is the observed value, $\hat{y}_i$ is the regressed value, $\overline{y}$ is the average value, and n is the number of years ($n = 11$). According to the F statistics for the significance test, we divided the trend into three classes: extremely significant ($p < 0.01$), significant ($0.01 < p < 0.05$) and not significant ($p > 0.05$).

2.4.2. Correlation Analysis

The relationship between HANPP and the driving factors was analysed using the Pearson correlation coefficient:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{12}$$

where x_i and y_i are the observed values of the variables; $\overline{x}$ and $\overline{y}$ are the average values of the variables; and n is the number of samples.

The population, GDP, fertilizer use, and farmland irrigation area datasets used for the correlation analysis were obtained from the statistical yearbooks of Liangyungang, Yanchen, and Nantong (Statistics Bureau of Lianyungang, Yancheng and Nantong).

3. Results

3.1. NPP_{pot} and NPP_{act}

NPP_{pot} changed with fluctuations from 661 g·C/m^2/year to 623 g·C/m^2/year over the period from 2000–2010, and NPP_{act} presented a basically similar trend to NPP_{pot}, with values changing from 627 g·C/m^2/year to 574 g·C/m^2/year (Figure S1). The spatial distribution of the average NPP_{pot} in the observed period indicated a decreasing trend from north to south in the study area, with values ranging between 603–832 g·C/m^2/year. The average NPP_{act} over the period 2000–2010 was concentrated in the interval between 600–800 g·C/m^2/year, which mainly occurred in the cultivated land area of the counties. There was a gradient distribution of NPP_{act} in the tidal flat reclamation zones, where NPP_{act} increased gradually from the sea to the land. Land use and land cover had a significant impact on the spatial distribution of NPP_{act} (See Figure S2).

3.2. $HANPP_{harv}$

$HANPP_{harv}$ increased from 298 g·C/m^2/year to 393 g·C/m^2/year during the period from 2000 to 2010 (Figure 2a) but declined significantly in 2003 because of the reduced food crop yields, due in large part to the large decrease in the rice yields in Lianyungang and Yancheng caused by meteorological disasters, such as abnormal floods or long-term continuous rain. The proportions of $HANPP_{harv}$ increased from 45.2% to 61.3% of NPP_{pot}, which exhibited a continually increasing trend after 2007.

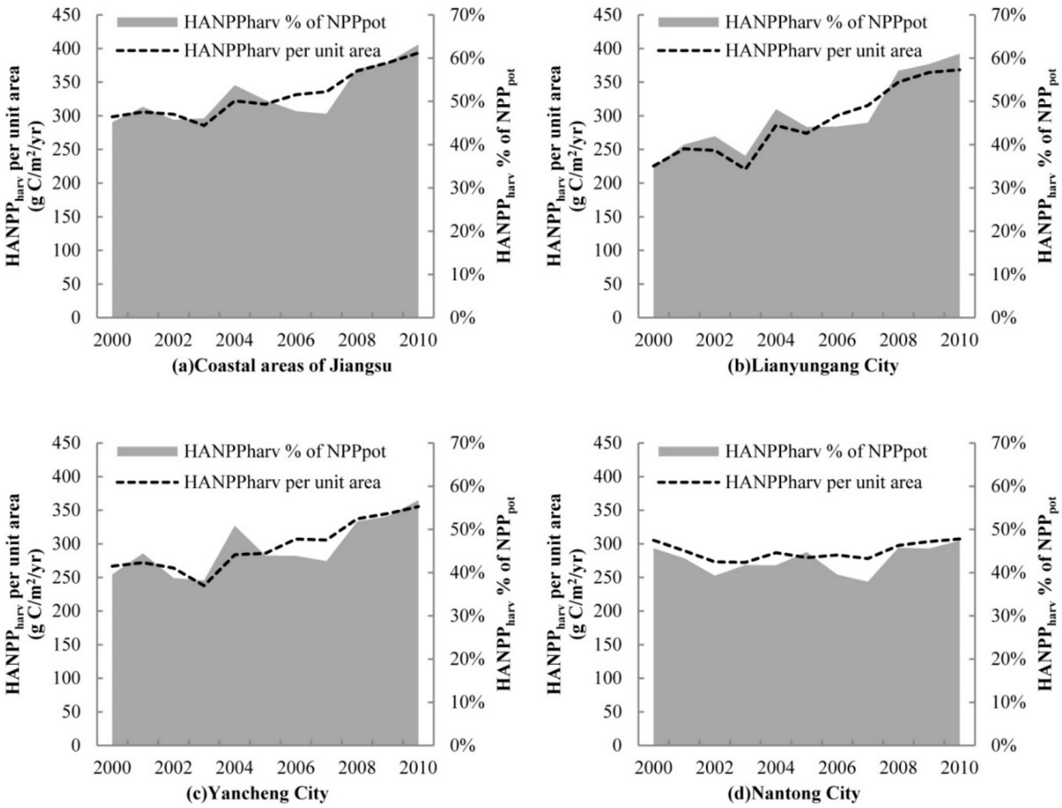
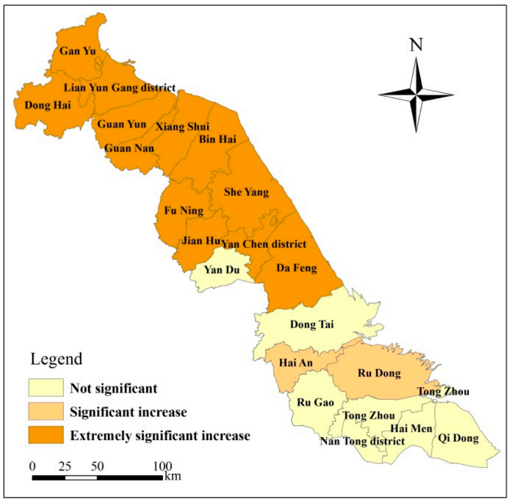


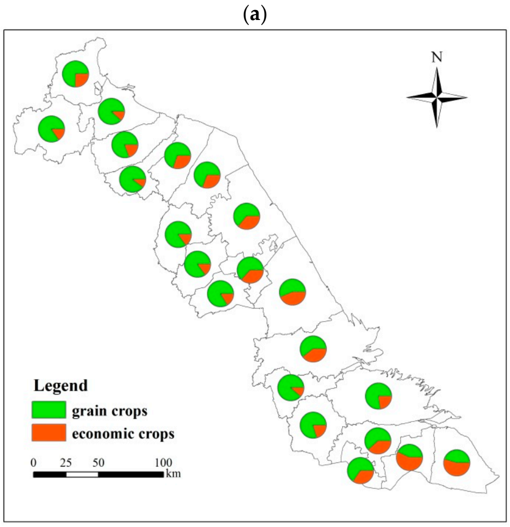
Figure 2. $HANPP_{harv}$ trends in the coastal areas of Jiangsu (**a**); Lianyungang City (**b**); Yancheng City (**c**); and Nantong City (**d**).

Clear differences in $HANPP_{harv}$ trends among the cities of Lianyungang, Yancheng, and Nantong are evident in Figure 2b–d. In Lianyungang and Yancheng, $HANPP_{harv}$ increased significantly ($p < 0.01$) in contrast to Nantong ($p > 0.05$). $HANPP_{harv}$ in Lianyungang presented the greatest increase, *i.e.*, from 34.9% to 61.0% of NPP_{pot} between 2000 and 2010. In contrast, $HANPP_{harv}$ in Nantong exhibited the smallest increase, *i.e.*, 45.6% to 47.4% of NPP_{pot}.

To further reveal the spatial variations in $HANPP_{harv}$ trends, we performed linear regression analysis of the $HANPP_{harv}$ time series for the counties in the coastal areas of Jiangsu to obtain the slope (k) of $HANPP_{harv}$ for the period from 2000 and 2010, where $k > 0$ indicates an increasing and $k < 0$ indicates a decreasing $HANPP_{harv}$ trend. According to the F statistic for the significance test of the trend, we divided the trend into three classes: extremely significant ($p < 0.01$), significant ($0.01 < p < 0.05$) and not significant ($p > 0.05$). The results shown in Figure 3a illustrate that $HANPP_{harv}$ trends shifted from extremely significant increases to no significant trends in the counties from Lianyungang to Nantong, where the dominant crops changed from grain crops (including rice, wheat, barley, and maize) to economic crops (including peanut, rapeseed, sesame, and cotton) (Figure 3b, Table S1). The difference in the crop structure among the counties is one of the causes of the difference in $HANPP_{harv}$ trends. The stable increase in the yield of grain crops compared with economic crops may be another cause.



(**a**)



(**b**)

Figure 3. The significance of $HANPP_{harv}$ trends (**a**); and the average proportions of grain crops and economic crops (**b**) in the counties of the coastal areas of Jiangsu from 2000 to 2010.

3.3. HANPP

HANPP increased from 332 g· C/m^2/year in 2000 to 442 g· C/m^2/year in 2010, with an average annual growth rate of 2.9%. It reached its peak in 2006 due to the peak in HANPP$_{luc}$. The proportions of appropriated NPP increased from 50.3% to 71.0% of NPP$_{pot}$, mainly driven by HANPP$_{harv}$ with an increase from 45.2% to 61.3% of NPP$_{pot}$ (Figure 4a). The proportion of HANPP$_{harv}$ in HANPP ranged between 77.4% (in 2006) and 106.8% (in 2008) in the observed period, with a mean value of 92.7%. In counties, the proportion of HANPP showed an obvious increase since 2000, especially in Guanan and Guanyun, increasing by approximately 42% and 37% of NPP$_{pot}$ respectively (Table S2).

The average proportion of HANPP in the 21 counties from 2000 to 2010 was calculated to derive the spatial distribution of HANPP (Figure 4b). Overall, HANPP ranged from 21.8% to 63.8% of NPP$_{pot}$ over the period from 2000 to 2010, with the highest appropriation in Jianhu County and the lowest in Lianyungang District. In almost half of the counties, HANPP was greater than 50% of NPP$_{pot}$.

The average HANPP$_{harv}$ ranged from 15.6% to 64.0% of NPP$_{pot}$ over the period from 2000 to 2010. Regions with a higher harvest appropriation occurred in the counties far from the sea and with a high proportion of cultivated land, such as Yandu, Funing, Jianhu, and Hai'an County.

The average HANPP$_{luc}$ exhibited a significant spatial variation (Figure 4c) but only accounted for approximately 7.3% of the total HANPP. The higher positive values of HANPP$_{luc}$ occurred in the counties with a large area of construction land expansion or tidal flats reclamation such as Nantong District, Qidong, Haimen, Dafeng, and so on, where the key land conversions were the transition from tidal flats to cropland or from cropland to construction land.

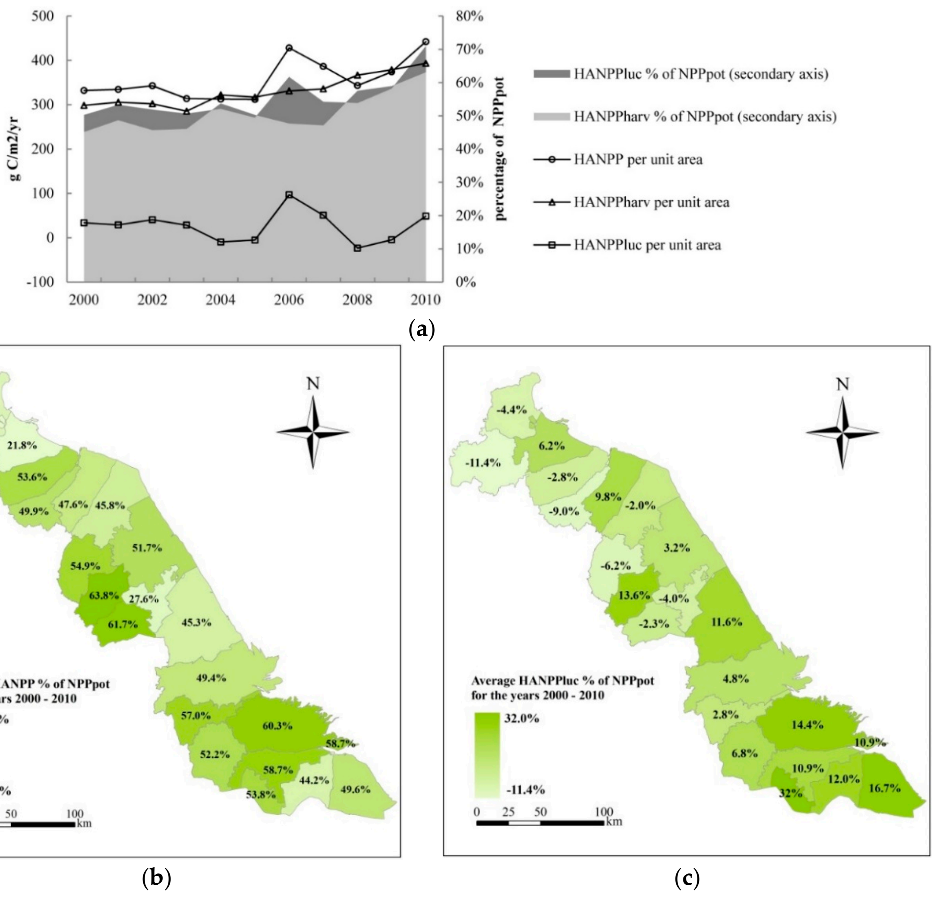


Figure 4. HANPP trends from 2000 to 2010 (**a**); and the spatial distributions of average HANPP (**b**); and HANPP$_{luc}$ (**c**) as a proportion (%) of NPP$_{pot}$ for the years 2000-2010 in the coastal areas of Jiangsu.

4. Discussion

4.1. Comparison with Previous Studies

Land use classes in the study area were aggregated to five types, namely cropland, forestland, construction land, water areas, and unused land. The NPP_{pot} of the natural waters (accounting for approximately 71% of the total water areas) including tidal flats, lakes, and Yangtze River was set to be equal to NPP_{act} in our calculation. Although the proportion of construction land is relatively high, it did not result in a high $HANPP_{luc}$ proportion of NPP_{pot} in the whole area because much of the construction land is villages (approximately 52% of the construction land), with little impervious surface and lots of trees or other vegetation. In our estimate, the average NPP_{pot} and NPP_{act} of construction land were 698 $g \cdot C/m^2$/year and 463 $g \cdot C/m^2$/year respectively for the years 2000–2010. Additionally, as stated in Section 2.2., $HANPP_{harv}$ in our calculation focus on biomass harvest from cropland. Thus, HANPP estimate in our study may be slightly lower than the actual value in the coastal areas of Jiangsu for the period 2000–2010.

On a global scale, estimates of HANPP vary from 20% to 40% (Table 2) because of differences in the definition, method and conversion factors. On a country or regional scale, the spatial variation in HANPP is striking. Imhoff *et al.* generated a spatial balance sheet of the global NPP "supply" and "demand". This sheet shows that western Europe and south-central Asia appropriate more than 70% of their regional NPP, whereas South America appropriates approximately 6% of the NPP. As shown in Table 2, our results are similar to the estimates of HANPP in the United Kingdom, Philippines, Spain, Italy, Czech Republic, and China, where the proportion of appropriated NPP is greater than 55% because of the higher proportion of agricultural land. HANPP in Nova Scotia, Canada (25.5% of NPP_{pot}) is low because only 3%–8% of the area is covered by agricultural land. Land use is one of the important factors that influences HANPP. Generally, a high proportion of agricultural land leads to a high HANPP, which is consistent with the results obtained in the coastal areas of Jiangsu.

Table 2. Comparisons between the estimates of HANPP in this paper and previous studies.

References	Study Scale	Year	HANPP% of NPP_{pot}
Vitousek [9]	Global	1970s	30.7(3.8–38.8)
Rojstaczer [32]	Global	1980s–1990s	32(10-55)
Imhoff [10]	Global	1995	20.3(14.1–26.07)
Haberl [33]	Global	2000	23.8
Ma *et al.* [34]	Global	2000	28
Haberl [35]	Austria	1950–1995	50
Musel [36]	United Kingdom	1800–2000	71–68
Kastner [37]	Philippines	1910–2003	35–62
Schwarzlmüller [38]	Spain	1955–2003	67–61
Kohlheb and Krausmann [39]	Hungary	1961–2005	67–49
Niedertscheider [40]	South Africa	1961–2006	21–25
Niedertscheider [41]	Italy	1884–2007	78–56
Fetzel *et al.* [42]	New Zealand	1860–2005	34–32
Vackar and Orlitova [43]	Czech Republic	2006	56
Chen *et al.* [8]	China	2001–2010	49.5–57.8
O'Neill [44]	Nova Scotia (Canada)	1999–2003	25.5
This study	Coastal areas of Jiangsu (China)	2000–2010	50.3–71.0

Different HANPP trends can also be observed in countries and regions outlined in Table 2. Descending HANPP trends in the United Kingdom, Spain, and Italy, compared with increasing trends in China and the Philippines, which is consistent with our study area. The factors that influence HANPP trends will be discussed in the following sections.

4.2. Influence of Climate Conditions on HANPP

NPP_{pot} and NPP_{act} were estimated using the Miami model and CASA model, respectively, driven by the climate data, which exhibited annual fluctuations in the study area over the period from 2000 to 2010. Furthermore, NPP_{pot} and NPP_{act} varied significantly within individual years as a result of the high interannual variation in the climatic conditions. In particular, the 2007 annual mean temperature was the highest value recorded in Jiangsu province since 1950.

Calculations based on the data from 14 meteorological stations (19 stations in 2009 and 2010) and five radiation stations (Figure S3) indicated that NPP_{pot} decreased (in 2004) or increased (in 2006 and 2007) significantly because of remarkable drought or high temperature and rainy climate, respectively, which resulted in the $HANPP_{harv}$ proportion of NPP_{pot} being extremely high or low in the corresponding years (Figure 4a). Furthermore, a decrease in solar radiation caused by long-term continuous rain resulted in a decrease in NPP_{act} which was calculated using the light use efficiency model (the CASA model). $HANPP_{luc}$, which was determined as the difference between NPP_{pot} and NPP_{act}, increased significantly in 2006 (Figure 4a).

Additionally, $HANPP_{luc}$, which accounted for a very small part of HANPP, exihibited a relatively strong sensitivity to the climate fluctuations. $HANPP_{luc}$ may drop below zero (in 2004 and 2008) under particular weather conditions, which result in that $HANPP_{harv}$ being higher than HANPP in these years.

4.3. Influence of Agricultural Production Conditions on HANPP

In an agricultural ecosystem, fertilizer use and irrigation area are important driving factors for the amount of harvested NPP [45]. Here, fertilizer use per unit area (the amount of fertilizer use divided by the cropland area) and the farmland irrigation rate (the ratio of irrigation area to cropland area) were selected as indicators of the agricultural production conditions to analyze the response of $HANPP_{harv}$ to these factors in the coastal areas of Jiangsu. During the observed period, the fertilizer use increased from 643 kg/hm^2 to 710 kg/hm^2, and the farmland irrigation rate increased from 74.2% to 80.6%. As shown in Figure 5, $HANPP_{harv}$ was significantly positively correlated with fertilizer use and farmland irrigation rate ($p < 0.05$). Overall, the increase in fertilizer use and irrigation rate on cropland resulted in an increase in crop yields in the study area. Generally, effective irrigation can weaken the effect of water stress and increase crop yields, and fertilizer use can increase the crop leaf nitrogen content, which accelerates the photosynthetic rate and also increases crop yields.

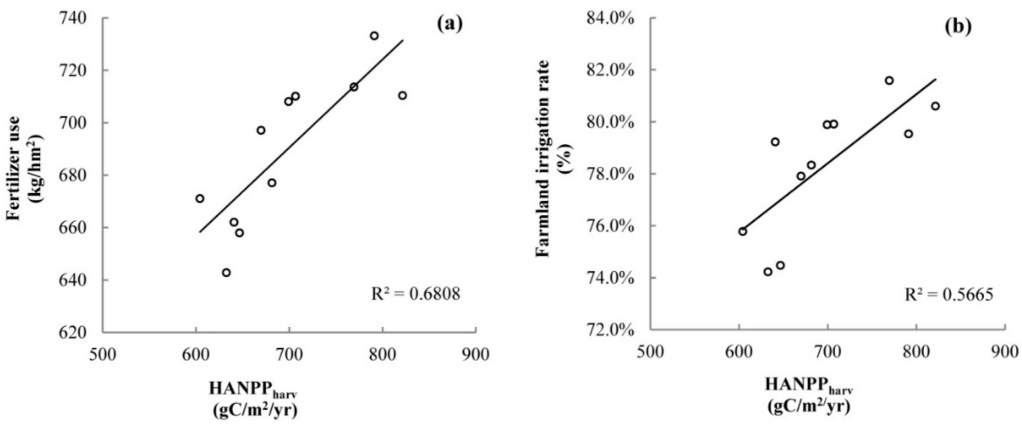


Figure 5. Correlation between (**a**) $HANPP_{harv}$ and fertilizer use and (**b**) $HANPP_{harv}$ and farmland irrigation rate during the observed period.

Similar studies on HANPP [36,38,39] indicated that agricultural intensification (including increasing fertilizer use) led to a decline in HANPP as areas of marginal productivity in agricultural land were abandoned or reforested, which is different from our results. In our study area HANPP increased with the increase in agricultural intensification because the cropland converted to construction land instead of being reforested.

4.4. Influence of Socio-Economic Conditions on HANPP

Population and economic growth increase human demand for biomass. Long-term trajectories of HANPP on a country scale, as analysed by Krausmann [45], indicated that HANPP trends were similar to those of the population, and a positive correlation was observed between the biomass harvest and the population. The total population and GDP increased during the study period (Figure S4), and these trends were consistent with the trends observed for HANPP. The per capita GDP and population density were significantly positively correlated with HANPP from 2000 to 2010 (Figure 6a,b). The relationship of the population and economy with HANPP among 21 counties was also analyzed. Due to the significant spatial variation in $HANPP_{luc}$ among the counties, the relationship of the population and economy with $HANPP_{luc}$ would be uncertain. Thus, we chose to analyze the relationship of the average $HANPP_{harv}$ with the population density and per capita GDP. The results (Figure 6c) showed that per capita GDP was significantly negatively correlated with $HANPP_{harv}$. Regions with a high level of per capita GDP were primarily located in urban districts, where a low proportion of cultivated land resulted in a low level of $HANPP_{harv}$. However, the relationship between $HANPP_{harv}$ and the population density was not as significant as that of the per capita GDP (Figure 6d). Generally, regions of high population density may be located in urban areas with a low proportion of agricultural land, and also in agricultural areas with a high proportion of agricultural land. This uncertainty led to the poor relationship between $HANPP_{harv}$ and population density.

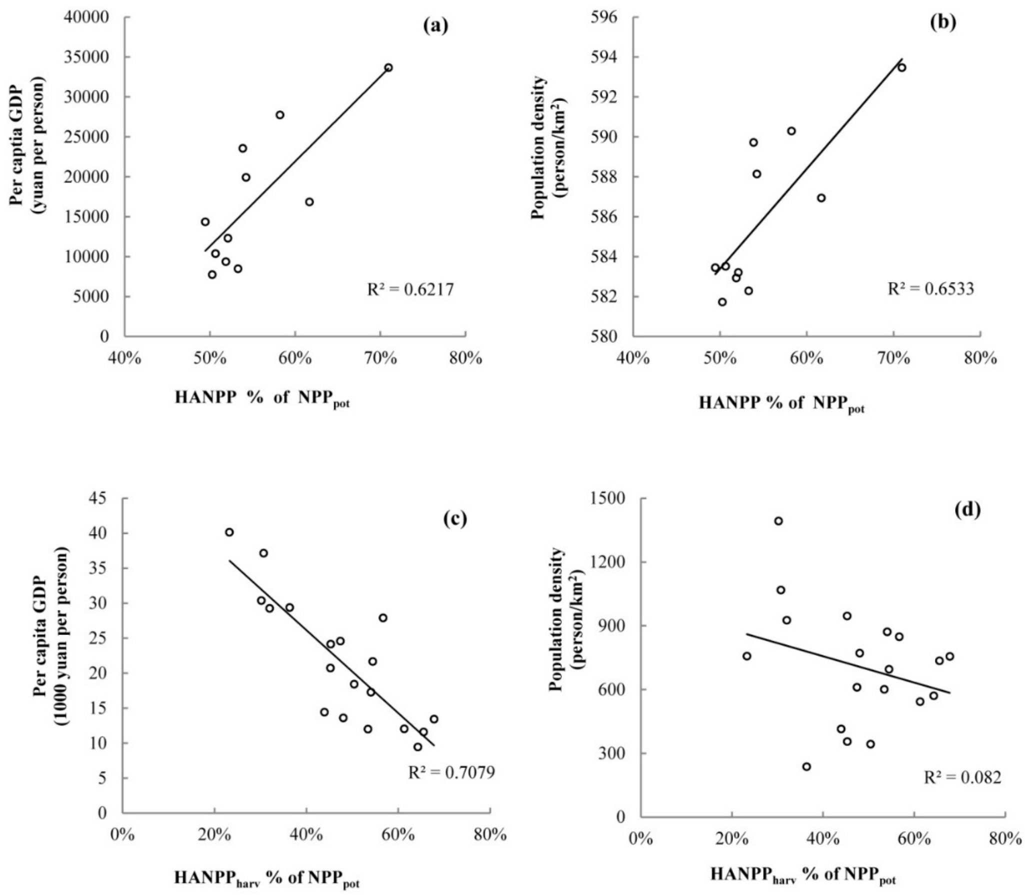


Figure 6. Correlation between (**a**) HANPP and per capita GDP; (**b**) HANPP and population density during the observed period; (**c**) $HANPP_{harv}$ and per capita GDP, and (**d**) $HANPP_{harv}$ and population density in the 21 counties.

5. Conclusions

In this study, HANPP was calculated in the coastal areas of Jiangsu from 2000 to 2010. It increased significantly over this period, and the proportion of appropriated NPP increased from 50.3% to 71.0% of NPP_{pot}. The $HANPP_{harv}$ proportion of HANPP ranged between 77.4% (in 2006) and 106.8% (in 2008) in the observed period, with a mean value of 92.7%. Similar work on HANPP indicated a relatively high HANPP, which was mainly determined by agricultural harvest. The results from our study are reasonable compared with those of previous studies and show that Haberl's method is suitable for use in the study area. Increased fertilizer use and irrigation are linked to improvements in crop yields, which result in increased biomass harvest in the study area dominated by cropland and also place further pressure on the local ecosystems. Additionally, this study showed that agricultural intensification did not lead to a decline in HANPP as cropland converted to construction land instead of being reforested in the study area, which provides essential information for agricultural policies. Further work is needed to improve the method by incorporating the local trade and by calibrating the conversion parameters according to field survey data. Finally, future studies on the relationships between HANPP trajectories at different economic development stages with the goal of achieving sustainable development will likely yield interesting results.

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References

1. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: Synthesis*; Island Press: Washington, DC, USA, 2005.
2. Krausmann, F.; Haberl, H.; Erb, K.-H.; Wiesinger, M.; Gaube, V.; Gingrich, S. What determines geographical patterns of the global human appropriation of net primary production? *J. Land Use Sci.* **2009**, *4*, 15–33. [CrossRef]
3. Vitousek, P.M.; Mooney, H.A.; Lubchenco, J.; Melillo, J.M. Human domination of earth's ecosystems. *Science* **1997**, *277*, 494–499. [CrossRef]
4. Costanza, R. Ecosystem services: Multiple classification systems are needed. *Biol. Conserv.* **2008**, *141*, 350–352. [CrossRef]
5. Wang, Q.; Jin, X.; Zhou, Y. Dynamic analysis of coastal region cultivated land landscape ecological security and its driving factors in Jiangsu. *Acta Ecol. Sin.* **2011**, *31*, 5903–5909.
6. Wang, Q.; Li, Z.; Fan, J.; Hao, X.; Yuan, X. The change and its ecological responses of cultivated land intensive use in Jiangsu coastal district. *Chin. Agric. Sci. Bull.* **2012**, *28*, 186–191.
7. Xiao, J.; Chen, D.; Xu, M.; Yu, Q.; Zhou, S.; Zhao, F. Evaluation of the loss values of the tidal wetlands ecosystem services by sea reclamation projects: A case of Jiangsu province. *Trans. Oceanol. Limnol.* **2010**, *4*, 95–100.
8. Chen, A.; Li, R.; Wang, H.; He, B. Quantitative assessment of human appropriation of aboveground net primary production in China. *Ecol. Model.* **2015**, *312*, 54–60. [CrossRef]
9. Vitousek, P.M.; Ehrlich, P.R.; Ehrlich, A.H.; Matson, P.A. Human appropriation of the products of photosynthesis. *Bioscience* **1986**, *36*, 368–373. [CrossRef]
10. Imhoff, M.L.; Bounoua, L.; Ricketts, T.; Loucks, C.; Harriss, R.; Lawrence, W.T. Global patterns in human consumption of net primary production. *Nature* **2004**, *429*, 870–873. [CrossRef] [PubMed]
11. Haberl, H. Human appropriation of net primary production as an environmental indicator: Implications for sustainable development. *Ambio* **1997**, *26*, 143–146.

12. Gingrich, S.; Niedertscheider, M.; Kastner, T.; Haberl, H.; Cosor, G.; Krausmann, F.; Kuemmerle, T.; Müller, D.; Reith-Musel, A.; Jepsen, M.R.; *et al*. Exploring long-term trends in land use change and aboveground human appropriation of net primary production in nine European countries. *Land Use Policy* **2015**, *47*, 426–438. [CrossRef]
13. Haberl, H.; Erb, K.H.; Krausmann, F. Human appropriation of net primary production: Patterns, trends, and planetary boundaries. *Annu. Rev. Environ. Resour.* **2014**, *39*, 363–391. [CrossRef]
14. Bi, Y.; Gao, C.; Wang, Y.; Li, B. Estimation of straw resources in China. *Trans. Chin. Soc. Agric. Eng.* **2009**, *25*, 211–217.
15. Wang, X.; Xue, S.; Xie, G. Value-taking for residue factor as a parameter to assess the field residue of field crops. *J. China Agric. Univ.* **2012**, *17*, 1–8. [CrossRef]
16. Xie, G.; Han, D.; Wang, X.; Lv, R. Harvest index and residue factor of cereal crops in China. *J. China Agric. Univ.* **2011**, *16*, 1–8.
17. Zhang, F.; Zhu, Z. Harvest index for various crops in China. *Sci. Agric.* **1990**, *23*, 83–87.
18. Huang, Y.; Zhang, W.; Sun, W.J.; Zheng, X.H. Net primary production of chinese croplands from 1950 to 1999. *Ecol. Appl.* **2007**, *17*, 692–701. [CrossRef] [PubMed]
19. Lobell, D.B.; Hicke, J.A.; Asner, G.P.; Field, C.B.; Tucker, C.J.; Los, S.O. Satellite estimates of productivity and light use efficiency in United States agriculture, 1982–1998. *Glob. Chang. Biol.* **2002**, *8*, 722–735. [CrossRef]
20. Lieth, H. Primary production: Terrestrial ecosystems. *Hum. Ecol.* **1973**, *1*, 303–332. [CrossRef]
21. Haberl, H.; Schulz, N.B.; Plutzar, C.; Erb, K.H.; Krausmann, F.; Loibl, W.; Moser, D.; Sauberer, N.; Weisz, H.; Zechmeister, H.G.; *et al*. Human appropriation of net primary production and species diversity in agricultural landscapes. *Agric. Ecosyst. Environ.* **2004**, *102*, 213–218. [CrossRef]
22. Cramer, W.; Kicklighter, D.W.; Bondeau, A.; Moore, B.; Churkina, G.; Nemry, B.; Ruimy, A.; Schloss, A.L.; The Participants of the Potsdam NPP Model Intercomparison. Comparing global models of terrestrial net primary productivity (NPP): Overview and key results. *Glob. Chang. Biol.* **1999**, *5*, 1–15. [CrossRef]
23. Del Grosso, S.; Parton, W.; Stohlgren, T.; Zheng, D.; Bachelet, D.; Prince, S.; Hibbard, K.; Olson, R. Global potential net primary production predicted from vegetation class, precipitation, and temperature. *Ecology* **2008**, *89*, 2117–2126. [CrossRef] [PubMed]
24. Raich, J.W.; Rastetter, E.B.; Melillo, J.M.; Kicklighter, D.W.; Steudler, P.A.; Peterson, B.J.; Grace, A.L.; Moore, B.; Vorosmarty, C.J. Potential net primary productivity in south-america—Application of a global-model. *Ecol. Appl.* **1991**, *1*, 399–429. [CrossRef]
25. Zaks, D.P.M.; Ramankutty, N.; Barford, C.C.; Foley, J.A. From miami to madison: Investigating the relationship between climate and terrestrial net primary production. *Glob. Biogeochem. Cycles* **2007**, *21*. [CrossRef]
26. Potter, C.S.; Randerson, J.T.; Field, C.B.; Matson, P.A.; Vitousek, P.M.; Mooney, H.A.; Klooster, S.A. Terrestrial ecosystem production—A process model-based on global satellite and surface data. *Glob. Biogeochem. Cycles* **1993**, *7*, 811–841. [CrossRef]
27. Los, S.O. *Linkages between Global Vegetation and Climate: An Analysis Based on Noaa Advanced very High Resolution Radiometer Data*; National Aeronautics and Space Administration, Goodard Space Flight Center: Greenbelt, MD, USA, 1998.
28. Field, C.B.; Randerson, J.T.; Malmström, C.M. Global net primary production: Combining ecology and remote sensing. *Remote Sens. Environ.* **1995**, *51*, 74–88. [CrossRef]
29. Piao, S.; Fang, J.; Guo, Q. Application of casa model to the estimation of chinese terrestrial net primary productivity. *Acta Phytoecol. Sin.* **2001**, *25*, 603–608.
30. Zhu, W.; Pan, Y.; He, H.; Yu, D.; Hu, H. Maxim light use efficiency of typical vegetation in China. *Chin. Sci. Bull.* **2006**, *51*, 700–706. [CrossRef]
31. Zhang, J.; Feng, X.; Ni, J. Calculation of maxim solar radiation base on regression analysis in China. *Resour. Sci.* **1981**, *3*, 38–46.
32. Rojstaczer, S.; Sterling, S.M.; Moore, N.J. Human appropriation of photosynthesis products. *Science* **2001**, *294*, 2549–2552. [CrossRef] [PubMed]
33. Haberl, H.; Erb, K.H.; Krausmann, F.; Gaube, V.; Bondeau, A.; Plutzar, C.; Gingrich, S.; Lucht, W.; Fischer-Kowalski, M. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 12942–12945. [CrossRef] [PubMed]

34. Ma, T.; Zhou, C.H.; Pei, T. Simulating and estimating tempo-spatial patterns in global human appropriation of net primary production (HANPP): A consumption-based approach. *Ecol. Indic.* **2012**, *23*, 660–667. [CrossRef]
35. Haberl, H.; Erb, K.H.; Krausmann, F.; Loibl, W.; Schulz, N.; Weisz, H. Changes in ecosystem processes induced by land use: Human appropriation of aboveground NPP and its influence on standing crop in Austria. *Glob. Biogeochem. Cycles* **2001**, *15*, 929–942. [CrossRef]
36. Musel, A. Human appropriation of net primary production in the United Kingdom, 1800–2000 changes in society's impact on ecological energy flows during the agrarian-industrial transition. *Ecol. Econ.* **2009**, *69*, 270–281. [CrossRef]
37. Kastner, T. Trajectories in human domination of ecosystems: Human appropriation of net primary production in the Philippines during the 20th century. *Ecol. Econ.* **2009**, *69*, 260–269. [CrossRef]
38. Schwarzlmuller, E. Human appropriation of aboveground net primary production in spain, 1955–2003: An empirical analysis of the industrialization of land use. *Ecol. Econ.* **2009**, *69*, 282–291. [CrossRef]
39. Kohlheb, N.; Krausmann, F. Land use change, biomass production and HANPP: The case of hungary 1961–2005. *Ecol. Econ.* **2009**, *69*, 292–300. [CrossRef]
40. Niedertscheider, M.; Gingrich, S.; Erb, K.H. Changes in land use in South Africa between 1961 and 2006: An integrated socio-ecological analysis based on the human appropriation of net primary production framework. *Reg. Environ. Chang.* **2012**, *12*, 715–727. [CrossRef]
41. Niedertscheider, M.; Erb, K. Land system change in Italy from 1884 to 2007: Analysing the north-south divergence on the basis of an integrated indicator framework. *Land Use Policy* **2014**, *39*, 366–375. [CrossRef] [PubMed]
42. Fetzel, T.; Gradwohl, M.; Erb, K.H. Conversion, intensification, and abandonment: A human appropriation of net primary production approach to analyze historic land-use dynamics in New Zealand 1860–2005. *Ecol. Econ.* **2014**, *97*, 201–208. [CrossRef]
43. Vackar, D.; Orlitova, E. Human appropriation of aboveground photosynthetic production in the Czech Republic. *Reg. Environ. Chang.* **2011**, *11*, 519–529. [CrossRef]
44. O'Neill, D.W.; Tyedmers, P.H.; Beazley, K.F. Human appropriation of net primary production (HANPP) in Nova Scotia, Canada. *Reg. Environ. Chang.* **2007**, *7*, 1–14. [CrossRef]
45. Krausmann, F.; Gingrich, S.; Haberl, H.; Erb, K.H.; Musel, A.; Kastner, T.; Kohlheb, N.; Niedertscheider, M.; Schwarzlmuller, E. Long-term trajectories of the human appropriation of net primary production: Lessons from six national case studies. *Ecol. Econ.* **2012**, *77*, 129–138. [CrossRef] [PubMed]