Agricultural and Forest Meteorology 189–190 (2014) 11–18

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau

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ARTICLE INFO

Article history:
Received 28 August 2013
Received in revised form
28 December 2013
Accepted 3 January 2014

Keywords:
The Qinghai–Tibet plateau
Alpine grassland ecosystem
Net primary production
Climate change
Anthropogenic activities

ABSTRACT

Climate change and anthropogenic activities are two factors that have important effects on the carbon cycle of terrestrial ecosystems, but it is almost impossible to fully separate them at present. This study used process-based terrestrial ecosystem model to stimulate the potential climate-driven alpine grassland net primary production (NPP), and Carnegie–Ames–Stanford Approach based on remote sensing to stimulate actual alpine grassland NPP influenced by both of climate change and anthropogenic activities over the Qinghai–Tibet plateau (QTP) from 1982 to 2011. After the models were systematically calibrated, the simulations were validated with continuous 3-year paired field sample data, which were separately collected in fenced and open grasslands. We then simulated the human-induced NPP, calculated as the difference between potential and actual NPP, to determine the effect of anthropogenic activities on the alpine grassland ecosystem. The simulation results showed that the climate change and anthropogenic activities mainly drove the actual grassland NPP increasing in the first 20-year and the last 10-year respectively, the area percentage of actual grassland NPP change caused by climate change declined from 79.62% in the period of 1982–2001 to 56.59% over the last 10 years; but the percentage change resulting from human activities doubled from 20.16% to 42.98% in the same periods over the QTP. The effect of human activities on the alpine grassland ecosystem obviously intensified in the latter period compared with the former 20 years, so the negative effect caused by climate change to ecosystem could have been relatively mitigated or offset over the QTP in the last ten years.

1. Introduction

Both global climate change and anthropogenic activities are the main driving forces of terrestrial ecosystems (Esser, 1987; Field, 2001; Haberl, 1997). Commonly, regional ecosystem changes are the consequence of both climate change and local anthropogenic activities, but it is almost impossible to directly differentiate between these two factors (Wessels et al., 2007). Especially in arid and semi-arid areas, heightened anthropogenic activities can easily lead to the degradation of certain ecosystems, even causing serious ecological and economical losses (Harris, 2010; Wessels et al., 2004). With the increase in climate warming and intensified anthropogenic activities over the last century (Consortium, 2013; Raupach et al., 2013), socioeconomic drivers are beginning to overwhelm the great forces of nature for some selected processes regionally or even on the global scale (Erb et al., 2009; Luck, 2007; Rojstaczer et al., 2001). As a result, separating and quantifying the influence of climate change and human activities on ecosystems has great significance to ecosystem management and adaptation; Thus, mankind can choose different adaptive management strategies to adapt to climate change or to counteract the negative effect of anthropogenic activities on ecosystems (Aldous et al., 2011; Lawler, 2009; Vignola et al., 2009). Therefore, it is imperative to use an objective and reproducible method to discriminate between the effects of climate change and anthropogenic activities on ecosystems (Wessels et al., 2008).

At present, the ways for indirectly evaluating the regional influence of anthropogenic activities on ecosystems include the Normalized Difference Vegetation Index (NDVI) residual trend method (Bai et al., 2008; Li et al., 2012; Wessels et al., 2004), and human appropriation of net primary productivity (HANPP) method based on models (DeFries, 2002; Haberl et al., 2007; Rojstaczer et al., 2001; Xu et al., 2009). Some studies reported that the NDVI significantly correlated with rainfall in arid and semi-arid areas, so the deviation between the actual and simulated NDVI can be regarded as the human activities effect on the ecosystem (Prince et al., 2007;

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http://dx.doi.org/10.1016/j.agrformet.2014.01.002

Wessels et al., 2004, 2007, 2008). Study on the temperate grassland in Inner Mongolia in China showed that the governmental ecological protection strategy applied after 2000 in this area significantly resulted in large-scale vegetation improvements (Li et al., 2012), but there are existing uncertainties about the rain–production relationship, and the climatic and anthropogenic influences on the ecosystem still cannot be fully differentiated. Otherwise, the alternative methods for simulating HANPP applied social statistical models (Krausmann et al., 2013; Rojstaczer et al., 2001; Vitousek et al., 1986) or required much social statistical data to simulate the human and actual productivity, which can easily lead to results uncertainties (DeFries, 2002; DeFries et al., 1999; Haberl et al., 2007; Xu et al., 2009). Another possible method is that comparing the process-based and remote-sensing ecosystem productivity models to simulate the human-induced production, which can be then used for trend analysis and avoiding uncertainties in some extent.

As the sole and largest geographical unit with the highest elevation on earth, the Qinghai–Tibet plateau (QTP) is called the "Third Pole" and acts as an important reservoir for water, regulating climate change and water resources in east Asia and even for the whole world (Qiu, 2008; Yang et al., 2011; Yao et al., 2012). The QTP also has a large variety of ecosystem types, from subtropical rain forest in southeast to alpine desert in the northwest. Among all types of land cover vegetation, alpine grassland is the dominant ecosystem over the QTP, covering more than 50% of the whole plateau area (Bartholomé and Belward, 2005; Gao et al., 2012). With both global climate warming and increasing anthropogenic activities, the QTP has experienced approximately a three times increase of the global warming rate over the last 50 years (Piao et al., 2011; Qiu, 2008). Meanwhile, natural grassland has been regionally degrading since the 1980s, which may be due to a combination of climate warming, increasing population, fast-growing grazing pressure and rodent damage (Harris, 2010; Liu et al., 2012; Wang et al., 2013; Yu et al., 2012). Regardless of the exact reason of ecosystem degrading, the local government is facing a serious issue in managing the vast grasslands in view of such complicated environmental problems (Du et al., 2004; Qiu, 2007; Yu et al., 2012). Although, recent studies have shown that the QTP has changed from a small or neutral carbon source to a carbon sink during the 20th century, and net primary production (NPP) simulation has been persistently enhanced over the last 50 years (Piao et al., 2012; Zhuang et al., 2010), but it is still hard to determine where and how serious anthropogenic activities influences grassland NPP in such a large scale. Nonetheless, alpine grassland is sensitive to climate warming and anthropogenic activities, so the QTP is the ideal place for studying the relationship between climate warming and the anthropogenic activities effects on alpine grassland.

In this study, our objective was to distinguish between the effects of climate change and anthropogenic activities on alpine grassland over the QTP, and trying to determine which is the main driving force for grassland ecosystem change over different time periods. We used grassland NPP as the index for measuring the degree of climate change and anthropogenic activities effects on the alpine grassland ecosystem, with a climate factor-driven model to simulate grassland potential NPP and a remote sensing model to simulate the actual NPP, which is affected by both of climate change and human activities, so the human-induced NPP is modelled as the difference of potential and actual NPP. For comparing the trend of the potential and human-induced NPP over periods, the main driving force to ecosystem change can be determined. This study could be used as a reproducible method for quantifying the impact of climate change and anthropogenic activities on terrestrial ecosystem NPP change and provide a theoretical basis for optimizing ecosystem management over rangelands.

2. Methods and data

2.1. Methods

The Terrestrial Ecosystem Model (TEM) was used to simulate the climatic potential NPP (NPP_P), which is the maximum grassland NPP and only driven by climatic factors and unaffected by human activities. The Carnegie–Ames–Stanford Approach (CASA) model was used to simulate actual NPP (NPP_A), which is the actual existing NPP that was influenced by both climate change and human activities, for the remote-sensing NDVI data represent the actual vegetation greenness. So, the human-induced NPP (NPP_H) only affected by human activities can be simulated in corresponding to timescales as follows:

$$NPP_H = NPP_P - NPP_A \quad (1)$$

The TEM is a widely used process-based ecosystem model that simulates the carbon and nitrogen dynamics of plants and soils within terrestrial ecosystems (Melillo et al., 1993; Raich et al., 1991; Tian et al., 1998; Zhuang et al., 2010). It is driven by spatially referenced information on vegetation type, climate, elevation, soils, and water availability to calculate the monthly carbon and nitrogen fluxes and pool sizes of terrestrial ecosystems. The formula for calculating monthly NPP is as follows:

$$GPP = (C_{max})\frac{PAR}{PAR + k_i}\frac{C_i}{k_c + C_i}(TEMP)(KLEAF) \quad (2)$$

$$NPP_P = GPP - R_a = GPP - (R_m + R_g) \quad (3)$$

where C_{max} is the maximum rate of carbon assimilation under optimal environmental conditions, which is determined according to vegetation types; PAR is the photosynthetically active radiation at canopy level; k_i is the irradiance at which carbon assimilation proceeds at one-half its maximum rate; C_i is the concentration of CO_2 inside leaves; k_c is the internal CO_2 concentration at which assimilation proceeds at one-half its maximum rate; TEMP and KLEAF are unitless multipliers expressing the influences of air temperature and plant phenology. The GPP is the ecosystem gross primary production, assuming that the conversion efficiency of photosynthate to biomass is 100%, and the NPP_P is estimated as the GPP minus the R_a (autotrophic respiration), which includes R_m (maintenance respiration) and R_g (growth respiration) (Raich et al., 1991). In this study, we mainly calibrated TEM parameters of C_{max} as 949.6 g C m^{-2} $month^{-1}$ for alpine meadow, 617.9 g C m^{-2} $month^{-1}$ for alpine steppe and 251.2 g C m^{-2} $month^{-1}$ for alpine desert steppe, and the ratio of photosynthetically active radiation (PAR) to solar global radiation as 0.44(Raich et al., 1991; Zhang et al., 2000; Zhou et al., 2004).

The CASA model was developed to estimate NPP on a large geographical scale, based on remote sensing and climatic data (Field et al., 1995; Gao et al., 2013; Potter, 1999, 2004; Potter et al., 1993, 1999, 2011). In the model, the simulation was determined by two variables: absorbed photosynthetically active radiation (APAR) and light energy conversion (ε), as follows:

$$NPP_A = APAR \times \varepsilon = fPAR \times PAR \times \varepsilon^* \times T_\varepsilon \times W_\varepsilon \quad (4)$$

where fPAR is the fraction of the incoming PAR intercepted by green vegetation, which is calculated from the NDVI image dataset; ε^* is the maximum possible light energy conversion efficiency, this term was set uniformly at 0.55 g C MJ^{-1} PAR (Potter et al., 2011); and T_ε and W_ε are unitless varying scalar terms for temperature (T) and water (W).

Formula (5) was used to calculate the long-term grassland NPP changing trend; n represents the sequential years and the NPP_i is the NPP in the year i. A positive slope value suggests that the NPP is in an increasing trend while a negative one indicates that the

Table 1
The causes of actual NPP_A change and its corresponding to mathematical methods. *Note*: the $sNPP_A$, $sNPP_P$ and $sNPP_H$ represent the absolute slope value for NPP_A, NPP_P and NPP_H change trend in every pixel.

Method (comparing slope)	Cause of NPP change
$sNPP_A = 0$	NPP_A has no change (NC)
$sNPP_A > 0$ and $sNPP_P > sNPP_H$	NPP_A increase due to climate change (ICC)
$sNPP_A > 0$ and $sNPP_P < sNPP_H$	NPP_A increase due to human activities (IHA)
$sNPP_A < 0$ and $sNPP_P > sNPP_H$	NPP_A decrease due to climate change (DCC)
$sNPP_A < 0$ and $sNPP_P < sNPP_H$	NPP_A decrease due to human activities (DHA)

NPP is decreasing; then a slope of zero means that the NPP shows no change trend and remains steady (Ma et al., 2006; Stow et al., 2003). In this study, the relative slope ($\bar{s}_i$) in Formula (6) was used to indicate the relative NPP change in every pixel point.

$$\text{Slope} = \frac{n \times \sum_{i=1}^{n}(i \times \text{NPP}_i) - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} \text{NPP}_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \quad (5)$$

$$\bar{s}_i = \frac{slope_i}{(1/n) \times \sum_{i=1}^{n} NPP_i} \quad (6)$$

In order to determine the reasons of NPP_A change in every pixel, the absolute slope values of the NPP_P and NPP_H in the same period were compared for defining the causes of NPP_A change. Table 1 shows the five types of different conditions that leading to NPP_A change.

2.2. Data

In this study, an advanced very high resolution radiometer (AVHRR) NDVI dataset developed by the Global Inventory Modeling and Mapping Studies (GIMMS) group (http://glcf.umd.edu/data/gimms/) was processed for simulating the NPP_A. This dataset has a spatial resolution of 8 km and a temporal resolution of 15 days intervals, available online from 1982 to 2006. Also, the moderate-resolution imaging spectroradiometer (MODIS) NDVI product (MYD13A2.5) with a spatial resolution of 1 km and a temporal scale of 16 days can be obtained from the website https://lpdaac.usgs.gov/get_data/data_pool, which covers images from 2001 to 2011. All the remote-sensing data for the QTP were downloaded and composited as a monthly data set using the maximum value composite (MVC) method. For reducing the residual noise caused by haze and clouds, the 432 composited NDVI images were cleaned by employing an adaptive Savitzky–Golay smoothing filter, using the TIMESAT package (Jiang et al., 2012; Jönsson and Eklundh, 2004).

The meteorological data were collected from the China Meteorological Administration (http://www.cma.gov.cn/) via permanent meteorological stations across China. 200 long-term observing stations with complete monthly meteorological records from 1982 to 2011 for the QTP and its around were selected, and interpolated the meteorological data by using ANUSPLIN version 4.2 software to form monthly raster data layers with spatial resolutions of 1 km and 8 km.

During the course of the investigation in the north of the QTP, we sampled both fenced and open alpine grassland paired in different places with various grassland types–in the summer from 2009 to 2011 continuously. The collected dataset included 108 sites (5 plots per site) of alpine grassland above- and below-ground biomass; further details of the sampling methods can be found in other publications (Li et al., 2011; Wu et al., 2013). Then we calculated the NPP from the collected grass biomass data, assuming that the above-ground biomass as the accumulated above- ground NPP, which is about equal to the below- ground NPP and about half of the total NPP (Wu et al., 2009).

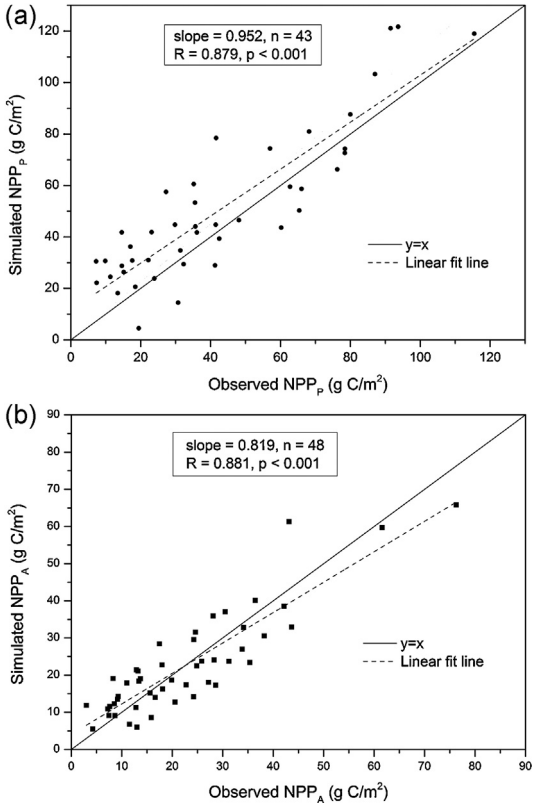

Fig. 1. Comparisons of TEM-simulated NPP_P and CASA-simulated NPP_A with the observed NPP data in the year of 2009, 2010, and 2011; (a) NPP_P and observed fenced grassland data and (b) NPP_A and observed open grassland data.

3. Results

3.1. Validation of NPP

We used the fenced grassland sample NPP data to calibrate the parameters of the TEM and validate the simulations, meanwhile the open grassland sample data was used to validate the CASA simulation. Comparisons of the results showed that the simulated NPP data matched well with the observed data from 2009 to 2011 ($P < 0.001$) and can be used in the following analysis. Fig. 1 a showed that the regression linear slope of the NPP_P against sampled fenced

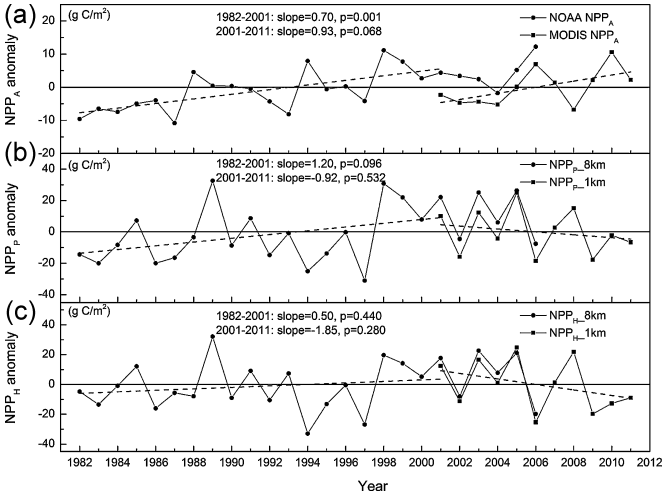

Fig. 2. Inter-annual variation in anomalies of: (a) CASA-modeled NPP_A, (b) TEM-modeled NPP_P, and (c) NPP_H over the QTP alpine grasslands from 1982 to 2011.

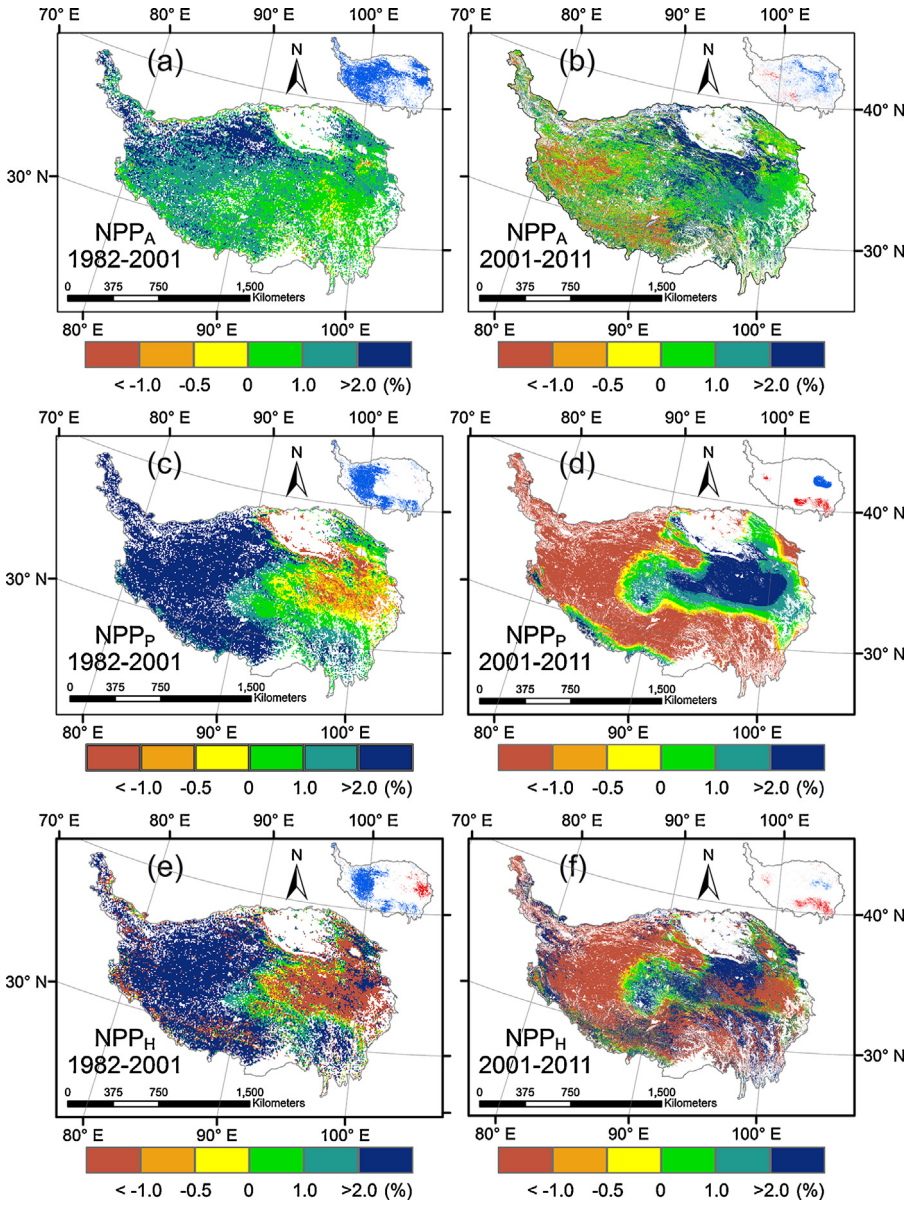

Fig. 3. Spatial distributions of (a–f) trends in annual NPP over the QTP grasslands in the periods 1982–2001 and 2001–2011. (a) NPP_A simulation from 1982 to 2001, (b) NPP_A simulation from 2001 to 2011, (c) NPP_P simulation from 1982 to 2001, (d) NPP_P simulation from 2001 to 2011, (e) NPP_H simulation from 1982 to 2001, (f) NPP_H simulation from 2001 to 2011. The inset maps show significant ($P<0.05$) NPP increase (blue), and significant ($P<0.05$) NPP decrease (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

grassland NPP is 0.952, with 43 points, and the coefficient reaches 0.879 (Fig. 1a); Fig. 1b showed that the regression slope of the NPP_A against observed open grassland NPP is 0.819, with 48 sample points, and the coefficient is 0.881 (Fig. 1b).

3.2. NPP_A change over the QTP

The simulated results showed that the alpine grassland NPP_A over the QTP increased in the past thirty years, but shared different increasing rate in the two periods of 1982–2001 and 2001–2011 (Fig. 2 a). From 1982 to 2001, the simulated NPP_A increased with a rate of about 0.70 g C m^{-2} yr^{-1} (Fig. 2a), with a significantly total increase of 16.83% ($P<0.01$). The NPP_A increment mainly occurred in the north and west of the QTP, as well as a small area in the middle-east, but the north margin appeared to be following a decreasing trend (Fig. 3 a). In the period 2001–2011, the NPP_A increased with a rate of 0.93 g C m^{-2} yr^{-1} (Fig. 2a), with a NPP_A increase of 8.05%. In this period, the NPP_A decrement mostly occurred in the west and southwest of the QTP, while the increment occurred in the east (Fig. 3b).

Because of that the NPP_A in the two periods were simulated using different remote-sensing NDVI data sources with varied spatial resolutions, so there existed a systematic difference between the two periodic simulations. In the overlapped time from 2001 to 2006, the simulation results showed a disproportionate deviation between the two remote sensing data driven NPP_A (Fig. 2a), which is possibly caused by the 2001–2006 GIMMS NDVI datasets quality over western QTP (Zhang et al., 2013a). So, the overlapped time simulations for NPP_A based on GIMMS NDVI dataset and its corresponding NPP_P and NPP_H simulations from 2001 to 2006 are not analyzed in this study for avoiding the uncertainties.

3.3. NPP_P and NPP_H change over the QTP

The NPP_A change relates to the NPP_P and NPP_H, and its change trend is determined by the change trend of NPP_P and NPP_H according to the formula 1. For the alpine grassland over the QTP, both of the NPP_P and NPP_H showed increasing trends in 1982–2001 as the model simulations, but with decreasing trends in 2001–2011 with different slopes (Fig. 2). Fig. 2b and c illustrated the annual variation in anomalies of NPP_P and NPP_H from 1982 to 2001, when the NPP_P increased by 1.20 g C m^{-2} yr^{-1} (Fig. 2b) and mainly occurred in the south and west of the QTP, but it showed a declined trend in the middle and eastern areas (Fig. 3c). The NPP_H was also enhanced at a rate of 0.50 g C m^{-2} yr^{-1} in this period (Fig. 2c), and most of the increments occurred in the middle west and north of the QTP, with decreasing in the south and middle east (Fig. 3e). In this twenty years period, the increasing rate of NPP_P change is greater than that of NPP_H variation, which suggested that effect of climate change on alpine grassland ecosystem over the QTP is larger than that of human activities, and the increased NPP_H cannot offset the enhanced climate change influence, so NPP_A increased from 1982 to 2001.

However, the mechanism has changed in the latter period from 2001 to 2011. On account of the continuous drought caused by climate warming over the QTP, NPP_P was in a decreasing trend with the rate of −0.92 g C m^{-2} yr^{-1} (Fig. 2b); and the NPP_P was in a declining trend in most of the QTP except for the middle or the southern margin (Fig. 3d). Furthermore, NPP_H also decreased at a rate of −1.85 g C m^{-2} yr^{-1} (Fig. 2c), and the decreasing NPP area distributed in the middle west and north of the QTP, but the east and west margins exhibited an increasing trend (Fig. 3f). Overall, the decreasing rate of NPP_H change was greater than that of NPP_P change, this led to an increasing in NPP_A change trend in the latter ten years. In this period of 2001 to 2011, the Chinese government has enforced a national conservation policy on payment for supporting the ecological project Grazing Withdrawal Program (GWP) over the north China grassland around 2003, which brought about the evidently declining the number of livestock and implementation of many large scale ecological projects, such as fencing degrading grassland, ecological compensation and restoring the land cover vegetation (Feng et al., 2013; Mu et al., 2013). All the policies and projects enforcements help reducing the grazing pressure over the QTP, leading to the NPP_A increasing under the circumstances of both the NPP_P and NPP_H decreasing caused by climate warm-dry and human activities disturbances respectively.

3.4. The causes of NPP_A change in two periods

As the annual NPP_A has been driven by two different drivers in 1981–2001 and 2001–2011 separately, the area percentage of NPP_A change caused by different reasons would also has been changed in the two periods. Comparing the absolute value of the slopes of NPP_P and NPP_H in every pixel by using the mathematical regulation in the table over the QTP in the last thirty years (Table 1), we can find where and how large of the determinants for NPP_A change in the past. From 1982 to 2001, most of the alpine grassland NPP_A increment area was caused by climate change; only a small area was in a decreasing trend or remaining unchanged in the middle-east and north margin of the QTP (Fig. 4 a). Meanwhile, in the southeast and north margin of the QTP, human activities caused regional NPP_A to decline, but it led to a regional NPP_A increase in the middle-east (Fig. 4a). From 2001 to 2011, most of the grassland NPP_A in the QTP was increasing, which mostly occurred to the east of the QTP. In the middle of the eastern QTP, the grassland NPP_A increased because of climate change, but the NPP_A increased as a result of a NPP_H decrease in the south and north-east. However, the grassland NPP mostly decreased in the west of the QTP, much of which was caused by climate change and some of which was caused by human activities, which occurred in the south, middle and north-east of the QTP and fitted with the population distribution (Fig. 4b). The NPP_H has increased more in the last ten years than in the previous twenty years, and increases more from east to west.

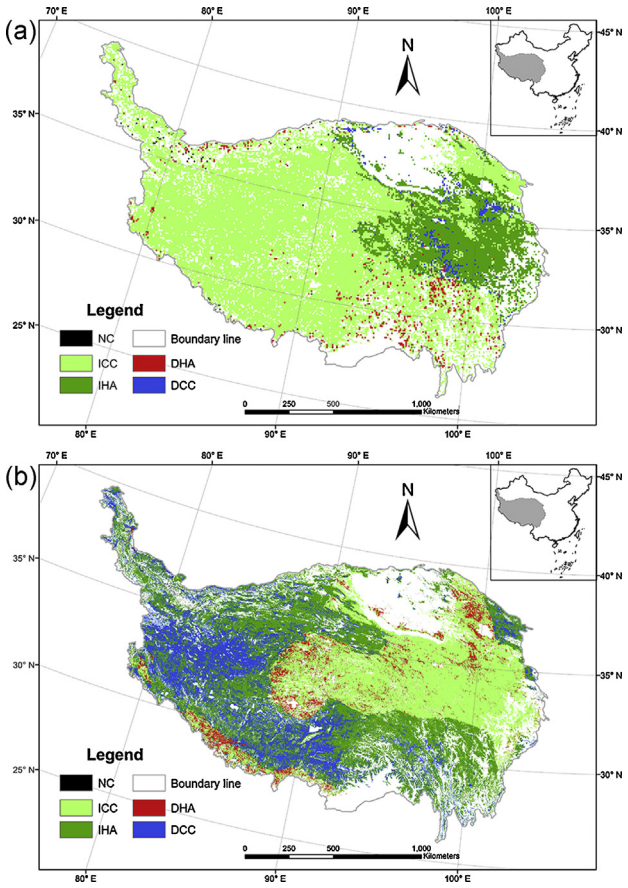

Fig. 4. Spatial distribution of different causes for alpine grassland NPP change in the periods 1982–2001 (a) and 2001–2011 (b). *Note*: NC is NPP_A had no change; ICC is NPP_A increased due to climate change; IHA is NPP_A increased due to human activities; DCC is NPP_A decreased due to climate change and DHA is NPP_A decreased due to human activities.

Calculating the area percentages of the factors that led to the alpine grassland NPP_A change in the two periods, we can compare and analyze the area percentages for climate change and human activities and summarize the developing tendency pattern of the two determinants of alpine grassland NPP_A, then providing a scientific basis for regional alpine grassland ecosystem management over the QTP. The statistical data showed the following: there was little change in the NPP_A no-change area between the two periods 1982–2001 and 2001–2011, increasing from 0.22% to 0.33%; the NPP_A increase due to climate change (ICC) percentage largely decreased from 78.03% to 32.87%; the NPP_A increase due to human activities (IHA) increased from 17.67% to 37.90%; the NPP_A decrease due to climate change (DCC) increased from 1.59% to 23.82%; and the NPP_A decrease due to climate change (DHA) increased from 2.49% to 5.08% (Table 2). Overall, the total area percentage of NPP_A change caused by climate change, including ICC and DCC, declined from 79.62% to 56.59%, but that percentage resulting from human activities, including IHA and DHA, enhanced from 20.16% to 42.98% between the periods of 1982–2001 and 2001–2011. The effect of human activities on the alpine grassland ecosystem over the QTP significantly intensified in the latter period compared with the previous 20 years, and the climate change effect has been relatively mitigated or offset.

Table 2
The NPP_A change area percentage in the periods 1982–2001 and 2001–2011.

NPP_A change area	1982–2001 (%)	2001–2011 (%)
NC	0.22	0.33
ICC	78.03	32.87
IHA	17.67	37.90
DCC	1.59	23.82
DHA	2.49	5.08

4. Discussion

4.1. NPP_P and climate change over the QTP

Simulated TEM NPP_P prediction is only influenced by climatic factors and has been regarded as the maximum NPP of an ecosystem (Raich et al., 1991), which can be considered as the alpine grassland NPP_P that is not disturbed by animals or anthropogenic activities over the QTP. However, most of the alpine grassland is distributed in semi-dry and dry areas over the QTP, and these areas are sensitive to precipitation and vulnerable to climate warming (Qin et al., 2013). In this study, the main driving force of the alpine grassland NPP_P is annual precipitation, which is also the reason for NPP_P decline as the rainfall decrease since 2000 (Fig. 5 a). The NPP_P has a strong relationship with annual rainfall, but the rapidly increasing temperature exerts complicated effects on the NPP_P (Piao et al., 2012; Zhuang et al., 2010). In the latest 30 years, the interpolated meteorological dataset showed a more significant warming trend of about 0.06 °C per year ($P < 0.001$) (Zhang et al., 2013b), which is approximately double the warming rate in the last 50 years over the QTP. However, the rainfall increasing trend in the same period was just only about 0.14 mm per year, which is about one-sixth of the rainfall rate in the last 50 years (Piao et al., 2012). Both the increasing warming trend and decreasing rainfall trend may suggest that the warming and drying phenomena over the QTP were more serious in the past 30 years than that of latest 50 years, which could make the alpine grassland ecosystem more vulnerable to climate warming and more sensitive to grassland degradation as a result of human activities.

4.2. Grazing pressure and climate change

The major anthropogenic activities over the QTP that can influence alpine grassland NPP are grazing and human-induced land cover change (Chen et al., 2013; Harris, 2010); the former is the dominant one and can lead to grassland degradation, even desertification in the plateau. However, it is not clear whether the number of livestock directly affects NPP_H or whether there are other influencing factors, so we recorded the number of total livestock over the

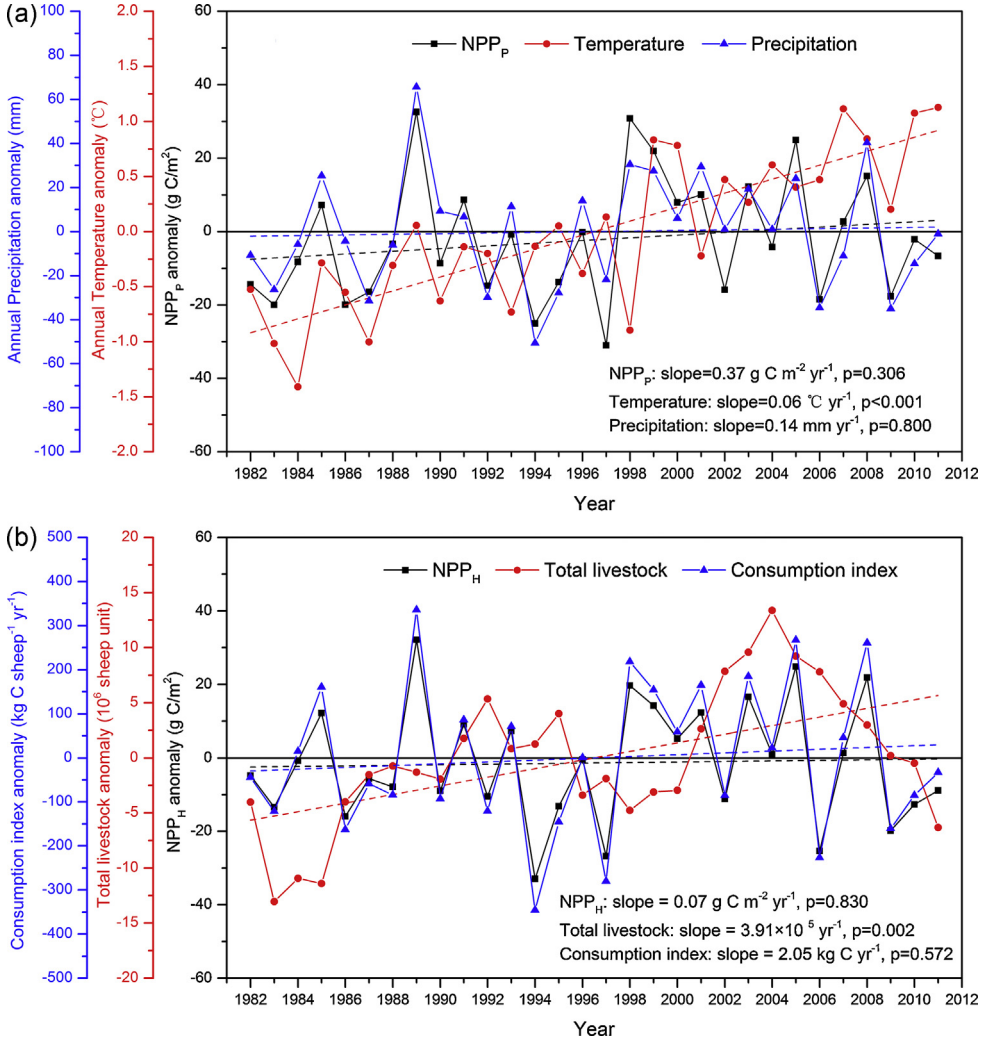

Fig. 5. Time series of (a) alpine grassland NPP_P, annual temperature, and precipitation and (b) the NPP_H consumption index per sheep unit, NPP_H, and total livestock number anomalies over the QTP from 1982 to 2011. *Note*: the total number of livestock is the sum of horses, yaks, donkeys, and sheep. In calculating the NPP_H consumption index per sheep unit, large animals, such as horses, were changed to standardized sheep units (e.g., one yak = four sheep).

QTP, which all the statistical data were obtained from the National Bureau of Statistics of China, and large animals such as cattle and horses are regarded as equivalent to four sheep units (Fan et al., 2010). We then estimated the average NPP consumption for one sheep unit over alpine grassland, calculated as the NPP_H amount consumed by per sheep unit in the 30-year period, and determined that consumption index was not a constant value but has slightly increased in the past 30 years, with the increasing rate of 2.05 kg C yr^{-1} per sheep unit, and a total increase of about 15.67% (Fig. 5b). Moreover, the predicted NPP_H also enhanced in this thirty years, suggesting that grazing pressure over the alpine grassland ecosystem was a little increasing from 1982 to 2011 in generally. As the GWP implemented around 2003, the number of livestock come up to dramatically decrease since 2004, which also brought about a relatively decrease of NPP_H and its consumption index per sheep unit (Fig. 5b), letting alpine grassland ecosystem over the QTP with a slight recover from heavy grazing pressure.

As the NPP_H was relatively unrelated to the number of livestock over the QTP, but changed along with NPP_H consumption per sheep unit in the last 30 years (Fig. 5b), accompanying with the NPP_H has related with NPP_P (Fig. 2b and c), that could be deduced by alpine grassland NPP_H consumption per sheep unit also has a strong connection with the amount of rainfall in this arid and semi-arid plateau. The phenomenon could roughly be accounted for by the theory that animal consumption per sheep unit of grass biomass varies in different years, and the animals could eat more aboveground grass biomass in a good harvest year and less in a poor year, so to some extent natural laws maintain the grassland in such a condition whereby sufficient grass grows for the animals. However, with the dramatic growth in animal rearing, the grassland cannot meet the vast demand, so widespread degradation has occurred over the QTP. Furthermore, human-induced land cover change could induce retrogressive succession, whereby more inedible sedge grass species make up most of the alpine grassland, so there is a need for human intervention to eliminate the invading grass species or to reseed the local fine gramineous species to balance the natural ecosystem (Shang et al., 2012; Wang et al., 2013).

4.3. Ecological projects achievements

The total number of livestock is the key to alpine grassland effective management over the QTP, which showed a significant increase in the last thirty years ($P < 0.01$, Fig. 5b). Though rearing livestock is the main source of income to local herdsman, increasing the number of animals also creates a potential threat to the alpine grassland ecosystem balance. So, in view of climate warming, it is both necessary and highly critical to evaluate alpine grassland ecosystem natural capacity and control the number of animals reared. The national policy of GWP and ecological compensation over the QTP, implemented around 2003, aimed for protecting degrading rangeland and controlling the number of animals bred within a proper level, then has led to an obvious decline in the NPP_H trend since 2004 (Fig. 5b). In this study, we can see that the IHA area increased obviously to 37.90% in the past 10 years, from 17.67% in the previous 20 years. Such positive effects of this grassland protection policy have also been found in Inner Mongolia and Losses plateau (Feng et al., 2013; Li et al., 2012; Mu et al., 2013). These studies findings indicate that the national ecological protection policy has achieved positive ecological effects in northern China and the QTP.

5. Conclusions

In this study, we discriminated and quantified the effects of climate change and anthropogenic activities on alpine grassland ecosystem over the QTP, finding the different driving forces for the actual NPP_A consistently enhanced in the periods of 1982–2001 and 2001–2011. Under the influences of climate change and human activities, the prime determinants of the increase in NPP_A in the two periods were changed. A warm-wet climate and less human activities caused a rapid increase in NPP_P and a relatively slow increase in NPP_H, which led to an NPP_A increase from 1982 to 2001. However, as the warm-dry climate decreased the alpine grassland NPP_P over the QTP from 2001 to 2011, marked human intervention on the alpine grassland ecosystem (fencing degrading grassland and reducing livestock number) played a much more important role in the grassland restoration, which still resulted in NPP_A increasing in this period. This implies that the obvious decline in the number of livestock animals and large-scale building the fences over the QTP alpine grassland in recent years relieved the grazing pressure of the rangeland, and indirectly caused an NPP_A increase in this latter 10 years period. Furthermore, for further fully and precisely separating the effects of climate change and human activities on ecosystem in sub-region, more field data and accurate process-based ecosystem models are needed.

Acknowledgements

This study was jointly supported by Chinese Academy of Sciences project (XDB03030400), the National Basic Research Program of China (No. 2010CB951704), and the National Sciences Foundation of China (41171044). The constructive comments and suggestions from anonymous reviewers are also highly appreciated.

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