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Quantifying and Mapping Human Appropriation of Net Primary Productivity in Qinghai Grasslands in China

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Abstract: Human appropriation of net primary productivity (HANPP) is an important indicator for assessing ecological sustainability. However, the spatiotemporal dynamics of HANPP in the Qinghai grasslands remain unclear. In this study, we used the spatially explicit Biome-BGCMuSo model to quantify and map HANPP in the Qinghai grasslands from 1979 to 2018. Generally, the actual net primary productivity (NPP_{act}) was slightly lower than the potential net primary productivity (NPP_{pot}), and the difference between the NPP_{pot} and NPP_{act} increased slightly over time. From 1979 to 2001, the NPP_{pot} and NPP_{act} were relatively stable; however, from 2001 to 2018, both showed significant fluctuating upward trends. From 1979 to 2018, HANPP showed a fluctuating upward trend from 6.36 to 31.85 $gC/m^2/yr$, with an average increase of 2.14 $gC/m^2/yr$. The average HANPP was 16.90 $gC/m^2/yr$, which represented 18.80% of the NPP_{pot} of Qinghai grasslands. High HANPP mainly occurred in eastern Qinghai, whereas it was low in central and western Qinghai. Conversely, from 1979 to 2018, the HANPP efficiency decreased in a fluctuating way from 98.28% to 72.05%, with an average annual decrease of 0.66%. The interannual variations in the HANPP efficiency and harvest were negatively correlated, with a correlation coefficient of −0.46 ($p < 0.01$). The average HANPP efficiency was 85.33%, and the values in most grids were between 80% and 100%, being relatively low in southern and eastern Qinghai. In rare cases, the HANPP efficiency was greater than 1. This study clarifies the details of spatiotemporal dynamics of HANPP in the Qinghai grasslands and indicates the need to optimize local management of grassland resources to ensure future ecological sustainability.

Keywords: ecological sustainability; HANPP; spatiotemporal dynamics; grassland management; model

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1. Introduction

The sustainability of ecosystem services is the basis of human survival and sustainable development [1,2]. However, the carrying capacity of natural ecosystems is limited. Excessive disturbance inevitably destroys ecosystem structure and functioning, leading to the decline and loss of ecosystem services [3]. Previous studies have shown that environmental change and human activities are changing ecosystem patterns and processes in different regions on earth [4–6]. These changes inevitably affect human survival and global sustainable development [7,8]. Thus, it has become urgent for future global development to increase ecological security and achieve sustainable natural resource utilization. In particular, assessing ecosystem sustainability is a core issue in sustainable development research [7,9].

Several quantitative methods have been used to assess ecological sustainability [10–13]. Among them, human appropriation of net primary productivity (HANPP) is one of the popular methods of assessing ecological sustainability [13–15]. HANPP is the difference between the potential net primary productivity (NPP_{pot}) and the net primary productivity (NPP) remaining in the ecosystem after human extraction of resources [14,15]. It directly uses the total NPP as the index factor to comprehensively consider the ecological processes of an ecosystem and the direct (or indirect) interference of human activities [14,16]. It reflects the interaction between the ecosystem and human activities from the perspective of resource supply and demand and intuitively displays the degree of utilization of the ecosystem for human activities. In addition, HANPP is a method that is simple and easy to use [15,17,18]. Therefore, it has been widely used in research on related topics.

Qinghai, located in the northeastern part of the Qinghai–Tibet Plateau, is the source of the Yellow, Yangtze, and Lancang Rivers [19]. It has an extremely important and strategic ecological position [20,21]. Grassland ecosystems are widely distributed in this region, accounting for 58.11% of the total land area, and they have high ecological and economic values [20,22–24]. As a basis for animal husbandry, grazing is the most important human activity in the Qinghai grasslands [9,25]. Over the past few decades, part of these grassland ecosystems has been severely degraded by overgrazing [26,27]. Overgrazing in Qinghai grassland ecosystems indicates that they have been over-utilized by humans [28,29]. Excessive HANPP reduces the available resources for other species and affects the biodiversity, carbon–water cycle, and ecosystem services, resulting in serious ecological and environmental problems [17,29,30]. Previous studies have suggested that moderate grazing increases the NPP when compared to ungrazed areas [31,32]. Thus, assessing the HANPP of grassland ecosystems is conducive to understanding the impact of anthropogenic stressors on them. It helps authorities scientifically guide human activities to utilize and protect ecosystems and achieve harmonious development of the social economy and natural environment [15,33]. However, an estimation of HANPP is lacking for the Qinghai grassland ecosystem.

Although HANPP estimations have been conducted at global, national, and regional scales, there are relatively few specific or systematic reports on the spatiotemporal dynamics of HANPP in grassland ecosystems [15,16,33–35]. In addition, previous studies on grassland HANPP estimation did not effectively consider the effects of grazing or the specific natural environment on grass growth, leading to considerable uncertainty in the HANPP estimation of grazing grasslands [14,16,31]. To overcome this, we selected the Biome-BGCMuSo model to estimate the storage and fluxes of carbon in Qinghai grasslands. This is a mechanistic model developed from the Biome-BGC that has been successfully applied in many regions, including the Qinghai–Tibet Plateau [31,36–38]. The Biome-BGCMuSo model can better simulate grass growth than the Biome-BGC model, especially when considering the impact of certain physiological and ecological processes on grass productivity under energy and water stress; both of these stress conditions are in accordance with the characteristics of alpine environments and the wide distribution of arid and semi-arid grasslands in Qinghai [39]. In addition, the Biome-BGCMuSo model also effectively considers the grazing process [39,40]. Based on the Biome-BGCMuSo model, we aimed to estimate the HANPP and explore its spatiotemporal dynamics in the Qinghai grasslands from 1979 to 2018. This will further our knowledge of the HANPP in grasslands and provide theoretical guidance and data support for future local grassland management.

2. Materials and Methods

2.1. Study Area

Qinghai is located in the northeastern part of the Qinghai–Tibet Plateau, which is called "the roof of the world" [19], and has an average altitude of 3000–4000 m a.s.l. It experiences a plateau continental climate, with an average annual temperature of 1.37 °C and average annual precipitation of 365.70 mm. Its climate is characterized by a low temperature, large temperature differences between the day and night, low but concentrated rainfall, long sunshine duration, and strong solar radiation. Winters are cold and long, and summers are cool and short. Qinghai has a grassland area of 41.9 million hm^2, accounting for 58.11% of the total land area [20,22–24]. Grasslands are mainly distributed in the southern Qinghai Plateau, Qaidam Basin, and around Qinghai Lake. The plants occurring in this region grow under energy stress, and arid and semi-arid grasslands are also widespread. The grassland ecosystem in this region is sensitive and vulnerable to climate change and anthropogenic activities. Parts of the grassland ecosystems in Qinghai have been severely degraded over the past few decades due to grazing disturbance (Figure 1) [22,24,26,27].

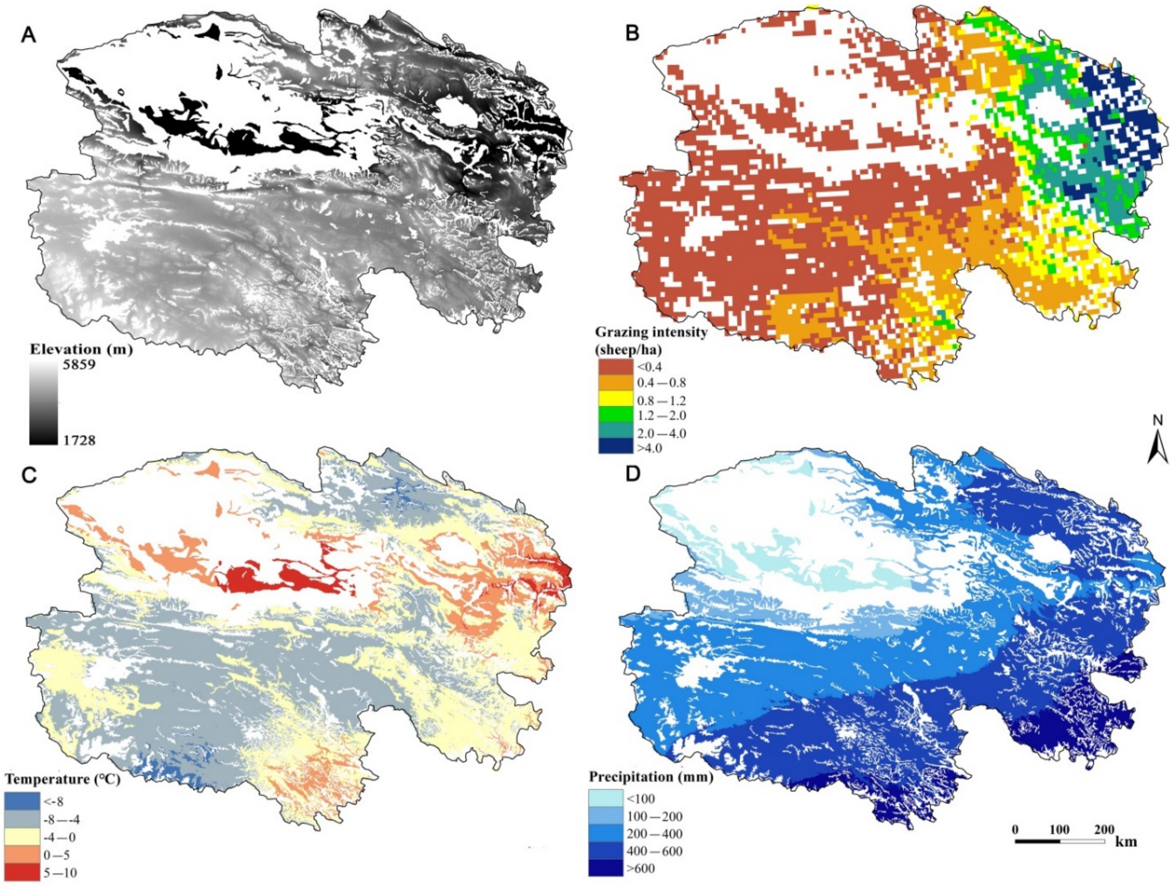

Figure 1. Distribution of elevation (**A**), average annual grazing intensity (**B**), average annual temperature (**C**), and average annual precipitation (**D**) in Qinghai grasslands in the period of 1979 to 2018.

2.2. Methods

In the present study, as proposed by Haberl et al. [14] and Huang et al. [31], HANPP was defined as the sum of the harvest and the difference between NPP_{pot} and the actual net primary productivity (NPP_{act}). In Qinghai, the grasslands are mainly used for grazing, and other human disturbances are very weak and difficult to quantify because the necessary data are lacking. Thus, when estimating HANPP in Qinghai grasslands, we assumed that grazing was the only human disturbance [9,25].

The Biome-BGCMuSo model is a process-based ecosystem model developed from the Biome-BGC model to improve its ability to simulate the carbon cycle in managed ecosystems by integrating the multilayer soil module, soil-moisture-related plant senescence, dynamic phenology, grazing, and so on. A detailed description of the Biome-BGCMuSo model can be found in Hidy et al. [39]. In this model, HANPP and HANPP efficiency were calculated step by step as follows.

The total NPP_{pot} (NPP under a non-grazed scenario (gC/m^2)) was calculated as follows:

$$NPP_{pot} = C_{veg} + C_{litter} \tag{1}$$

where C_{veg} is the vegetative carbon and C_{litter} is the litter carbon.

This model defines grazing based on the "livestock unit" (LSU) terminology, where 1 LSU refers to an average animal. The grass eaten by domestic animals is considered to be harvested by humans. Thus, the total NPP_{act} (NPP under the grazed scenario (gC/m^2)) was calculated as follows:

$$NPP_{act} = C_{veg} + C_{litter} + harvest \quad (2)$$

where harvest (g C/ha) is the carbon consumed by domestic animals.

Furthermore, HANPP was calculated as follows:

$$HANPP = NPP_{pot} - NPP_{act} + harvest \quad (3)$$

HANPP efficiency was calculated as described by Fetzel et al. [41]:

$$HANPP\ efficiency = harvest/HANPP \quad (4)$$

HANPP efficiency is used to express how efficiently the key natural resource NPP entered the socio-ecological system and is closely related to the rationality of land use [41,42].

The Biome-BGCMuSo model developed by Hidy et al. [39] was originally used for simulation at the site scale. In the present study, to apply the Biome-BGCMuSo model over a large area, we assumed that the Qinghai grasslands consisted of many grids with a spatial resolution of 10 × 10 km. A loop program was designed to run the Biome-BGCMuSo model in each grid before the outputs of the Qinghai grasslands could be acquired. Then, the spatiotemporal dynamics of HANPP and HANPP efficiency could be acquired according to the statistics of the model outputs.

In the present study, we compared the simulated NPP with the observed NPP to further validate the suitability of this model for the Qinghai grasslands. We found that the Biome-BGCMuSo model performed well in the NPP simulation under both the grazed (R^2 = 0.92) and non-grazed (R^2 = 0.96) scenarios (Figure 2).

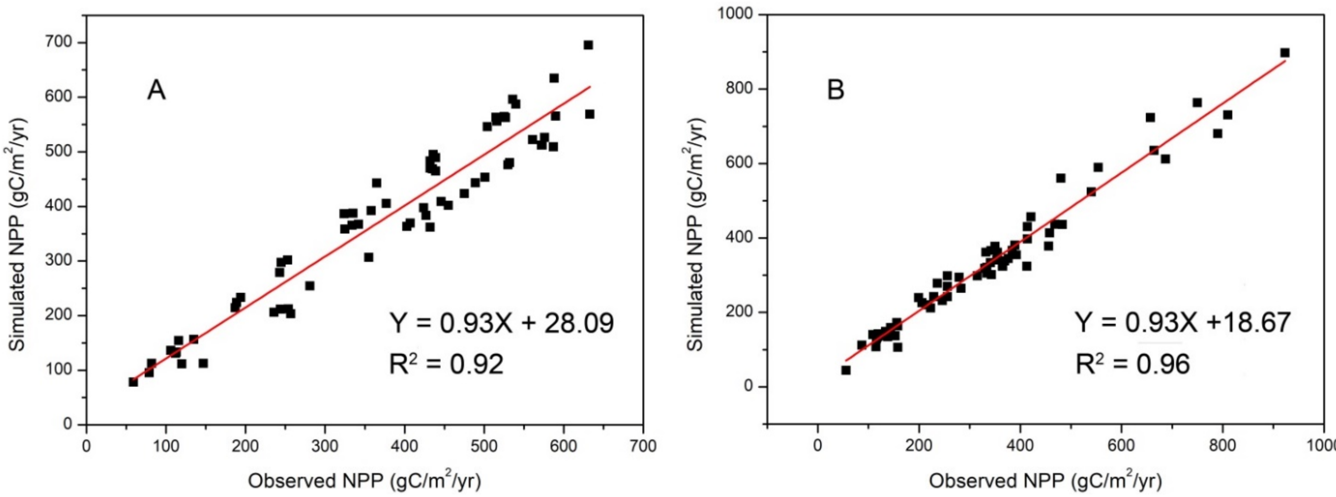

Figure 2. Comparisons of the annual NPP between the simulated and observed data under grazed (**A**) and non-grazed (**B**) conditions in Qinghai grasslands (NPP—net primary productivity).

2.3. Data

The data used in the present study included the observed NPP, grazing, meteorological, and ancillary data. The observed NPP data were used as model validation data, and other data were used to drive the model. To facilitate the operation of the Biome-BGCMuSo model at different grids, all regional data were extracted and smoothed to a 10 × 10 km resolution using Python and R.

2.3.1. Observed NPP Data

The observed NPP data were collected from previous publications [43,44] and field observations of the Qinghai grasslands. A total of 55 plots were used to sample the annual NPP data, among which 24 and 31 plots were used to collect annual NPP data outside and inside the enclosure under the grazing and non-grazing scenarios, respectively. Among all the sampling sites, five were used to collect annual NPP data under both the grazed (outside the enclosure) and non-grazed (inside the enclosure) scenarios. We collected the aboveground and belowground biomass at each plot at the end of the growing season. The annual total biomass was then converted into the annual observed NPP by multiplying the value by 0.45, which was the conversion coefficient adopted by JingYun and Wei [45]. In this study, the observed NPP values were compared with the simulated NPP values to validate the reliability of the simulation results.

2.3.2. Grazing Data

Grazing data were produced by integrating multi-source data. The grazing intensity data for 2010 were extracted from the Food and Agriculture Organization (FAO) page "Gridded Livestock of the World" (GLW) (12 June 2021). The GLW uses the reference year of 2010 for global distributions of livestock, with a spatial resolution of 5 min of arc (approximately 10 km at the equator). Moreover, it is a peer-reviewed spatial dataset. The average spatial resolutions of the underlying census data are between 100 and 250 km^2 in Qinghai, China. In each of the census polygons, the livestock numbers were divided by the surface area of the administrative unit polygon to estimate the densities of livestock, and they were corrected by a mask excluding unsuitable areas [46]. To produce a time series of the grazing intensity data for the years from 1979 to 2018, we corrected these data using livestock statistics from the local government in different administrative regions from 1979 to 2018, which also further ensured a high accuracy of the grazing intensity data. A grazing calendar was created using the information obtained from herders in the Qinghai grasslands. In the present study, all livestock were converted into sheep units (a female sheep that eats 1.8 kg of hay with 14% moisture per day) using the conversion coefficient provided by the Ministry of Agriculture of the People's Republic of China (16 June 2021) and the data obtained from a survey of local herders—one cattle equals six sheep, one yak equals 4.5 sheep, one horse equals six sheep, one goat equals 0.9 sheep, and one camel equals eight sheep.

2.3.3. Meteorological Data

Meteorological data included the daily values of air temperature, precipitation, humidity, radiation, and day length. The regional meteorological data for the Qinghai grasslands in the period from 1979 to 2018 were derived from the China Meteorological Forcing Dataset because their data were evaluated according to the observed data and proved to be more accurate than the existing reanalysis data worldwide [47]. This dataset was produced by integrating multi-source data (including ground-based observations and several gridded datasets from remote sensing and reanalysis) and can provide driving data for land surface process simulations in China [47]. The Biome-BGCMuSo code assumes that all years have 365 days; therefore, we omitted December 31 from leap years within the study period.

2.3.4. Ancillary Data

Soil data, including the texture and PH, were derived from the Harmonized World Soil Database (HWSD) (10 January 2021). The HWSD is a 30 arc-second raster database. In this database, the soil data for the China region were obtained from the second national land survey by the Nanjing Soil Institute, Chinese Academy of Sciences. Elevation data were derived from the Shuttle Radar Topography Mission (SRTM) (12 January 2021) with a 30-m resolution. Ecophysiological parameters were mainly derived from the default parameters of the model plant (C_3 grass), which were acquired from a large number of ecophysiological studies [48]. In the present study, some key parameters were corrected in accordance with the field investigations in the Qinghai grasslands.

3. Results

3.1. Interannual Variation in HANPP in Qinghai Grasslands

Figure 3A shows the interannual variations in the NPP components (HANPP, NPP_{pot}, NPP_{act}, and harvest) in the Qinghai grasslands from 1979 to 2018. Generally, the NPP_{act} was slightly lower than the NPP_{pot}, and the difference between the NPP_{pot} and NPP_{act} (NPP_{pot} minus NPP_{act}) increased slightly as the grazing intensity increased from 1979 to 2018. From 1979 to 2001, the NPP_{pot} and NPP_{act} were both relatively stable; the NPP_{pot} fluctuated around 74.58 gC/m^2/yr, while the NPP_{act} fluctuated around 73.15 gC/m^2/yr. From 2001 to 2018, the NPP_{pot} and NPP_{act} both showed fluctuating upward trends; the NPP_{pot} increased from 65.41 to 130.91 gC/m^2/yr, with an average increase of 3.64 gC/m^2/yr, while the NPP_{act} increased from 63.91 to 122.01 gC/m^2/yr, with an average increase of 3.23 gC/m^2/yr. From 1979 to 2018, HANPP increased in a fluctuating way from 6.36 to 31.85 gC/m^2/yr, with an average increase of 2.14 gC/m^2/yr. On an annual temporal scale, harvest was the main contributor to HANPP in the Qinghai grasslands from 1979 to 2018. The interannual variations in HANPP and harvest had a significant positive correlation, with a correlation coefficient of 0.98 ($p < 0.001$).

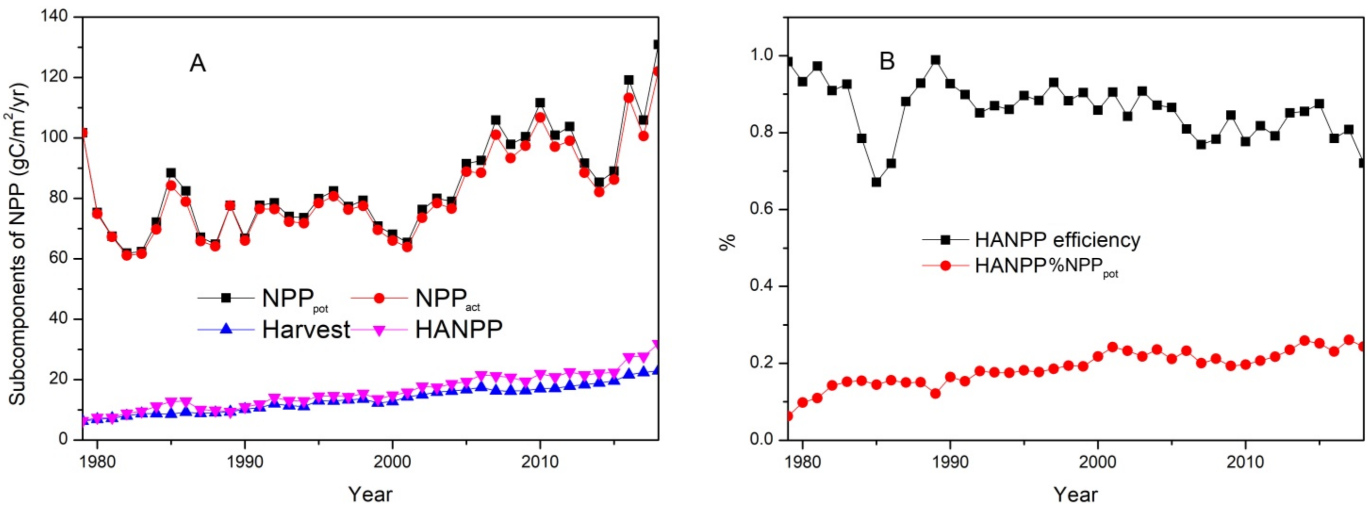

Figure 3. Interannual variations in the (**A**) components of NPP and (**B**) HANPP efficiency and HANPP%NPP_{pot} (percentage that HANPP accounted for NPP_{pot}) in Qinghai grasslands in the period of 1979 to 2018 (NPP—net primary productivity; NPP_{pot}—potential net primary productivity; NPP_{act}—actual net primary productivity; HANPP—human appropriation of net primary productivity).

Figure 3B shows the interannual variations in HANPP efficiency and HANPP%NPP_{pot} (the percentage that HANPP accounted for NPP_{pot}) in the Qinghai grasslands from 1979 to 2018. The HANPP efficiency showed a weak fluctuating downward trend from 1979 to 2018 (98.28% to 72.05%), with an average annual decrease of 0.66%. The interannual variations in HANPP efficiency and harvest showed a negative correlation, with a correlation coefficient of -0.46 ($p < 0.01$). HANPP%NPP_{pot} showed a fluctuating upward trend from 1979 to 2018 (6.25% to 24.33%), with an average annual increase of 0.45%. The interannual variations in HANPP%NPP_{pot} and harvest had a significant positive correlation, with a correlation coefficient of 0.90 ($p < 0.001$).

3.2. Spatial Pattern of HANPP in Qinghai Grasslands

The NPP_{pot} and NPP_{act} followed similar spatial patterns in the Qinghai grasslands. High values mainly occurred in eastern and southeastern Qinghai, whereas low values mainly occurred in central and western Qinghai (Figure 4A,B). In general, HANPP is used to evaluate the extent to which humans disturb ecosystems. Our estimates show that the average HANPP was 16.90 gC/m^2/yr, representing 18.80% of the Qinghai grassland NPP_{pot}. High HANPP mainly occurred in eastern Qinghai, whereas low HANPP mainly occurred in central and western Qinghai (Figure 4C). The average HANPP declined with increasing altitude, as follows: 56.61 (<3000 m), 38.56 (3000–4000 m), and 6.97 gC/m^2/yr (>4000 m). The HANPP efficiency was used to evaluate the efficiency of the human utilization of ecosystems. We found that, in most grids, the average annual HANPP efficiency values were between 80% and 100%; they were relatively low in southern and eastern Qinghai and at different altitudes, as follows: 90.09 (<3000 m), 82.59 (3000–4000 m), and 90.04 (>4000 m) (Figure 4D). In rare cases, the HANPP efficiency was greater than 1. Overall, the average harvest in the Qinghai grasslands was 14.43 gC/m^2/yr, contributing 85.38% to HANPP. High harvest mainly occurred in eastern Qinghai, whereas low harvest mainly occurred in central and western Qinghai (Figure 4E). At different altitudes, the average annual harvest decreased with increasing altitude, as follows: 51.25 (<3000 m), 31.49 (3000–4000 m), and 5.99 gC/m^2 (>4000 m) (Table 1).

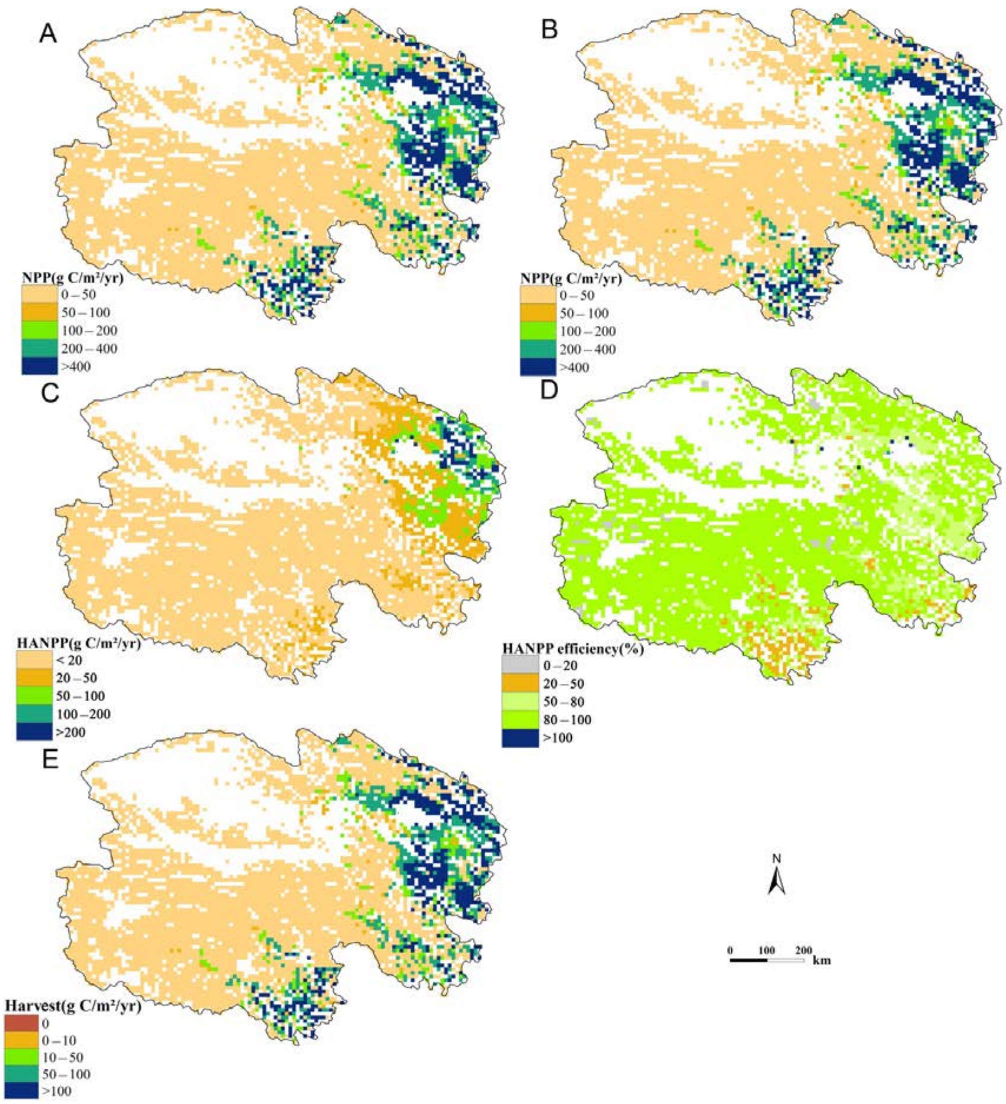

Figure 4. Spatial distribution of the (**A**) average annual potential net primary productivity (NPP_{pot}), (**B**) average annual actual net primary productivity (NPP_{act}), (**C**) average annual human appropriation of net primary productivity (HANPP), (**D**) average annual HANPP efficiency and (**E**) average annual harvest in Qinghai grasslands in the period of 1979 to 2018.

Table 1. NPP_{pot}, NPP_{act}, HANPP, HANPP efficiency, and harvest (consumed by livestock) at different altitudes in Qinghai grasslands in the period of 1979 to 2018.

	<3000 m	3000–4000 m	>4000 m	Whole Area
NPP_{pot} ($gC/m^2/yr$)	157.86	244.41	33.48	84.93
NPP_{act} ($gC/m^2/yr$)	152.50	237.32	32.55	82.45
HANPP ($gC/m^2/yr$)	56.61	38.56	6.97	16.90
HANPP efficiency (%)	90.09	82.59	90.04	85.33
Harvest ($gC/m^2/yr$)	51.25	31.49	5.99	14.43

NPP_{pot}—potential net primary productivity; NPP_{act}—actual net primary productivity; HANPP—human appropriation of net primary productivity.

4. Discussion

4.1. Uncertainties in the Results

In the present study, the outputs of the Biome-BGCMuSo model were compared with the observed data, which proved the reliability of the research results. However, uncertainties in the present study were still inevitable due to the complexity of carbon cycling in reality [49–52].

First, uncertainty was introduced by the method itself. In this study, we assumed that grazing was the only human-related disturbance in the study area, which resulted in uncertainties in the HANPP estimates. We assumed that grazing was the only human-related disturbance due to the lack of sufficient data for assessing the impacts of other human disturbances in this region. Although the grasslands in Qinghai were mainly used for grazing, and other human disturbances contributed much less to the HANPP estimates [9,25], ignoring other human disturbances would inevitably introduce uncertainty. In addition, the model structure itself introduced uncertainty. All models are simplified representations of the real world, which means the complex carbon cycle cannot be fully considered in the Biome-BGCMuSo model. For example, the freezing–thawing cycle that substantially influences plant growth could not be fully considered in the Biome-BGCMuSo model because few studies have quantified its underlying effect on plant productivity in alpine grasslands. Livestock trampling has an indirect impact on plant growth by directly influencing soil compaction, water, and so on. However, the trampling effect could not be included in the Biome-BGCMuSo model because it has been challenging to quantify in previous studies [39,40].

Second, the model input data can be an important limiting factor when estimating the HANPP. The accuracy of the model simulation results is directly related to the accuracy of the model input data. Previous studies have shown that meteorological input data have the greatest impact on the accuracy of model simulation results [39,40,49]. Although the meteorological data used in the present study were validated with observed data (including observed data in Qinghai), showing that this dataset has higher accuracy than other available reanalysis data [47], the accuracy of the data was still lower than that of the observed data, which inevitably led to uncertainty in the results. The grazing data were the key inputs used to estimate the grazing effects. The livestock distribution data for 2010 were extracted from the GLW database (12 June 2021), which was developed to provide a statistically-informed estimate of how livestock may be distributed within a given census unit. Although we corrected the data according to survey statistics from the government to further ensure high precision, uncertainty was inevitable due to the macroscopic nature of livestock statistics from the government.

4.2. Interannual Variation in HANPP in Qinghai Grasslands

HANPP showed a fluctuating upward trend from 1979 to 2018, and the difference between the NPP_{pot} and NPP_{act} (NPP_{pot} minus NPP_{act}) increased slightly in the Qinghai grasslands during this period, indicating that the grazing pressure on the grassland ecosystems increased [34,49]. In addition, we found that the NPP_{pot} and NPP_{act} significantly increased in a fluctuating way from 2001 to 2018; we inferred that climate change led to improvements in the ecological environment of the Qinghai grasslands in recent years. This conclusion is inconsistent with some previous studies that have shown that the Qinghai grasslands have been somewhat restored in recent years by effective government-led ecological restoration measures [53–56]. Apart from the increase in HANPP, we found that the HANPP%NPP_{pot} slightly increased from 1979 to 2018. This also indicates that grazing pressure increased during this period. However, the NPP_{act} showed a clear increase from 2001 to 2018 due to climate change, which alleviated grazing pressure on the grassland ecosystem (Figure 3A). High HANPP would notably alter ecosystem energy flows, and excessive HANPP would inevitably lead to a reduction in biodiversity and ecological degradation [14,34]. In the present study, we found that HANPP efficiency showed a weak fluctuating downward trend from 1979 to 2018, indicating that irrational utilization of grassland resources was increasing in Qinghai during this period [41,42]. Nevertheless, government efforts cannot be denied, and we believe that the situation would have been worse without them. Implementing more effective measures to reduce anthropogenic pressures on the grassland ecosystem in Qinghai is still required because the future impacts of climate change are uncertain. To ensure future sustainable ecological improvements, scientific and effective management measures must be implemented.

4.3. Spatial Pattern of HANPP in Qinghai Grasslands

Generally, in the Qinghai grasslands, the spatial pattern of HANPP was similar to that of grazing intensity, indicating that the strong regional variation in HANPP was mainly caused by the difference in grazing intensity. There were distinct differences in the natural environments (climate, terrain, and so on) and government management practices among the different regions within the Qinghai grasslands, which accounted for the difference in grazing densities (Figure 1) [20,22,31,57]. Generally, grass growth was better in eastern Qinghai because of relatively good hydrothermal conditions. Thus, more livestock were supported in these regions, leading to higher HANPP. In contrast, grass growth in central and western Qinghai was worse due to the relatively poor hydrothermal conditions. In addition, the government implemented strict ecological protection measures in the central and western regions, resulting in lower grazing intensity and HANPP [57,58]. To a large extent, the spatial patterns of HANPP efficiency were opposite to those of HANPP (Figure 4). A low HANPP efficiency was mainly observed in the southern and eastern Qinghai grasslands, whereas a high HANPP efficiency was mainly observed in the central and western Qinghai grasslands. There was relatively high vegetation growth and dense residents in the eastern and southern Qinghai grasslands, which explains the low HANPP efficiency. Excessive grazing activities in the eastern and southern regions became widespread due to the need to support human survival and economic interests, resulting in severe and widespread grassland degradation [20,22,58]. However, in the central and western Qinghai grasslands, grazing intensity was low due to the poor vegetation growth and stricter ecological protection in these regions, resulting in low ecological degradation [22]. In rare cases, the HANPP efficiency was greater than 1, indicating that overcompensation occurred due to moderate grazing [31,49].

4.4. Significance

To date, HANPP has been estimated on different scales [15,16,33–35]. However, there are relatively few specific or systematic reports on this topic in grassland ecosystems [15,16,33–35]. Baeza and Paruelo [59] studied the HANPP in 2001/2002 and 2012/2013 in the Rio de la Plata grasslands of South America, which showed that HANPP accounted for more than

40% of the annual productivity. In their study, the NPP_{pot} was assumed to be equal to the NPP_{act} in perennial forage resources, indicating that the effect of grazing on productivity was not considered, whereas the NPP_{act} estimates were based on official agricultural statistics or modeled from a time series of satellite images. The harvest in perennial forage resources was calculated as a fixed proportion of the aboveground NPP using the biomass harvest index by domestic herbivores. Notably, the estimate of HANPP through the combined application of multiple methods inevitably increased the uncertainty of the results due to the methodological differences [16,17,31]. Huang et al. [31] estimated and analyzed the spatiotemporal patterns of HANPP in Central Asian grasslands using the Biome-BGC model, which showed that HANPP was 47 gC/m^2/yr, accounting for 34% of grassland productivity. In their study, the NPP_{pot}, NPP_{act}, and harvest were estimated using the same Biome-BGC model, adopting a functionally holistic approach. In the present study, to obtain more accurate results, we selected the Biome-BGCMuSo model and designed a loop program to run this model over a large area to estimate and analyze the spatiotemporal patterns of HANPP from 1979 to 2018 in the Qinghai grasslands. The Biome-BGCMuSo model is an upgrade of the Biome-BGC model that can obtain a more accurate simulation of vegetation productivity in terrestrial ecosystems, especially under energy and water stress [39]. In this study, the NPP_{pot}, NPP_{act}, and harvest were estimated using the same Biome-BGCMuSo method when estimating HANPP, which is also a functionally holistic approach. Our study contributes to a deep understanding of grassland HANPP and provides more reliable and detailed data to support the scientific management of local grassland resources.

5. Conclusions

In the present study, we quantitatively assessed the spatial and temporal distribution of HANPP in the Qinghai grasslands from 1979 to 2018 using the spatially explicit Biome-BGCMuSo model. HANPP and HANPP%NPP_{pot} showed fluctuating upward trends, and the difference between the NPP_{pot} and NPP_{act} (NPP_{pot} minus NPP_{act}) slightly increased in the Qinghai grasslands from 1979 to 2018, indicating an increase in grazing pressure on this grassland ecosystem. From 2001 to 2018, the NPP_{pot} and NPP_{act} both showed fluctuating upward trends, indicating that climate change has improved the ecological environment of the Qinghai grasslands in recent years. The HANPP efficiency showed a weak fluctuating downward trend from 1979 to 2018, indicating that irrational utilization of the Qinghai grasslands was increasing during this period. There was a strong regional variation in HANPP, mainly caused by the difference in grazing intensity. High HANPP mainly occurred in eastern Qinghai, with high grazing intensity, whereas low HANPP mainly occurred in central and western Qinghai, with low grazing intensity. The average harvest contributed 85.38% to HANPP in the Qinghai grasslands. The HANPP efficiency values in most grids were between 80% and 100%, being relatively low in southern and eastern Qinghai with relatively high plant productivity and density of residents, indicating that grazing was relatively irrational in this region. In rare cases, the HANPP efficiency was greater than 1, indicating that moderate grazing promoted plant growth in this region. This study furthers our knowledge of HANPP in grasslands and indicates that local management of grassland resources should be optimized to ensure sustainable ecological resource use in the future.

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