How much aboveground net primary production can be used for human activities in the alpine grasslands in the Three Rivers Source Region (TRSR), China?

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Abstract

Sustainable management of grasslands has always been an urgent issue for policy-makers. The three rivers source region (TRSR) contains widely distributed natural grasslands and is sensitive to climate warming. To enable the sustainable development of the human-nature system in the TRSR, we propose a novel indicator based on the allocation of aboveground net primary production (ANPP). The indicator we proposed is the ANPP that can be used for human activities (UANPP). In the study, we simulated the spatial and temporal patterns of the UANPP in the alpine grasslands in the TRSR during 1979–2016 and explored the main driving factors of the UANPP. The results revealed that (a) the annual total UANPP in the TRSR was 13.22 TgC, approximately accounting for 47% of total ANPP. (b) The areas with negative UANPP values accounted for 16% of the entire TRSR, and they were primarily located within the Nature Reserve of the Yangtze and Yellow river source regions, while three-quarters of the area exhibited improvement trends. (c) The regional mean UANPP significantly increased during 1979–2016, at a rate of 0.28 gC m⁻² yr⁻¹ (p < 0.01). In the entire TRSR, 87% of the area exhibited increasing trends. (d) The UANPP in most areas of the TRSR was strongly correlated with precipitation, and the effect of human activities on the UANPP increased slightly during the 38 year study period. The UANPP represents the upper limit of human use of nature. These findings provide a reference for policy-makers to make decisions toward human-nature system sustainability while meeting human needs for grassland resources. ANPP allocation between nature and human system is a potentially important tool from the standpoint of sustainable development.

1. Introduction

Net primary production (NPP) is the amount of photosynthetically fixed carbon, and it determines energy flow and mediates biogeochemical cycles in ecosystems (Cramer et al 2001, Nemani et al 2003). It forms the basis of ecosystem functions and the supply of ecosystem services (Zhang et al 2021). It is also a key indicator of the health and balance of an ecosystem (Zhao and Running 2010). Grassland ecosystems can provide multiple ecosystem services, including food production, water and soil conservation, windbreaks and sand fixation (Egoh et al 2011). However, the NPP of a natural ecosystem is limited. When humans try to harvest more NPP for development, some ecosystem services will be reduced, especially...
in ecologically vulnerable areas that are sensitive to climate change and human activities (Zhao and Wu 2014, Eigenbrod et al 2015). Therefore, to ensure sustainable management, it is necessary to quantify the part of the NPP that can be used for human activities while maintaining the ecological balance.

In an effort to achieve sustainable management of ecosystems, numerous studies have been conducted (Hou et al 2014, Liang et al 2019). For example, Chen et al (2014) analyzed the difference between the potential NPP and the actual NPP on the Qinghai-Tibet Plateau to determine the impact of anthropogenic activities on the ecosystem. Abdi et al (2014) assessed the socioecological vulnerability from the perspective of the balance between the supply and demand of the NPP. Moreover, the human appropriation of NPP was introduced as an integrated socioecological indicator to estimate the upper limits for the biosphere’s capacity to provide humanity with biomass (Haberl et al 2014, Zhang et al 2018). However, previous studies on sustainable development mostly focused on the ecosystem’s capacity of NPP supply and human consumption of NPP (Imhoff et al 2004) but did not pay enough attention to the impact of NPP harvesting on ecological functions and the diversity of ecosystem services. This may cause an overestimation of the ecological carrying capacity to a certain extent, but the effect of such an overestimation is not immediately apparent as unfavorable to the long-term development of a region. Therefore, a novel indicator of the NPP or aboveground NPP (ANPP) should be proposed.

The proposed indicator should emphasize the sustainable development of the human-natural system, imply the potential ecosystem service trade-offs, such as the trade-off between biomass production and climate regulation, and identify the upper limit of human use of nature, beyond which the regulating services will not be guaranteed and the ecosystem will be at risk of degradation.

The Three Rivers Source Region (TRSR) which contains wildly distributed natural grasslands, is located in the center of the Qinghai-Tibet Plateau and is the headwater of three of Asia’s largest rivers (Xu et al 2011). The ecosystem stability of the region is important to the security of itself and the surrounding regions. The alpine grasslands in the TRSR experienced severe degradation from the 1970s to the 1990s, which was followed by soil erosion (An et al 2017, Zhou et al 2017). One of the main reasons for this degradation was overgrazing (Zhou et al 2017, Yu et al 2020). Therefore, several ecological restoration projects have been implemented in this area to alleviate the stress of grazing, including the Grazing Withdrawal Program (which is aimed at conserving grassland through the banning of grazing, rotational grazing, or converting grazing land to cultivated pastures, Liu et al 2008). The implementation of these ecological projects contributed to vegetation restoration but did not fundamentally reverse the degradation of the grasslands (Chen et al 2020, Yu et al 2021a). The TRSR is still at risk of increased soil erosion (Teng et al 2018), so the reasonable intensity of human activities in the region needs to be carefully determined.

Therefore, we developed a novel indicator based on the ANPP allocation, that is, the ANPP that can be used for human activities (UANPP), to provide a scientific basis for ecological managers and policymakers. Moreover, the objectives of this study were: (a) to simulate the spatial and temporal patterns of the UANPP and analyze its proportion of total ANPP in the TRSR during 1979–2016 (38 years), and (b) to explore the main driving factors of the changes in the UANPP from the perspectives of both climatic and human factors. In this study, we hypothesized that the ANPP allocation is based on the natural ANPP in the study area and does not include anthropogenic recharge outside of the area to avoid the issue of forage transport causing fossil fuel CO2 emissions.

2. Materials and methods

2.1. Study area

As the source region of the Yangtze, Yellow, and Lancang rivers, the TRSR (73.45–104.70°E, 26.85–39.96°N) is located on the highest plateau in the world, i.e. the Qinghai-Tibet Plateau, with an area of approximately 3.51 × 105 km² and an average altitude of 4587 m (figure 1). To provide suggestions for managers, we set the administrative unit that overlaps the catchment of the Three Rivers as the study area rather than the real catchment area of the TRSR. The TRSR includes 16 counties. The western part is the source region of the Yangtze River (YSR), the eastern part is the source region of the Yellow River (YSR), and the southern part is the source region of the Lancang River (LSR), which is the upper reaches of the Mekong River. Due to the high altitude, the entire area has a cold and dry climate, which results in slow vegetation growth and a vulnerable ecosystem. Frozen ground occupies the entire area, and the permafrost regions account for 67% of the total area (Zou et al 2017). In this area, grassland is the most widely distributed type of vegetation, including alpine meadows and steppes, which account for 58% and 22% of the total area, respectively. Therefore, grazing has consistently been the most intense human activity in the TRSR for a long time. In 2014, approximately 16 million sheep units of herbivorous livestock were raised in the TRSR (Zhang et al 2014).

2.2. Methods

2.2.1. Framework for the estimation of the UANPP

The UANPP is defined as the remaining ANPP after deducting the ANPP required for wild herbivores (ANPPwild), the ANPP required for the natural generation of grassland (ANPPGR), and the ANPP...
required to support regulating services (ANPP_{RE}) from the total ANPP in an area (table 1). The estimation of the UANPP is the process of ANPP allocation (figure 2). In this study, the ANPP was divided into the UANPP, ANPP_{wild}, ANPP_{NR}, and ANPP_{RE} due to the landscape-scale trade-off between provisioning and regulating services and the fact that a greater diversity of ecosystem services was found to be positively correlated with the provisioning of regulating services. Among the regulating ecosystem services of the grasslands, the service of preventing soil loss is directly related to the survival of the vegetation. In brief, if the soil loss is severe, the vegetation will no longer flourish, and vice versa. Moreover, considering the fact that the grasslands can simultaneously support natural generation and regulating services, the equations for the ANPP allocation are as follows:

\[ \text{UANPP} = \text{ANPP} - \text{ANPP}_{\text{wild}} - \text{MAX}(\text{ANPP}_{\text{NR}}, \text{ANPP}_{\text{WAEP}}, \text{ANPP}_{\text{WIEP}}), \]

\[ \text{ANPP}_{\text{WAEP}} = f(\text{EVC}_{\text{water}}), \]

\[ \text{ANPP}_{\text{WIEP}} = f(\text{EVC}_{\text{wind}}), \]

where ANPP_{wild} was derived using the random forest model. EVC_{water} and EVC_{wind} were simulated using the models of EVC-RUSLE and EVC-RWEQ, which were deduced using the revised universal soil loss...
Flowchart of the estimation of the UANPP. The rounded rectangles denote the input data; the ellipses represent the output data; the rectangles represent the computational models; and the arrows represent the data flow.
2.3. Dataset and processing

2.3.1. In situ measured ANPP and regional simulated ANPP

The key to estimating the UANPP was identifying the relationship between normalized difference vegetation index (NDVI) and ANPP, so we established an empirical relationship between in situ measured ANPP and NDVI. ANPP measurements were conducted at 126 sites through field surveys (figure 3(a)). Among them, we harvested the peak above-ground biomass (AGB) in August in 2008, 2018, and 2019, at 41 sites; and the ANPP values of 85 sites were obtained from previous studies that harvested the peak AGB and below-ground biomass (BGB) during 2001–2004 (Yang et al. 2010b). During the field campaign, the AGB and BGB were collected in 3–6 independent $1 \times 1$ m$^2$ plots at each site. To acquire as much data as possible, we included data from areas of the Qinghai-Tibet plateau outside the TRSR, and in all of the cases, only the sites (64 sites) in the alpine grasslands with ANPP measurements for at least 3 years were used.

Therefore, a significant exponential relationship between ANPP and NDVI was established using the measured ANPP and the corresponding NDVI (figure 3(b)):

$$\text{ANPP} = 4.167e^{4.1584\text{NDVI}} \\
\times (R^2 = 0.1376, n = 126, P < 0.001).$$

For simulated ANPP, we selected the simulated NPP dataset derived from Lin et al. (2019a), including the ANPP, BNPP, and total NPP during 1979–2016. The NPP dataset was simulated using CLM4.5 and was verified to capture the long-term spatial variations using the measured data ($R^2 = 0.844, n = 79, p < 0.001$).

2.3.2. Climate data

The climate data for the EVC-RUSLE and EVC-RWEQ were obtained from the WorldClim database (www.worldclim.org), including Bio1–Bio19, with a spatial resolution of 2.5 min ($\sim 21$ km$^2$).

2.3.3. Soil data

The soil texture data for the EVC-RUSLE and EVC-RWEQ were obtained from the Harmonized World Soil Database v1.1 (HWSD), including the organic carbon, clay ($<0.002$ mm), silt ($0.002–0.05$ mm), and sand ($0.05–2.00$ mm) contents. The HWSD is a 30 arc-second raster database with over 16,000 different soil mapping units. It combines existing regional and national updates of soil information worldwide, and it was established by the Food and Agriculture Organization.

2.3.4. Remote sensing data

The NDVI, digital elevation model (DEM), and snow depth data were derived from remote sensing data. The peak monthly NDVI was based on surface reflectance data acquired by the Advanced Very High-Resolution Radiometer, with a high spatial resolution of $0.05^\circ$ latitude $\times 0.05^\circ$ longitude (Tucker et al. 2005, Pinzon and Tucker 2014).

Figure 3. (a) Spatial distribution of the sampling sites, and (b) regression function between the NDVI and measured ANPP.
The daily snow depth data for 1979–2016 were obtained from the long-term series of the daily snow depth dataset in China (1979–2019) provided by the National Tibetan Plateau Data Center (https://data.tpdcc.ac.cn), which has a resolution of 25 km (Che et al 2008, Dai et al 2012, 2017, Che 2015).

The DEM used to calculate the EVC was the Shuttle Radar Topography Mission DEM data for the Tibetan Plateau (2012), which were obtained from the National Tibetan Plateau Data Center (https://data.tpdcc.ac.cn), with a resolution of 90 m in the project coordinate system.

The data for the human foot was derived from a human footprint dataset for the Qinghai-Tibet Plateau during 1990–2017, which reflected the human activity intensity (Luo et al 2018, 2020, Duan and Luo 2021).

2.3.5. Species distribution coordinate data

The species distribution coordinate data were obtained using the sample line survey method, with a total of 5771 records. The wild herbivores in the surveys included Equus kiang, Procavia picticaudata, Pantholops hodgsonii, Pseudois nayaur, Bos mutus, Przewalskium albirostris, Cervus elaphus, Equus kiang, Procapra Picticaudata, and Moschus berezovskii, in which were identified at 512, 610, 16, 156, 19, 44, 16, and 3 points, respectively.

3. Results

3.1. Spatial pattern of UANPP

The variation in the spatial distribution of the UANPP was large over the entire TRSR (figure 4(a)). The areas with positive UANPP values accounted for 84% of the entire TRSR, and the areas with negative UANPP values were mainly located in the northwestern TRSR and the central area of the YSR and YESR. The mean UANPP in the TRSR from 1979 to 2016 was 45.03 gC m⁻² (only areas with UANPP values of greater than 0 gC m⁻² were counted), and the annual total UANPP was 13.22 TgC, accounting for 47% of the total ANPP (figure 5(a)). The UANPP decreased from southeast to northwest, which was consistent with the hydrothermal gradient in the TRSR. The UANPP was higher in Baima, Jigzhi, and Nangqeen counties, with regional average values of greater than 70 gC m⁻². The UANPP was lower in Golmud County and the western part of Zhidoi County (to the west of 95°E), with a value ranging from −52 to 40 gC m⁻².

The ANPP allocation for the different vegetation types was calculated (figures 4(c) and (d)). The UANPP of the meadows (25th to 75th percentile ranged from 25.88 to 65.33 gC m⁻²) was distinctly larger than that of the steppe (25th to 75th percentile ranged from −6.16 to 26.14 gC m⁻²). The ANPP_WIEP of the steppe was greater than that of the meadows, but the opposite was true for the ANPP_WAEIP. The ANPP allocation for the different frozen soil types was shown in figures 4(b) and (e).

The UANPP in the seasonally frozen ground areas was larger than that in the permafrost region, similar to the ANPP_NR. The ANPP_WAEIP of the seasonally frozen ground was larger than that of permafrost and the ANPP_WIEP of the seasonally frozen ground was similar to that of permafrost. Additionally, The ANPP_wild was low in the entire TRSR, with a maximum value of 8.36 gC m⁻².

The UANPP was higher in the LSR (25th to 75th percentile ranged from 62.71 to 81.77 gC m⁻², figure S1) than in the YESR (25th to 75th percentile ranged from 16.66 to 63.77 gC m⁻²) and the YSR (25th to 75th percentile ranged from 12.94 to 52.96 gC m⁻²). The ANPP_WAEIP and ANPP_WIEP exhibited different spatial patterns. The ANPP_WAEIP was higher in the LSR (25th to 75th percentile ranged from 5.76 to 14.23 gC m⁻²) and the YESR (25th to 75th percentile ranged from 3.37 to 12.16 gC m⁻²) than in the YSR (25th to 75th percentile ranged from 3.02 to 5.15 gC m⁻²); while the pattern of the ANPP_WIEP was YSR > YESR > LSR.

In terms of the proportion of UANPP to ANPP, the areas with UANPP proportions of greater than 40% accounted for 84% of the areas with positive UANPP values and were centered in the YSR and LSR (figure 5). In contrast, the UANPP proportion in the YSR ranged from 0.1% to 50%. The UANPP proportions in the areas with meadows and seasonally frozen ground were approximately 50%, with the 25th to 75th percentile range being 48% to 50% and 49% to 50%, respectively.

The proportion of the ANPP_WIEP in the steppes and permafrost regions was larger than that in the areas with meadows and seasonally frozen ground. The ANPP_wild exhibited a similar pattern. The proportion of ANPP_WIEP and ANPP_wild exhibited the pattern of LSR < YESR < YSR.

3.2. Changes in UANPP

For the UANPP during 1979–2016, most of the areas exhibited positive trends, accounting for 87% of the entire region, of which 68% passed the significance test (p < 0.05) (figure 6). The areas with increasing trends of greater than 1 gC m⁻² yr⁻¹ were distributed in the upstream regions of the YSR and YESR, and all of the areas passed the significance test (p < 0.05). The areas with trends between 0 gC m⁻² yr⁻¹ and 1 gC m⁻² yr⁻¹ were wildly distributed, accounting for 85% of the entire TRSR, of which 68% passed the significance test (p < 0.05). The areas with negative trends accounted for 13% of the total area and mainly occurred in Yushu and Maqeen counties, but approximately 77% failed to pass the significance test (p < 0.05).

The mean UANPP at the regional scale exhibited a significant increase with a rate of 0.281 gC m⁻² yr⁻¹.

The ANPP allocation for the different frozen soil types was shown in figures 4(b) and (e). The UANPP in the seasonally frozen ground areas was larger than that in the permafrost region, similar to the ANPP_NR. The ANPP_WAEIP of the seasonally frozen ground was larger than that of permafrost and the ANPP_WIEP of the seasonally frozen ground was similar to that of permafrost. Additionally, The ANPP_wild was low in the entire TRSR, with a maximum value of 8.36 gC m⁻².
Figure 4. (a) spatial pattern of the mean UANPP during 1979–2016 in the TRSR and the ANPP allocation in the (b) seasonally frozen ground, (c) meadows, (d) steppes, and (e) permafrost regions. The maximum whisker length is defined as 1.0 times the interquartile range. The data points beyond the whiskers are not displayed.

Figure 5. The mean proportion of the ANPP allocation from 1979–2016 in the (a) TRSR, (b) YSR, (c) YESR, (d) LSR, (e) meadow, (f) steppe, (g) permafrost, and (h) seasonally frozen ground regions. The maximum whisker length was defined as 1.5 times the interquartile range. The data points beyond the whiskers are not displayed. Only the areas with UANPP values of greater than 0 gC m\(^{-2}\) were counted.

\((p < 0.01)\) during 1979–2016, ranging from 28.23 gC m\(^{-2}\)–46.71 gC m\(^{-2}\) (figure 7). The regional mean UANPP during 1979–1996 decreased at a rate of \(-0.261 \text{ gC m}^{-2} \text{ yr}^{-1}\) (\(p < 0.05\)): while during 1997–2016, it significantly increased at a rate of 0.476 gC m\(^{-2}\) yr\(^{-1}\) (\(p < 0.05\)).

4. Discussion

4.1. Drivers of UANPP variations
Similar to the ANPP, the UANPP is driven by environmental management for sustainable development, it is more important to learn more about
the relationships between the climate factors and the UANPP than between the climate factors and the ANPP, as well as the role of humans in the UANPP over a long time period, especially the impacts of easy-to-measure climate factors such as temperature and precipitation. In most areas, both the MAT and MAP were positively correlated with the UANPP (figure 8), accounting for 64% of the whole region. The areas with a negative correlation between UANPP and MAT and a positive correlation between UANPP and MAP occurred in the northwest and the lower reaches of YSR. For the northwest of YSR, it may be because the increased temperature could increase the evapotranspiration and lead to a decrease in ANPP. For the lower reaches of YSR, the area was covered by seasonally frozen ground, where the increased temperature could promote the thawing of the active layer and further exacerbate soil erosion. The UANPP and precipitation were negatively correlated in most areas of the LSR and in the eastern part of the YESR, which is different from the relationship between the NPP and precipitation in arid and semi-arid regions (Zhang et al. 2016). This is probably because the ANPP$_{WAEP}$ was increased by the concentration of rainfall events. Nevertheless, in the entire TRSR, the UANPP increased with increasing temperature and precipitation (figure 9), which is consistent with the vegetation growth on the Qinghai-Tibet Plateau (Huang et al. 2016). The UANPP increasing rate has slowed down when MAT is greater than 0 $^\circ$C, which is possible because in arid and semi-arid regions, warming increases evaporation and further aggravates the water stress, as well as increases the population and distribution of pests and diseases, which puts forage production at risk (Piao et al. 2010).

In addition, RDA reflected the relationship between multiple environmental drivers and the ANPP components. The first two axes explained 77.22% and 10.77% of the variations in ANPP components, respectively (figure 10). Temperature, precipitation, topsoil clay fraction, topsoil organic carbon fraction, and aspect were impact factors of UANPP and ANPP$_{NR}$, among which temperature and precipitation were the most important impact factors affecting the variations in UANPP and ANPP$_{NR}$, respectively. Slope and precipitation were the main impact factors of ANPP$_{WAEP}$; elevation, slope, and wind speed were the main impact factors of ANPP$_{wild}$; and wind speed, elevation, and solar radiation were the main impact factors of ANPP$_{WIEP}$. ANPP$_{wild}$ was mainly affected by terrain factors, which may be due to the forage and habitat competition between domestic livestock and wild herbivores. The livestock...
Figure 8. Spatial patterns of the correlation between the UANPP and mean annual temperature (MAT) and the correlation between the UANPP and mean annual precipitation (MAP). E.g. the 'positive & negative' refers to the correlation between the UANPP and MAT is positive and the correlation between the UANPP and MAP is negative. The slash indicates that both the correlation between UANPP and MAT and the correlation between UANPP and MAP have passed the significant test ($p < 0.05$).

Figure 9. Variations in the UANPP along (a) the mean annual temperature and (b) mean annual precipitation in the TRSR. The color of the hexagonal dot represents the amount of data that is packed into the hexagon.

tends to occupy flatter or lower elevation spaces (Xu et al 2020). The total interpretation rate of environmental factors was 51.6% (table 2). The interpretation rates of climate factors were relatively high, a total of 40.93%, while the terrain factors had low interpretation rates of 8.73%.

4.2. Comparisons and implications

The UANPP in the TRSR exhibited an upward trend during the 38 year study period, which is consistent with the results of most previous studies on the NPP (Shao et al 2016, Zhang et al 2016, Yu et al 2021b).

In addition, numerous studies have also shown that in the TRSR, the NPP decreased before the 21st century and increased after about 2004, which is similar to our results for the UANPP (An et al 2017). The proportion of the regional mean UANPP ranged from 45% to 48% (figure S2), and its fluctuations suggested that the increases and decreases in the UANPP and ANPP were inconsistent in time. The higher proportion of the UANPP represents improved environmental conditions and provisioning ability. For example, years with a higher NPP (i.e. 1986, 2000, and 2012) had lower wind erosion modulus values...
Redundancy analysis of the ANPP components (red) and environmental drivers (blue) in the TRSR. The angles between arrows represent the strengths of the correlations between the ANPP components and environmental drivers. The angle between the variables less than 90° means that they are positively correlation, and more than 90° means that they are negatively correlation. RDA: redundancy analysis; U: UANPP; NR: ANPPNR; WA: ANPPWAEP; WI: ANPPWIEP; WH: ANPPwild; T: temperature; P: precipitation; W: wind speed; SR: solar radiation; D: elevation; SL: slop; AS: aspect; CL: topsoil clay fraction; C: topsoil organic carbon fraction.

Table 2. Environmental factors and their interpretation rates to the variations in the ANPP components.

| Environmental factors                  | Percentage of variance explained | F-value   | P-value |
|----------------------------------------|----------------------------------|-----------|---------|
| Wind                                   | 14.26                            | 5413.37   | <0.001  |
| Precipitation                          | 10.43                            | 18834.31  | <0.001  |
| Temperature                            | 8.15                             | 3127.77   | <0.001  |
| Solar radiation                        | 8.09                             | 3629.89   | <0.001  |
| Slope                                  | 5.13                             | 2128.88   | <0.001  |
| Elevation                              | 3.58                             | 10434.61  | <0.001  |
| Topsoil clay fraction                  | 1.83                             | 1083.21   | <0.001  |
| Topsoil organic carbon fraction        | 0.13                             | 275.19    | <0.001  |
| Aspect                                 | 0.02                             | 13.24     | <0.001  |

(Teng et al 2021). In the entire TRSR, 16% of the areas had negative UANPP values, indicating that the natural ecosystem in these areas suffered degradation and was unable to support human production activities. Fortunately, most of the areas (75%) with negative UANPP values exhibited increasing trends, demonstrating that the degradation in these areas was recovering. A large area of the TRSR is covered by frozen soil. The freeze-thaw cycle will aggravate soil wind erosion and soil water erosion (Ferrick and Gatto 2005, Sun et al 2021). A reason why ANPPWAEP was higher in the seasonally frozen soil region than in the permafrost region was that soil water erosion occurs intensively in summer (He et al 2020). The thawing of the active layer in seasonally frozen ground provides a material source for soil erosion (Gao et al 2021), whereas permafrost is rarely thawed. The ANPPWIEP of the seasonally frozen ground is similar to that of permafrost, possibly because the TRSR is dry, cold, and windy in winter, and wind erosion mainly occurs from December to April (Gong 2014), when both seasonally frozen ground and permafrost regions are in the freezing period (Zhao et al 2021) and covered by snows (Che et al 2008).

The UANPP in Maqeen, which supports the majority of the plateau’s population, was negative and exhibited a downward trend, which is an early warning for policy-makers. Decision-makers should develop grassland restoration policies while considering the livelihood of the indigenous people in Maqeen. Similar to Maqueen, the UANPP decreased in Yushu, but the mean value was more than 0 gC m⁻², so the policies for grazing management in Yushu should be more tolerant than those for Maqeen, but the changes in the UANPP should be considered. In addition, the decreasing trends of the UANPP were spatially consistent with the negative correlation between the UANPP and temperature, indicating that the soil desiccation caused by climate warming cannot be ignored. Therefore,
different regions should formulate targeted policies according to the UANPP. For the areas with negative UANPP values, grazing and other human activities should be limited as much as possible. For the areas with positive UANPP values but decreasing trends, light and seasonal rotational grazing is recommended. Additionally, the areas with negative UANPP values were primarily located within the Nature Reserve of the Yangtze and Yellow river source regions, which was probably because the unfavorable environment (low temperatures, less precipitation, and poor soil) led to slow vegetation growth and weak resilience in these areas (Zhang et al. 2016). Strong wind erosion in the Yangtze River Source Nature Reserve (Gong et al. 2014) exacerbated grassland degradation and the difficulty of restoration so that more ANPP\textsubscript{WIEP} was needed in the area to maintain environmental stability. Compared with other areas in the TRSR, lower ANPP in the nature reserve was not enough to support the ANPP\textsubscript{WIEP} and the ANPP\textsubscript{WAEP} so the UANPP was less than 0, which also confirmed the necessity and scientificity of the national nature reserve division.

In the study, UANPP was examined and discussed in various vegetation types and frozen soil classifications. The estimated framework of UANPP considered wildlife grazing, soil wind erosion, soil water erosion, and the natural regeneration of grasslands, which are common to grassland ecosystems. Therefore, UANPP is applicable to any grassland ecosystem.

5. Conclusions

In the study, we developed a novel indicator based on the ANPP allocation, UANPP. The annual total UANPP in the TRSR during 1979–2016 was found to be 13.22 TgC, accounting for 47% of the total ANPP. The areas with positive UANPP values accounted for 84% of the entire TRSR, and the UANPP negative values primarily occurred within the Nature Reserve of the Yangtze and Yellow river source regions. The regional mean UANPP significantly increased during 1979–2016, with a rate of 0.28 gC m\(^{-2}\) yr\(^{-1}\) (p < 0.01). In the entire TRSR, 87% of the area exhibited increasing trends; and especially in the areas with negative UANPP values, 75% of the area exhibited increasing trends. In most areas of the TRSR, the UANPP was strongly correlated with precipitation, and the effects of human activities on the UANPP increased slightly during the 38 year study period. UANPP determines an upper limit for the human use of nature, which is applicable to any grassland ecosystem.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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