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Assessment of ecological restoration projects under water limits: Finding a balance between nature and human needs

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ABSTRACT

Revegetation has significantly contributed to improvements in ecosystem services, such as carbon sequestration and soil retention. Yet, vegetation expansion in water-limited regions may generate conflict of water demand between nature and humans. Present studies are still lacking when it comes to identifying the permissible vegetation capacity, i.e. net primary productivity (NPP) threshold, based on the local water resources limits, and further proposing adjustment and optimization strategies to keep water use balanced in anthropogenic-biological systems. Under such a circumstance, this study assesses the difference between the actual NPP and NPP thresholds at regional and ecosystem scales in China. The results show that 8 out of 31 provinces have their provincial actual NPP above the regional NPP thresholds, mainly concentrated in northern China between 400 and 800 mm iso-precipitation line, i.e. North China Plain (Beijing-Tianjin-Hebei), the middle reaches of the Yellow River Basin (Shaanxi and Henan provinces), and the Northeast China (Heilongjiang, Jilin and Liaoning). Forest ecosystems dominate the difference between the actual total woodland and grassland ecosystems NPP and the permissible NPP thresholds in these regions, ranging from 67% (Beijing) to 99% (Tianjin). If the current vegetation intensity in these regions remains unchanged, the areas of woodland and grassland ecosystems should be optimized 0–48% and 0–100% of their present areas to balance the water demand between the ecosystems and humans, without considering the potential consequence of climate change and soil erosion. Although 23 provinces have their regional actual NPP below their permissible NPP thresholds, 6 out of 23 provinces still have their woodland and grassland ecosystems NPP above the corresponding NPP thresholds, mainly focusing on the Northwestern China north over the 400 mm iso-precipitation line, including Inner Mongolia, Qinghai, Hainan, Shanxi, Gansu and Xinjiang. Forest ecosystems also dominate the negative NPP differences in these regions, ranging from 91% (Inner Mongolia) to 46% (Gansu). These reveal the hidden and potential pressure in the 6 provinces to balance limited water resources in the local anthropogenic-biological system. This study provides a method to assess the water-resources permissible NPP threshold and further proposes the specific adjustment and optimization plans for the areas with actual NPP above the corresponding NPP thresholds, which can provide guidance for ecological restoration program implementations in a more sustainable way.

1. Introduction

Greening is defined as statistically significant increases in the annual average green leaf area at a location over a period of several years (Chen et al., 2019). China leads in greening worldwide through land-use management in the past two decades with 42% of the greening stemming from forest ecosystems (Chen et al., 2019). There are still many academic debates on the mid to long-terms effects of China's greening, including an important study published in the *Nature* journal which stated that the actions to block deserts in China, *i.e.* China's tree-planting

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programs, could strain water resources (Zastrow, 2019). Related studies also indicated that afforestation caused a reduction of water availability for humans under different natural climate conditions: including a runoff reduction of 32% in the simi-arid or arid areas in China's Loess Plateau during 1956–1980 (Huang et al., 2003), 31% in the temperate Glendhu, New Zealand between 1991 and 1996 (Fahey et al., 1998), 40% in the Mediterranean Pyrenean Basin, Spain between 1965 and 2009 (Buendia et al., 2016), 23% in the tropical Ecuador between 2013 and 2016, and 41% in Peru between 2001 and 2007 (Ochoa-Tocachi et al., 2016). These results contradict the general belief that afforestation increase water supply. A critical driving process of these results is evapotranspiration (ET). When other land uses are converted to forests, the partitioning of rainfall into green (part of water available for vegetation use) and blue (part of water available for human use) water fluxes changes. ET is a typical green water flux, while runoff discharge and groundwater are major blue water fluxes. According to the water balance formula, if more water is used by vegetation, less water will flow into rivers and lakes or recharge the groundwater that humans can directly use. This situation is exacerbated in arid climates because natural ecosystems and humans both depend on the same source of water, namely precipitation (Feng et al., 2016; Quiggin, 2001), thus leading to a reduction of water supply for human activities (Zastrow, 2019). All the previous quoted studies greatly highlight the need to identify permissible revegetation capacity i.e. the amount of net primary productivity (NPP: the difference between the energy fixed by autotrophs and their respiration, usually in annual g C/m^2 unit) permitted by local natural conditions to balance the water usage between natural vegetation and human activities, aiming to maximize the sustainable management of ecological programs.

Although there is a lack of biophysical-based studies on nature-human conflict related to water demand (Feng et al., 2016), some important works can be quoted. For example, Knapp et al. (2014) indicated that four primary factors generally restrict the amount of NPP of terrestrial ecosystems, including sunlight, water, temperature, and mineral nutrients, which vary greatly with human activities; generally, two or more of these factors simultaneously or subsequently limit NPP increase, but water shortage is the most extensive single factor affecting global NPP (Knapp et al., 2014). For example, Zhao et al. (2019), taking a semiarid watershed on the Loess Plateau, China as a case, found the firmly positive responses of utmost vegetations to precipitation, indicating that precipitation dominantly drives the vegetation production (Gentine et al., 2019; Li et al., 2020; Lohse et al., 2009; Reyer et al., 2013; Wang et al., 2015). Feng et al. (2016) defined the threshold of regional vegetation capacity by subtracting human water demand from precipitation, as the permissible NPP (*i.e.* NPP threshold = precipitation-human water demand) for the integrated biological-human system. Based on this method, the authors estimated that the permissible NPP threshold in Loess Plateau, China, between 2000 and 2010 is about 395–405 g C/m^2/yr. For the year 2008, the actual NPP had already been 400 g C/m^2/yr in that region, indicating that the amount of revegetation is about to exceed the calculated threshold and that additional revegetation would result in a shortage of water supply for human activities. Feng et al. (2016) provides an accounting method of water resources-permissible NPP threshold and this study applies this method to assess NPP thresholds.

The NPP threshold approach provides the upper limit for revegetation programs, acting as a guidance for governments or project managers to adjust and optimize the extent and intensity of ecological restoration programs. Zhang et al. (2018a) suggested that managers should set a prioritization of diverse thresholds based on a clear understanding of management objectives for ecological programs. For example, an appropriate threshold of the sustainable intensity or extent of ecological projects should be based on local natural conditions to meet diverse ecosystem services (defined as ecosystem processes and functions that directly or indirectly benefit humans, see details in Section S1 in the Supplementary Material) (Braat, 2013; Costanza et al., 1997), including carbon sequestration, soil retention, biodiversity conservation, etc. For example, if the ecosystem restoration threshold of tree canopy cover is 60% of the tree-covered area, vegetation plantation above this limit will absorb more precipitation and reduce surface runoff and consequently cause a shortage of water supply for human activities. Cao (2011) and Cao et al. (2011) indicated that since the 1980s, China's ecological projects have brought significant short-term benefits, yet its failure in applying corresponding vegetation thresholds has also caused long-term consequences of ecosystem degradation. For example, further revegetation in the Loess Plateau is likely to influence the local hydrological balance through increasing evapotranspiration, and thereby decreasing runoff and soil moisture (Cao et al., 2011; Chen et al., 2015; Fu et al., 2017; Ge et al., 2019; Jia et al., 2017; Jin et al., 2011; Lv et al., 2019; Xiao, 2014). Compared with barren surfaces or farmlands, planted forests facilitate greater evapotranspiration due to a larger leaf area, higher aerodynamic roughness and deeper roots (Anderson et al., 2011; Bonan, 2008; Bright et al., 2015; Ge et al., 2019; Yang et al., 2021). The current vegetation in the Loess Plateau is a result of decades of reforestation practices, which may have reached the permissible NPP and may have an influence on the water availability for human activities (Feng et al., 2016; Ge et al., 2020; Zhang et al., 2018b), because ecosystems and humans both rely on the same source of water source, i.e. precipitation, in that seasonally arid region (Quiggin, 2001).

Due to the current importance of balancing natural and human activities, especially those that demand water as an important input, this work aims to (1) estimate the specific NPP thresholds for different regions of China, and (2) propose specific intensity and area adjustment and optimization strategies for the ecological restoration programs where the actual NPP has already exceeded the NPP thresholds.

2. Method

2.1. Case study

Revegetation projects have significantly contributed to the improvement of China's ecosystem services from 2000 to 2010 (Ouyang et al., 2016), in which, according to Chen et al. (2019), China leads in global greening due to its implementing afforestation programs. On the other hand, natural ecosystems consume a huge amount of water and nutrients (Jackson et al., 2005) and raise doubts about the potential consequences of water availability for human proposes as a result of the ecological programs, especially in those water-limited areas. Due to its large territory under diverse climate conditions, allied to its experienced re-vegetation programs for decades, China is considered as a case study to assess the NPP thresholds at regional and ecosystems scales. Areas with actual NPP above the corresponding NPP threshold are identified to guide the implementation of more sustainable ecological programs, balancing human and natural water demand.

2.2. Regional total NPP threshold

Fig. 1 shows the well-known general hydrological cycle, which can be expressed by the following equation:

$$ET = Pr - (R_{out} - R_{in}) - \Delta RW - \Delta SW - \Delta GWg \quad (1)$$

where, ET indicates annual evapotranspiration; Pr refers to annual precipitation; R_{out} and R_{in} are annual outflow and inflow respectively; ΔRW, ΔSW and ΔGW are annual variations in river-reservoir water storage, in soil water storage and in groundwater withdrawal for vegetation growth, respectively (Feng et al., 2016).

The ΔGW variable in Equation (1) was set to zero because the underground water-irrigated areas correspond to 1.5% of China's area (MWRC, 2019), and the plains of 21 provinces across China are experiencing over-exploitation of groundwater. Notwithstanding, China's annual variations in soil water storage is also small, reaching 0.002

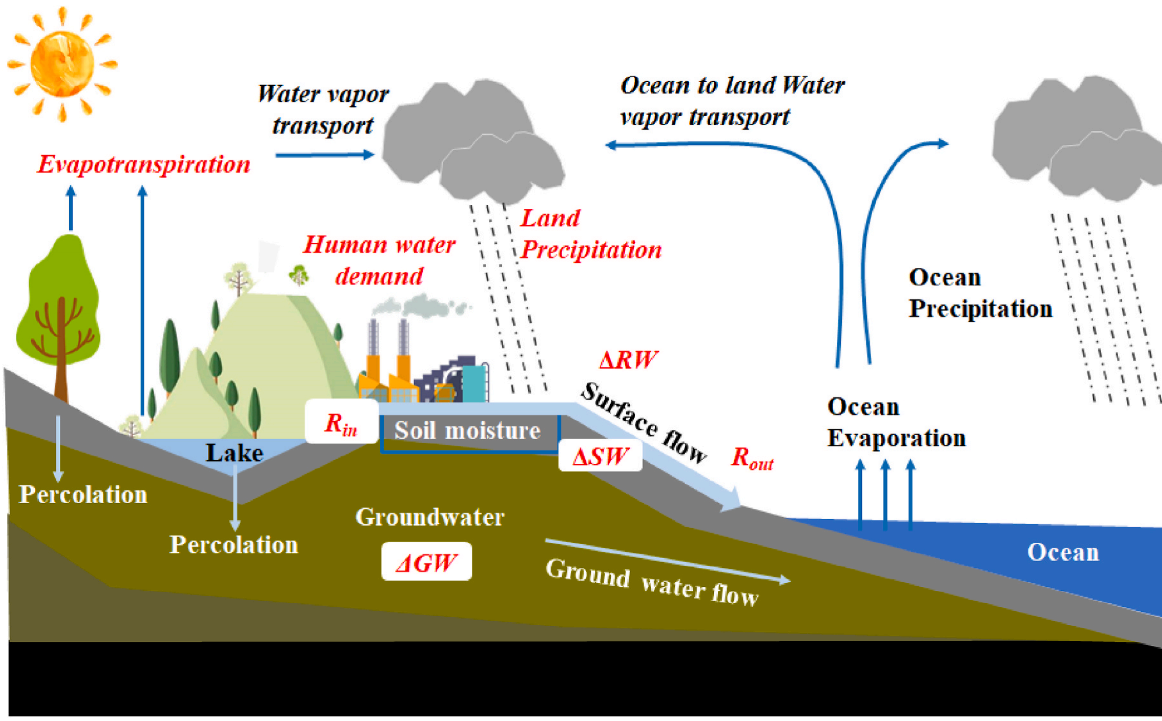

Fig. 1. The schematic diagram of hydrological cycle (R_{out} and R_{in} are annual outflow and inflow respectively; ΔRW, ΔSW and ΔGW are annual variations in river-reservoir water storage, in soil water storage and in groundwater withdrawal for vegetation growth).

m^3/m^3 (Bing et al., 2012), hence ΔSW was also assumed to be equal to zero. Otherwise, change in soil moisture cannot be ignored in translating the observed reduction of annual runoff into an increase of ET (Feng et al., 2016). After these considerations, Equation (1) becomes:

$$ET = Pr - (R_{out} - R_{in}) - \Delta RW \tag{2}$$

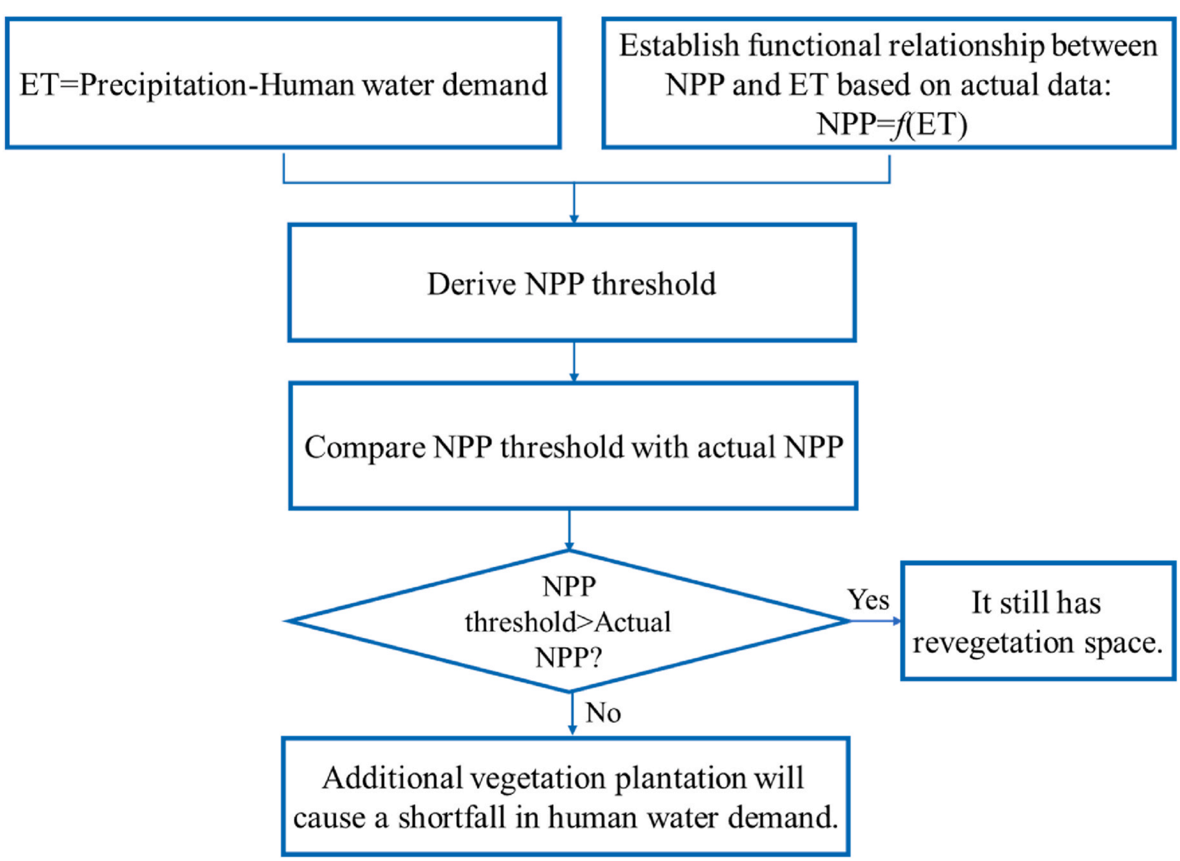

Fig. 2. The flow chart of assessing local NPP threshold (NPP: net primary productivity; ET: evapotranspiration).

According to Equation (2), when precipitation is constant, *ET* is affected by annual outflow and inflow, and variations in river-reservoir water storage. For the purposes of this study, it is assumed that the human water demand is taken exclusively from runoff, *i.e.* R_{out}, R_{in} and ΔRW in equation (1). Feng et al. (2016) suggested that *ET* corresponding to the permissible NPP threshold for the coupled anthropogenic-biological system can be expressed as follows: $ET = Pr - HWD$, where *Pr* is the annual precipitation and *HWD* is the human water demand. Human water demand includes activities of forestry, animal husbandry, fishery, livestock, and industry, as well as urban public, domestic and ecological environment water use. Agricultural irrigation was not considered because it was already included in the ET form farmland NPP.

Fig. 2 shows the flowchart used for assessing permissible NPP threshold. Based on historical MODIS remote sensing data of NPP and ET of China during the year 2000, 2005, 2010 and 2015 (please see details in Table S1 in Supplementary Materials), a linear regression is considered by associating annual *ET* with NPP, obtaining $NPP = f(ET) = a \times ET + b$. The significant NPP threshold is reached when the water demanded for ecosystem production and human activities can just be satisfied from the annual precipitation. For the regional scale, precipitation and human water demand data come from regional Statistical Yearbook and Water Resources Bulletin listed as presented in Table S1 in the Supplementary Material. After obtaining the regional total *ET*, the equation $NPP = f(ET) = a \times ET + b$, is used to calculate the permissible NPP. Finally, the calculated permissible NPP threshold is compared with the actual NPP; in a case where the actual NPP is lower than the permissible NPP, there are still areas that can be re-vegetated; in a case where the actual NPP is above the NPP threshold, it needs to further determine whether it has additional revegetation space or to adjust and optimize vegetation planation patterns.

2.3. NPP threshold calculation at ecosystem scale

The regional total NPP threshold reveals the aggregate local vegetation capacity allowed by local available water resources. To assess the contribution of specific ecosystems to the regional NPP differences between the actual NPP and the corresponding NPP thresholds, the actual NPP at ecosystem scale is compared against its corresponding NPP threshold. While farmland and aquatic ecosystems use water from other sources than precipitation (such as irrigation), woodland and grassland ecosystems use water from precipitation. With this being said, this study mainly investigates the NPP thresholds of woodland and grassland ecosystems to provide guidance for the implementation of ecological programs in more sustainable ways. According to the classification system of remote sensing data of land use and land cover in China (Xu et al., 2018), the subtypes of woodlands considered in this present study include forest, shrub, sparse and other woodlands, and grasslands

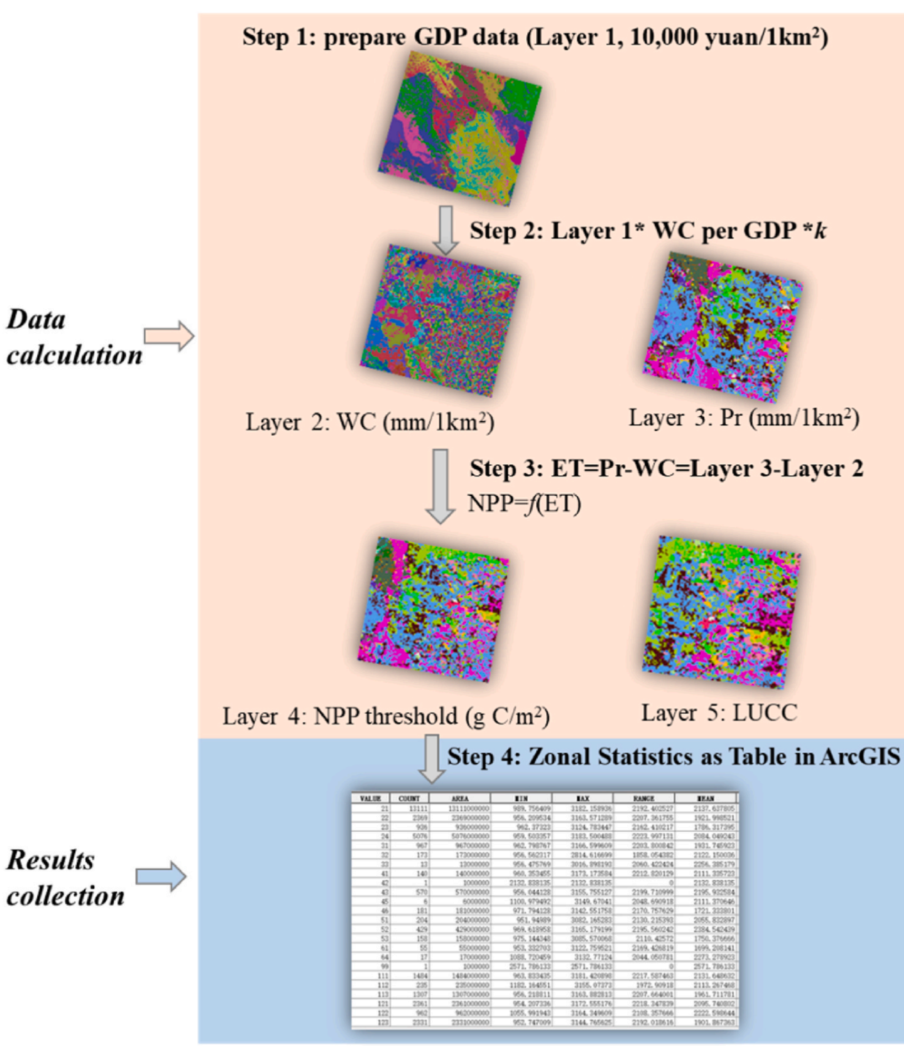

Fig. 3. Calculation steps of ecosystems' NPP thresholds (WC: water consumption, Pr: precipitation, ET: evapotranspiration, *k*: conversion factor from 10^8 m^3 to mm/yr).

include high, moderate and low coverage grasslands. Date in raster format is used to calculate the detailed ecosystems NPP threshold, because the original data about ecosystem types and their land areas data are in raster format as well.

Detailed procedure steps are presented in Fig. 3. Step 1 prepares gross domestic product (GDP) data in raster format (layer 1, 1km × 1 km, unit of 10,000 yuan/km^2). Step 2 uses layer 1 to multiply by the water consumption (WC: unit of 10^8m^3/10,000 yuan of GDP) and by the conversion factor k (mm/10^8 m^3). The Raster Calculator tool in the ArcGIS software is used to obtain raster data for GDP related to water use (layer 2; mm/km^2). In step 3, the precipitation layer (layer 3 in mm/yr) is subtracted by layer 2 to obtain raster data of ET, generating a raster layer for NPP threshold (layer 4) based on the NPP = $f(ET)$ equation through the Raster Calculator tool in the ArcGIS. Finally, Step 4 includes the Zonal Statistics as Table in the ArcGIS software, data inputs of the NPP threshold layer, land use and cover change (LUCC, 100m × 100m, see details in Table S1 in Supplementary Material) to obtain NPP threshold of each ecosystem as layer 5. All the data in raster format is at China's national scale, but it can be extended to other scales for different research purposes.

2.4. Ecosystem adjustment and optimization method based on the NPP threshold

For those regions with actual NPP above the NPP thresholds, implementing ecological programs would result in an unbalance between the water demanded by natural ecosystems and by human activities. In this case, adjustments are needed to optimize the local natural vegetation areas or its intensity, to guarantee more sustainable ecological restoration and socioeconomic development in those regions (Feng et al., 2016). Adjustment can be performed in two ways: focusing on the natural vegetation density (quality), or on the area occupied (quantity). Regarding density that occurs when the vegetation area is unchanged, the actual vegetation NPP can be adjusted within the NPP threshold by selecting water-saving and native species to reduce water use per unit area, or by selecting the combination of shrubs or herbs that demand lower amount of water. Regarding the occupied area that occurs when the natural vegetation intensity is unchanged, the difference between actual NPP and NPP threshold represents a constraint value for the maximum occupied area with natural vegetation. As an example, suppose that woodland and grassland ecosystems areas need to be adjusted X and Y (m^2), then while X is the adjustment area matrix for forest, shrub, sparse woodland and other woodland, Y is the adjustment area matrix for high, medium and low coverage grassland, both under the following restrictions:

$$\{X \times NPP_w + Y \times NPP_g = \Delta NPP_w \times S_w + \Delta NPP_g \times S_g = \Delta NPP_T \quad (3)$$

$$\{-S_f \leq X \ll 0 \quad (4)$$

$$\{-S_g \ll Y \ll 0 \quad (5)$$

where, X and Y are the areas of woodland and grassland ecosystems that need to be adjusted; NPP_w and NPP_g are the actual NPP of woodland and grassland ecosystems (g C/m^2/yr); ΔNPP_w and ΔNPP_g are differences value between the actual NPP of woodland and grassland ecosystems and their corresponding NPP thresholds (g C/m^2/yr); S_w and S_g are the actual areas of woodland and grassland ecosystems (m^2); and ΔNPP_T is the sum of differences between actual NPP and NPP thresholds of woodland and grassland ecosystems (g C/yr).

The two inequalities (4) and (5) indicate that the optimization areas of woodland and grassland ecosystems can range from zero to their corresponding current actual areas. The solution for the equations set shows the new ratio for X and Y to achieve a combination that meets the constraints established by the NPP threshold. It is important to emphasize that the areas which needed to be optimized are based on the current vegetation intensity. From the obtained results of this calculation procedure, and considering climate change and soil erosion as important drivers, stakeholders and decision-makers could optimize the natural vegetation areas by keeping natural vegetation unchanged in the current areas and working on water-saving species alternative. All data sources are available in Section S2 of the Supplementary Material.

3. Results

3.1. China's provincial theoretical NPP thresholds

The differences between China's provincial NPP thresholds and its actual NPP in 2015 are shown by Fig. 4. The green color indicates that actual NPP is below the NPP threshold, indicating that an additional vegetation capacity is allowed in these regions. The red color indicates the opposite situation in which provincial actual NPP has already achieved the NPP threshold, so additional areas with natural vegetation will lead to a water shortage for human activities; the darker red color shows larger differences between actual NPP and NPP threshold, implying the larger deficit in the water balance. Fig. 4 shows that red color areas are concentrated in the northern China between 400 and 800 mm iso-precipitation line, including Northeast China (Heilongjiang, Jilin and Liaoning), the Middle Reaches of the Yellow River Basin (YRB) (Shaanxi, Henan), and North China Plain (Beijing-Tianjin-Hebei, BTH region). Heilongjiang has the largest difference between the NPP threshold and actual NPP, achieving 1.50E+14 g C, followed by Jilin (4.73E+13 g C), Henan (3.28E+13 g C), Shaanxi (3.15E+13 g C), Liaoning (1.36E+13 g C), Beijing (7.26E+12 g C), Hebei (2.54E+12 g C) and Tianjin (1.22E+11 g C). These findings are consistent with previous studies showed that a reduction of annual rainfall in the Northeast China (Yang et al., 2016), that the YRB is a water-starved and drought-prone region (Ma et al., 2020), and that BTH region is severely constrained by water availability (Zhang et al., 2021).

Regarding those regions that still have potential areas to be re-vegetated, the highest differences between actual NPP and NPP threshold are concentrated in China's southwest and southeast regions. Specifically, Jiangxi has the largest vegetation capacity with 2.95E+14 g C, followed by Yunnan (2.12E+14 g C), Guangxi (2.03E+14 g C), Sichuan (1.99E+14 g C) and Fujian (1.98E+14 g C). Although still containing some areas to be re-vegetated, regions with lowest potential areas are Qinghai, Ningxia and some provinces in the middle and lower regions of the Yangtze and Yellow River Basin, including Shanghai (2.51E+12 g C), Ningxia (5.34E+12 g C), Hainan (1.22E+13 g C), Shandong (1.69E+13 g C), and Qinghai (1.75E+13 g C), implying these provinces have larger water resources pressure to expand vegetation planting area and intensity, and to balance water consumption between ecosystems and socio-economic activities.

3.2. Differences between NPP threshold and actual NPP at ecosystem scale

3.2.1. Ecosystems total difference between their actual NPP and NPP thresholds

The difference between actual NPP and the corresponding NPP thresholds of woodland and grassland ecosystems and their contribution ratio to the total difference value is evaluated and presented in Table 1. For the 8 provinces with actual NPP higher than NPP thresholds, the ratio of the total difference between the actual NPP of woodland and grassland ecosystems (NPP data at ecosystem's scale monitored by remote sensing satellites) to their corresponding provincial NPP difference ranges from 15% (Henan) to 181% (Hebei). The higher of this ratio means a higher contribution of woodland and grassland ecosystems to the total provincial NPP difference. With exception for Shaanxi with high coverage grassland accounting most for the ecosystems total NPP difference, forest ecosystems are the largest contributor for all other 8 provinces to the difference between ecosystems actual NPP and their

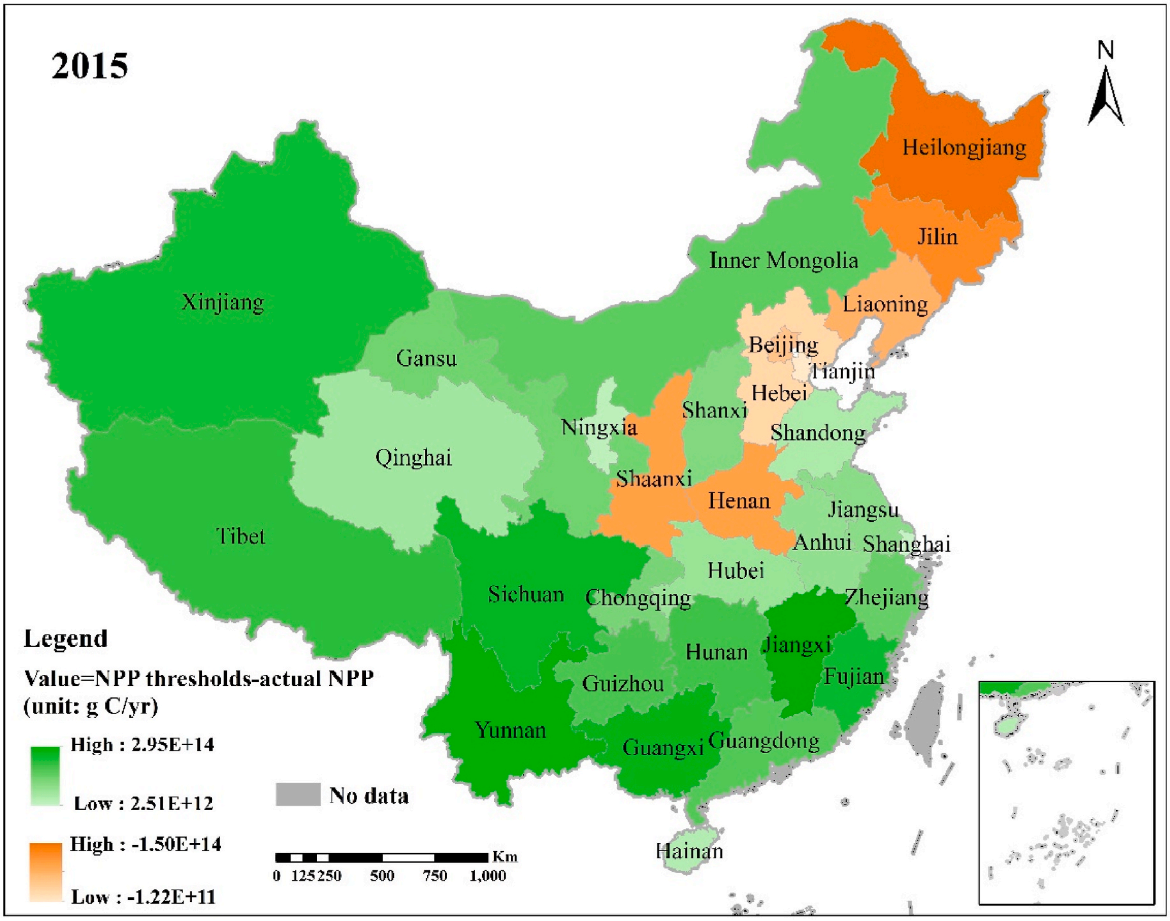

Fig. 4. The difference value between NPP thresholds and actual NPP in 2015.

Table 1
The difference between actual NPP and NPP threshold of woodland and grassland ecosystems.

NPP status	Provinces	Forest	Shrub	Sparse woodland	Other woodland	High coverage grassland	Moderate coverage grassland	Low coverage grassland	W&G total	Provincial total	Ratio
Above[a]	Heilongjiang	91.41%	2.36%	0.95%	0.24%	5.00%	0.05%	–	−7.87E+13	−1.50E+14	53%
	Jilin	95.81%	1.26%	1.19%	1.01%	–	0.74%	–	−2.88E+13	−4.73E+13	61%
	Shaanxi	23.30%	22.62%	12.50%	–	28.51%	13.07%	–	−1.63E+13	−3.15E+13	52%
	Liaoning	87.01%	5.52%	5.00%	0.89%	–	1.43%	0.15%	−1.24E+13	−1.36E+13	91%
	Henan	99.84%	–	–	0.16%	–	–	–	−4.81E+12	−3.28E+13	15%
	Hebei	82.02%	17.29%	0.67%	–	–	–	–	−4.60E+12	−2.54E+12	181%
	Beijing	66.67%	14.94%	8.76%	1.44%	7.21%	0.61%	0.35%	−2.46E+12	−7.26E+12	34%
	Tianjin	99.99%	0.01%	–	–	–	–	–	−3.60E+10	−1.22E+11	29%
Below[b]	Inner Mongolia	90.53%	–	8.55%	0.92%	–	–	–	−3.52E+13	7.65E+13	−46%
	Qinghai	2.73%	–	2.05%	–	18.23%	12.40%	64.58%	−6.00E+12	1.75E+13	−34%
	Hainan	97.74%	–	–	–	2.12%	0.14%	–	−4.90E+12	1.22E+13	−40%
	Shanxi	75.32%	24.68%	–	–	–	–	–	−3.89E+12	4.91E+13	−8%
	Gansu	46.41%	27.09%	14.45%	–	12.04%	–	–	−2.74E+12	5.82E+13	−5%
	Xinjiang	–	28.24%	37.30%	34.45%	–	–	–	−3.59E+11	1.47E+14	−0.24%
	Tibet	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	1.20E+14	n.a

Note: a and b mean that local actual NPP is above or below the NPP threshold respectively. Percentage in the table means the contribution ratio of the subtypes of woodland and grasslands to the total difference value of woodland and grassland ecosystems. W&G total means the total NPP difference of woodland and grassland ecosystems. "-" means the ecosystem's actual NPP is below the NPP threshold.

corresponding NPP thresholds, with a ratio ranging from 66.67% (Beijing) to 99.99% (Tianjin). Detailed numbers for each province are available in Section S3 of the Supplementary Material.

Although 23 provinces have their total actual NPP lower than their corresponding NPP thresholds, 6 of them still have the actual NPP of woodland and grassland ecosystems larger than their NPP thresholds (Table 1). This situation occurs mainly in Northwestern China north over the 400 mm iso-precipitation line, including Inner Mongolia, Qinghai, Hainan, Shanxi, Gansu and Xinjiang, emphasizing the existing potential risks on water scarcity. Precisely, the actual NPP of forest, sparse woodland and other woodland for Inner Mongolia; forest, sparse woodland and all grasslands for Qinghai; forest, high and moderate coverage grasslands for Hainan; forest and shrub for Shanxi; forest, shrub, sparse woodland and high coverage grassland for Gansu; shrub, sparse woodland and other woodland for Xinjiang, have all already exceeded their corresponding NPP thresholds. Among these 6 provinces, with the exception of Qinghai and Xinjiang, 4 have their forest ecosystem dominating the difference between ecosystems actual NPP and their corresponding NPP thresholds, achieving the ratios of 97.74%, 90.53%, 75.32%, 46.41% in Hainan, Inner Mongolia, Shanxi, and Gansu respectively. Low coverage grassland is responsible for 64.58% of the NPP difference in Qinghai, while the contribution ratio of woodland ecosystem is more balanced for Xinjian, achieving 37.30%, 34.45% and 28.24% for sparse woodland, other woodland, and shrub ecosystem respectively. These findings suggest that although regional actual NPP is lower than the NPP threshold, the intensities for some ecosystems vegetation have already surpassed their corresponding NPP thresholds, indicating risks for water available in these ecosystems and regions. The identified risks on water availability are more prominent in Inner Mongolia, because the actual NPP for woodland and grassland ecosystems reaches 46% of the provincial NPP difference, followed by Hainan (40%), Qinghai (34%), Shanxi (8%), Gansu (5%) and Xinjiang (0.24%). With the exception of Hainan, the remaining 5 provinces are located in arid and semi-arid regions, despite being considered key regions for the Three North Shelterbelt Project. This aspect highlights the importance of using similar approaches such as the one used in this present study, as well as the findings obtained, to encourage Project's decision-makers to put more focus on the ecosystems with higher potential to cause water resources pressures or risks.

3.2.2. The difference between actual NPP and NPP threshold per unit area at ecosystem scale

The negative number in Table 2 indicate that the actual NPP of ecosystems have already been above the corresponding NPP thresholds per unit area, while the positive values indicate the actual NPP lower than the NPP threshold per unit area. Woodland ecosystems, especially forest ecosystems dominate the difference between actual NPP and NPP threshold per unit area. For those provinces with regional actual NPP above the NPP threshold, there are still ecosystems with actual NPP below the vegetation capacity, such as grassland ecosystems in Tianjin and Hebei. Similarly, although the provincial actual NPP is below the NPP thresholds in Shanxi, Inner Mongolia, Hainan, Gansu, Qinghai and Xinjiang provinces, these provinces have ecosystems where actual NPP is already above the corresponding NPP thresholds regarding forest ecosystems. These findings imply that water availability is at risk for the ecosystems in these regions; also, numbers indicate the amount of vegetation intensity that needs to be adjusted towards a water balance between natural and human uses.

3.3. Ecological restoration optimization based on the NPP threshold

For those areas with actual NPP larger than the theoretical NPP thresholds, there is an ecological risk regarding water availability, where the larger the NPP difference value (actual NPP minus NPP threshold), the higher the risks will be, and the more policy support is needed. In a scenario where the current vegetation intensity remains, ecological programs for optimization are individually assessed for those 8 provinces with their actual NPP higher than NPP thresholds (Table 3).

(1) Beijing

Table 3a shows that woodland and grassland ecosystems in Beijing need to be optimized [(2.58E+09), (3.48E+09)], [0, (1.13E+09)] m^2, from about 35.44% to 47.80% and 0–100% of the total woodland and grassland ecosystem areas respectively, to meet the constrains established by balancing the provincial total actual NPP and NPP thresholds. In Beijing, X_{bj} and Y_{bj} are a 4×1 and 3×1 area matrix of subtypes of woodland and grassland ecosystems because they include four and three subtypes of ecosystems respectively, as presented in Table S2 of the Supplementary Material. Hence, the constraints would include an equation set with one equation and seven inequalities for the subtype areas of woodland and grassland ecosystems. Due to high complexity in solving such a set of equations, the total area of woodland and grassland ecosystems is considered to simplify the resolution (Table 3a). Thus, one equation and two inequalities are considered after simplification. Meanwhile, this study allocates the optimization areas to the subtypes of woodland and grassland ecosystems by multiplying the proportion of sub-category ecosystem areas. For example, the ratio of forest, shrub, sparse woodland and other woodland areas to the total woodland ecosystems area are 62%, 22%, 11% and 5%, and the percentage of high, moderate and low coverage grassland areas to the total grasslands area are 78%, 14% and 8% respectively. As a result, forest, shrub, sparse woodland, other woodland, high, moderate and low coverage grasslands need to be optimized (1.60E+09, 2.15E+09), (5.62E+08, 7.59E+08), (2.94E+08, 3.97E+08), (1.27E+08, 1.71E+08), (0, 8.76E+08), (0, 1.59E+08) and (0, 9.40E+07) m^2, which in percentage correspond to (35.48%, 47.67%), (35.41%, 47.83%), (35.42%, 47.83%), (35.57%, 47.90%), (0, 100%), (0, 100%) and (0, 100%) of their total areas respectively. Please note areas to be adjusted are a combination under the constraint of Equation (1), for example, in the case of $X_{bj} = -(3.48E+09)$ m^2, according to the constraint equation for Beijing in Table 3a, $Y_{bj} = 0$. For this specific case, this implies that when a woodland ecosystem is optimized 3.48E+09 m^2, i.e. forest, shrub, sparse woodland and other woodland are optimized 2.15E+09, 7.59E+08, 3.97E+08 and 1.71E+08 m^2 respectively, the grassland area remains the same to achieve a balance between actual and threshold NPPs.

Table 2
Differences between actual NPP and NPP thresholds per unit area (g C/m^2/yr).

NPP status	Provinces	Forest	Shrub	Sparse woodland	Other woodland	High coverage grassland	Moderate coverage grassland	Low coverage grassland
Above[a]	Beijing	−364	−232	−259	−99	−203	−95	−93
	Tianjin	−178	−0.15	58	79	126	150	7
	Hebei	−198	−54	−13	27	54	85	84
	Liaoning	−214	−151	−138	−90	53	−55	−62
	Jilin	−349	−178	−295	−381	63	−73	157
	Heilongjiang	−396	−287	−275	−346	−249	−6	218
	Henan	−222	42	73	−12	30	52	82
	Shaanxi	−205	−249	−163	119	−235	−47	173
Below[b]	Shanxi	−152	−57	76	161	86	149	151
	Inner Mongolia	−226	66	−232	−203	19	66	80
	Hainan	−368	395	423	461	−109	−42	871
	Gansu	−91	−46	−55	93	−13	115	96
	Qinghai	−56	1	−26	40	−33	−5	−17
	Xinjiang	71	−17	−21	−80	113	84	83

Note: a and b mean that local actual NPP is above or below the NPP threshold respectively.

Table 3
Land use area optimization plans for woodland and grassland ecosystems based on the constraints of NPP thresholds.

a

Items		Beijing	Tianjin	Hebei	Liaoning
Constraints		$706{\cdot}X_{bj}+564{\cdot}Y_{bj}=-(2.46E+12)$ $-(7.28E+09)\leq X_{bj}\leq 0$ $-(1.13E+09)\leq Y_{bj}\leq 0$	$659{\cdot}X_{tj}+472{\cdot}Y_{tj}=-(3.60E+10)$ $-(2.02E+08)\leq X_{tj}\leq 0$ $-(2.54E+07)\leq Y_{tj}\leq 0$	$542{\cdot}X_{hb}=-(4.60E+12)$	$688{\cdot}X_{ln}+397{\cdot}Y_{ln}=-(1.24E+13)$ $-(6.05E+10)\leq X_{ln}\leq 0$ $-(3.52E+09)\leq Y_{ln}\leq 0$
Solutions		$-(3.48E+09)\leq X_{bj}\leq -(2.58E+09)$ $-(1.13E+09)\leq Y_{bj}\leq 0$	$-(5.45E+07)\leq X_{tj}\leq -(3.63E+07)$ $-(2.54E+07)\leq Y_{tj}\leq 0$	$X_{hb}=-(8.47E+09)$	$-(1.80E+10)\leq X_{ln}\leq -(1.60E+10)$ $-(3.52E+09)\leq Y_{ln}\leq 0$
Forest	Area	(1.60E+09, 2.15E+09)	(3.63E+07, 5.45E+07)	4.43E+09	(1.33E+09, 1.50E+10)
	Ratio	35%–48%	18%–27%	23%	26%–30%
Shrub	Area	(5.62E+08, 7.59E+08)	(0, 2.54E+07)	3.46E+09	(1.19E+08, 1.34E+09)
	Ratio	35%–48%	0–100%	23%	26%–30%
Spare woodland	Area	(2.94E+08, 3.97E+08)	–	5.82E+08	(1.18E+09, 1.33E+09)
	Ratio	35%–48%	–	23%	26%–30%
Other woodland	Area	(1.27E+08, 1.71E+08)	–	–	(3.21E+08, 3.61E+08)
	Ratio	35%–48%	–	–	26%–30%
Woodland	Area	(2.58E+09, 3.48E+09)	–	8.47E+09	(1.60E+10, 1.80E+10)
	Ratio	35%–48%	–	23%	26%–30%
HCG	Area	(0, 8.76E+08)	–	–	–
	Ratio	0–100%	–	–	–
MCG	Area	(0, 1.59E+08)	–	–	(0, 3.22E+09)
	Ratio	0–100%	–	–	0–100%
LCG	Area	(0, 9.40E+07)	–	–	(0, 3.00E+08)
	Ratio	0–100%	–	–	0–100%
Grassland	Area	(0, 1.13E+09)	–	–	(0, 3.52E+09)
	Ratio	0–100%	–	–	0–100%

b

Items		Jilin	Heilongjiang	Henan	Shaanxi
Constraints		$844{\cdot}X_{jl}=-(2.86E+12)$ $402{\cdot}Y_{jl}=-(2.13E+11)$	$822{\cdot}X_{hlj}+580{\cdot}Y_{hlj}=-(7.87E+13)$ $-(1.91E+11)\leq X_{hlj}\leq 0$ $-(2.71E+10)\leq Y_{hlj}\leq 0$	$861{\cdot}X_{hn}+602{\cdot}Y_{hn}=-(4.81E+12)$ $-(2.16E+10)\leq X_{hn}\leq 0$ $-(6.35E+08)\leq Y_{hn}\leq 0$	$820{\cdot}X_{sax}+675{\cdot}Y_{sax}=-(1.63E+13)$ $-(4.59E+10)\leq X_{sax}\leq 0$ $-(6.53E+10)\leq Y_{sax}\leq 0$
Solutions		$X_{jl}=-(3.39E+10)$ $Y_{jl}=-(5.29E+08)$	$-(9.57E+10)\leq X_{hlj}\leq -(7.66E+10)$ $-(2.17E+10)\leq Y_{hlj}\leq 0$	$-(5.59E+09)\leq X_{hn}\leq -(5.14E+09)$ $-(6.35E+08)\leq Y_{hn}\leq 0$	$-(1.99E+10)\leq X_{sax}\leq 0$ $-(2.42E+10)\leq Y_{sax}\leq 0$
Forest	Area	3.23E+10	(7.27E+10, 9.08E+10)	(5.59E+09, 5.14E+09)	(8.05E+09, 1.86E+10)
	Ratio	41%	27%–35%	24%–26%	0–43%
Shrub	Area	8.31E+08	(2.60E+09, 3.25E+09)	–	(0, 8.05E+09)
	Ratio	41%	27%–35%	–	0–43%
Sparse woodland	Area	4.74E+08	(1.09E+09, 1.36E+09)	–	(0, 6.42E+09)
	Ratio	41%	27%–35%	–	0–43%
Other woodland	Area	3.11E+08	(2.18E+08, 2.73E+08)	(0, 6.35E+08)	–
	Ratio	41%	27%–35%	0–100%	–
Woodland	Area	3.39E+10	(7.66E+10, 9.57E+10)	–	(0, 1.99E+10)
	Ratio	41%	27%–35%	–	0–43%
HCG	Area	–	(0, 1.58E+10)	–	(0, 7.34E+09)
	Ratio	–	0–100%	–	0–37%
MCG	Area	5.29E+08	(0, 5.90E+09)	–	(0, 1.69E+10)
	Ratio	18%	0–100%	–	0–37%
LCG	Area	–	–	–	–
	Ratio	–	–	–	–
Grassland	Area	–	(0, 2.17E+10)	–	(0, 2.42E+10)
	Ratio	–	0–100%	–	0–37%

Note: HCG, MCG, and LCG mean high, moderate and low coverage grassland. X and Y indicate the area of woodland and grassland that need to be adjusted. The ranges of the area and ratio refer to the area of each ecosystem needed to shrink, and the ratio of the area needed to decrease to the total area of current woodland or grassland ecosystems.

(2) Tianjin

Tianjin has forest and shrub ecosystems' NPP above the corresponding NPP thresholds, therefore, both need to be optimized X_{tj} and Y_{tj} m^2 respectively to meet the constrains Table 3a. Results show that forest and shrub ecosystems need to be optimized (3.63E+07, 5.45E+07) and (0, 2.54E+07) m^2, which in percentage means 17.97%–26.98%, 0–100% of their total areas to achieve a balance between NPPs. For example, in the case of $X_{tj}=-(3.63E+07)$ m^2, shrub ecosystem needs to be optimized 2.54E+07 m^2 to balance local ecosystems and humans water consumption.

(3) Hebei

Considering that forest, shrub and sparse woodland ecosystems in Hebei need to be optimized a total of X_{hb} m^2 to meet the constrains in Table 3a, the solution would be $X_{hb}=-(8.47E+09)$ m^2, which corresponds to 23% of its total area of forest, shrub and sparse woodland ecosystems. Because the ratio of forest, shrub and sparse woodland ecosystems area to their total area are 52%, 41% and 7% respectively, forest, shrub and sparse woodland ecosystems should be optimized 4.43E+09, 3.46E+09 and 5.82E+08 m^2 to make their actual NPP equal to the NPP thresholds.

(4) Liaoning

Table 3a shows that woodland and grassland (excluding high coverage grassland) ecosystems for Liaoning need to be optimized (1.60E+10, 1.80E+10) and (0, 3.52E+09) m^2, representing 26.45%–29.75%, 0–100% of their total ecosystem areas. Because the ratio of forest, shrub, sparse woodland, other woodland ecosystems areas to the total woodland area are 83%, 7%, 7% and 2% respectively, and the rate of moderate and low coverage grasslands area to their total areas are 91% and 9% respectively. Hence, forest, shrub, sparse woodland, other woodland, moderate and low coverage grasslands need to be optimized (1.33E+10, 1.50E+10), (1.19E+09, 1.34E+09), (1.18E+09, 1.33E+09), (3.21E+08, 3.61E+08), (0, 3.22E+09) and (0, 3.00E+08) m^2 to achieve a balance between actual NPP and NPP thresholds.

(5) Jilin

Assuming woodland and moderate coverage grassland ecosystems in Jilin need to be optimized X_{jl} and Y_{jl} m^2 to meet the constrains in Table 3b. Table 3b suggests that the total optimization areas of woodland and moderate coverage grassland ecosystems in Jilin are 8.31E+10 and 2.91E+09 m^2 respectively, corresponding to 40.79% and 18.18% (*i. e.* 3.39E+10, 5.29E+08 m^2) of their total ecosystem areas to balance ecosystems and human activities water use. Because forest, shrub, sparse woodland and other woodland ecosystem areas account for 95.24%, 2.45%, 1.40% and 0.92% to the total woodland ecosystem area, suggesting these ecosystems need to be optimized 3.23E+10, 8.31E+08, 4.74E+08 and 3.11E+08 m^2 respectively.

(6) Heilongjiang

Assuming woodland and grassland (except for low coverage grassland) ecosystems in Heilongjiang need to be adjusted X_{hlj} and Y_{hlj} m^2 to meet the constrains Table 3b. Table 3b indicates that the woodland and grassland (without low coverage grassland) ecosystems in Heilongjiang need to be optimized (7.66E+10, 9.57E+10) and (0, 2.17E+10), representing 27.38%–35.39% and 0–100% of their corresponding total areas to meet local NPP thresholds. Because the ratio of forest, shrub, sparse woodland and other woodland areas to the total woodland ecosystem area are 94.90%, 3.39%, 1.42% and 0.28%, and the proportion of high and moderate coverage grassland areas to the total grasslands (without low coverage grassland) area are 73% and 27% respectively. Hence, forest, shrub, sparse woodland, other woodland, high and moderate coverage grasslands need to be optimized (7.27E+10, 9.08E+10), (2.60E+09, 3.25E+09), (1.09E+09, 1.36E+09), (2.18E+08, 2.73E+08), (0, 1.58E+10) and (0, 5.90E+09) m^2 respectively to balance local water use between ecosystems and humans.

(7) Henan

Assuming forest and other woodland ecosystems in Henan need to be adjusted X_{he} and Y_{he} m^2 to meet the constrains in Table 3b. Table 3b indicates that the forest and other woodland ecosystems in Henan need to be optimized (5.14E+09, 5.59E+09) and (0, 6.35E+08) m^2, corresponding to 23.80%–25.88%, 0–100% of the forest and other woodland ecosystems areas to balance water demand in an anthropogenic-biological system.

(8) Shaanxi

Assuming woodland (except for other woodland) and grassland (without low coverage grassland) ecosystems in Shaanxi need to be optimized X_{sax} and Y_{sax} m^2 to meet the constrains in Table 3b. Results indicates that the woodland (except for other woodland) and grassland (without low coverage grassland) ecosystems in Shaanxi need to be optimized (0, 1.99E+10) and (0, 2.42E+10) m^2, suggesting 0–43.36% and 0–37.06% of their current areas. Specifically, because the ratio of forest, shrub and sparse woodland ecosystems areas to their total area are 40.47%, 32.25% and 27.28%, and the percentage of high and moderate coverage grassland ecosystems area to their total area are 30% and 70%, respectively. Hence, forest, shrub, sparse woodland, high and moderate coverage grassland ecosystems need to be optimized (0, 8.05E+09), (0, 6.42E+09), (0, 5.43E+09), (0, 7.34E+09) and (0, 1.69E+10) m^2 to meet the corresponding ecosystems NPP thresholds.

4. Discussions

4.1. Implications of the obtained results

This section aims to provide a discussion about how to integrate the findings of this work with other studies for applicable policies. Table 3 shows that under the condition of unchanged vegetation intensity, the provinces with regional actual NPP above NPP thresholds need to be optimized 0–48% and 0–100% of their current woodland and grassland ecosystems areas to balance ecosystems and humans water use. The areas which needed to be adjusted are large. As well as this, other important issues related to ecosystem services were not taken into account in this study, such as climate change and soil erosion caused by the reduction in natural vegetation areas. As previously presented alternative ways to meet actual with NPP thresholds are to select water-saving and native species or adjust vegetation combination. For example, some studies suggested that the national forestry department has recognized the risks of planting trees in water-limited regions, and it has moved towards planting shrubs or herbs with less water demands in recent years (Ge et al., 2020; Zastrow, 2019). In another study, Zheng et al. (2021) assessed native vegetation species in the Yanhe River catchment (located in Loss Plateau, China) to explore the relationship between native species with environmental heterogeneity (meteorological and terrain factors, such as temperature, light, moisture, etc.) to establish the applicability of potential distribution of the habitat and identify the priority regions by integrating the MaxEnt and prioritizr models. Results suggested that the potentially suitable habitats for the grasslands, shrubs and forest were distributed in the central and northern of the case area, almost the entire study area and the southern of the study area, respectively. While, since 1999, large amounts of trees have been planted in this area, which is the opposite of what was proposed by the regional ecological restoration plan. The same authors (Zheng et al., 2021) also emphasized that the appropriate regions of shrubs and herbs are larger than that of trees in the study area. This highlights that, for the next ecological restoration practices and projects, it is worth integrating the two adjustment procedures as used in this present work: adjust revegetation area and vegetation combination, including especially native species (Chazdon, 2008; FAO, 2014). Because selecting native species is being recognized as an effective way to restore ecosystem functions and services, and to increase biodiversity in degraded areas across the world (Cernansky, 2018; Lu et al., 2017). At this point, the propositions and findings of this present work provide an alternative and scientific-based approach to estimate the most appropriate and optimal revegetation areas and species to avoid water availability risks for nature and humans.

4.2. The stress of water demand for socio-economic systems

This study assesses the permissible NPP balancing water used in the integrated human-biological system. Assuming there is no human water demand, i.e. HWD equals to zero. Under this circumstance, we can calculate the corresponding NPP thresholds (abbreviation: $NPP_{no\ hwd}$), and then compare the NPP thresholds with human water demand (abbreviation: $NPP_{with\ hwd}$, i.e. the results in section 3), to investigate the stress of water demand of human activities on the thresholds of local vegetation capacity. We mainly investigate the impacts in the provinces with regional actual NPP above the NPP thresholds (Table 4). Table 4 indicates that the water demand for socio-economic activities causes the largest pressures on the local NPP thresholds in Tianjin and Hebei. Specifically, in a scenario in which water resource for both provinces come from different sources than precipitation, these two provinces would transfer from regions with actual NPP above to below the NPP thresholds. The water demand by human activities has smallest pressure on Jilin because the ratio of NPP difference without human water use to

Table 4
Difference between provincial actual NPP and NPP thresholds with and without human water uses in 2015 (unit: g C/yr).

Provinces	NPP differences		Ratio
	With human use	Without human use	
Beijing	−7.26E+12	−3.98E+12	55%
Tianjin	−1.22E+11	1.31E+12	−1075%
Hebei	−2.54E+12	3.85E+12	−152%
Liaoning	−1.36E+13	−7.17E+12	53%
Jilin	−4.73E+13	−4.23E+13	89%
Heilongjiang	−1.50E+14	−1.13E+14	76%
Henan	−3.28E+13	−2.12E+13	65%
Shaanxi	−3.15E+13	−2.72E+13	86%

Note: % indicates the ratio between with and without human water use.

that of with human water use is the smallest (53%), followed by Shaanxi, Heilongjiang, Henan, Beijing and Liaoning.

4.3. Limitations and future efforts

Our study investigates the difference between actual NPP and their corresponding NPP thresholds, and further proposes the potential area adjustment plans for the regions where the actual NPP has already been above the NPP thresholds. Although it is recognized as important, this work has some uncertainties (please see in Section S4 in the Supplementary Material) and limitations. For example, precipitation is assumed as the main source of water in the studied regions due to data availability, but some regions may have other main water sources, including water transferred across regions. Our results are, to some extent, different from that obtained by Li et al. (2018) which reported a positive precipitation feedback to green in Northern China based on a Global Climate Model. The discrepancy could be induced by the functional relationship dependency of our results, for the NPP thresholds in our model were assessed by only one functional relationship, i.e. ET = Pr-HWD. Therefore, additional models might be necessary to develop a measurement of NPP thresholds. Future studies highly need to identify the relationship between environmental factors besides precipitation, including solar radiation, slope, climate conditions, and interregional water transfer, among others, to reach results that would support guidance for sustainable ecological restoration implementations.

This study proposes the area adjustment and optimization plans for woodland and grassland in section 3.1. Reducing more grassland areas may indicate remain more woodland areas. Yet, the adjustment and optimization procedures presented in this work ignored that these two ecosystems provide different services to human being. This means that, although when the actual NPP does not exceed the NPP threshold, it may affect the diversity and amount of ecosystem services provision. Future studies should consider the differences between the woodland and grassland ecosystem services in the process of ecological programs adjustment and optimization for natural vegetation.

Another variable disregarded in this work is the NPP thresholds of aquatic ecosystems such as wetland, lake, reservoir or pond and river. Except for the reason that both precipitation and runoff are water sources of aquatic ecosystems, another reason is the complex and non-liner relationship between NPP thresholds of aquatic ecosystems and water resources availability. Water resources shortage would change hydrological situation. On one hand, it can directly affect the vegetation communities and result in aquatic plants variation such as vegetation community succession. On the other hand, water shortage can indirectly affect the biogeochemical cycle, thereby affecting the succession direction of aquatic vegetation communities. Meanwhile, water shortage can exacerbate the level of eutrophication, thus affecting NPP level. Therefore, this study has not found an appropriate method to assess permissible NPP capability of water bodies due to their complex and non-liner relationship, and this research direction needs to be further investigated.

Overall, this study identifies the regional and ecosystems NPP thresholds and further proposes the potential vegetation adjustment plans to balance water use in anthropogenic-biological system, and can provide informed guidance for ecological restoration implementations in more sustainable ways.

5. Conclusions

Vegetation expansion should be implemented within the permissible NPP thresholds especially in water-limited areas to balance water demand between ecosystems and humans. This study investigates China's provincial and ecosystems actual NPP and their corresponding NPP thresholds. Eight provinces have their actual NPP above the NPP thresholds, indicating that no re-vegetation practices should be supported. Although 23 provinces have actual NPP below their NPP thresholds, six of them have woodland and grassland ecosystems NPP above their corresponding NPP thresholds, including Inner Mongolia, Qinghai, Hainan, Shanxi, Gansu and Xinjiang; this indicates the existing potential risks on water availability in these provinces. With the exception of Hainan, the other five provinces are located in currently water-limited regions, calling attention for the Three North Shelterbelt Program managers. Further, this paper proposes the adjustment and optimization strategies for the regions with actual NPP already above the NPP thresholds. Meanwhile, it also highly calls for integrating the area adjustment plans proposed in this study with habitat suitability identification and optimal revegetation patterns selection in other studies for the sustainable management of ecological programs, and further to achieve the win-win goals of both alleviating climate and curbing ecosystem degradation. Except for water resource, future studies also need to investigate the relationships among other environmental factors with regional permissible vegetation capacity. On aggerate, this study can provide methods to assess the regional and ecosystems NPP thresholds, and the adjustment and optimization plans based on the NPP thresholds. It is critical to guide ecological restoration programs implementations in a more sustainable way and balance water demand between ecosystems and human activities.

Credit author statement

ZF Yang and GY Liu were responsible for overall project supervision, conceptualization, project management, and final draft writing, review and editing; Q Yang contributed to methodology development, conducted validation, and contributed to the writing of early drafts; F Agostinho and BF Giannetti contributed to the data curation and revision checking.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Anderson, R.G., Canadell, J.G., Randerson, J.T., Jackson, R.B., Hungate, B.A., Baldocchi, D.D., Ban-Weiss, G.A., Bonan, G.B., Caldeira, K., Cao, L., Diffenbaugh, N. S., Gurney, K.R., Kueppers, L.M., Law, B.E., Luyssaert, S., O'Halloran, T.L., 2011. Biophysical considerations in forestry for climate protection. Front. Ecol. Environ. 9, 174–182.

Bing, L., Su, H., Shao, Q., Liu, J., 2012. Changing characteristic of land surface evapotranspiration and soil moisture in China during the past 30 years. J. Geo-inf. Sci. 14 (1), 1–13 *(in Chinese)*.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320, 1444–1449.

Braat, L.C., 2013. The value of the ecosystem services concept in economic and biodiversity policy. In: Jacobs, S., Dendoncker, N., Keune, H. (Eds.), Ecosystem Services, Global Issues, Local Practices. Elsevier, Boston.

Bright, R.M., Zhao, K.G., Jackson, R.B., Cherubini, F., 2015. Quantifying surface albedo and other direct biogeophysical climate forcings of forestry activities. Global Change Biol. 21, 3246–3266.

Buendia, C., Ramon, J.B., Sergi, S., Antoni, P., Rafael, M., 2016. Runoff trends driven by climate and afforestation in a Pyrenean Basin. Land Degrad. Dev. 27 (3), 823–838.

Cao, S., 2011. Impact of China's large-scale ecological restoration program on the environment and society in arid and semiarid areas of China: achievements, Problems, Synthesis, and Applications. Crit. Rev. Environ. Sci. Technol. 41 (4), 317–335.

Cao, S., Chen, L., Shankman, D., Wang, C., Wang, X., Zhang, H., 2011. Excessive reliance on afforestation in China's arid and semi-arid regions: lessons in ecological restoration. Earth Sci. Rev. 104, 240–245.

Cernansky, R., 2018. How to plant a trillion trees. Nature 560, 542–544.

Chazdon, R.L., 2008. Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320, 1458–1460.

Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R.K., Fuchs, R., Brovkin, V., Ciais, P., Fensholt, R., Tømmervik, H., Bala, G., Zhu, Z., Nemani, R.R., Myneni, R.B., 2019. China and India lead in greening of the world through land-use management. Nat. Sustain. 2, 122–129.

Chen, Y.P., Wang, K.B., Lin, Y.S., Shi, W.Y., Song, Y., He, X.H., 2015. Balancing green and grain trade. Nat. Geosci. 8, 739–741.

Costanza, R., et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

FAO (Food and Agriculture Organization), 2014. The State of the World's Forest Genetic Resources: Thematic Study. Genetic Considerations in Ecosystem Restoration Using Native Tree Species. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fahey, B., Rick, J., Lindsay, R., 1998. Hydrological effects of afforestation and pasture improvement in montane grasslands, South Island, New Zealand. In: Environmental Forest Science. Springer, Dordrecht, pp. 395–404.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., Wu, B., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Change 6, 1019–1022.

Fu, B.J., Wang, S., Liu, Y., Liu, J.B., Liang, W., Miao, C.Y., 2017. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. Annu. Rev. Earth Planet Sci. 45, 223–243.

Ge, J., Pitman, A.J., Guo, W., Zan, B., Fu, C., 2020. Impact of revegetation of the Loess Plateau of China on the regional growing season water balance. Hydrol. Earth Syst. Sci. 24, 515–533.

Ge, J., Guo, W., Pitman, A.J., Kauwe, M.G., Chen, X., Fu, C., 2019. The nonradiative effect dominates local surface temperature change caused by afforestation in China. J. Clim. 32, 4445–4471.

Gentine, P., Green, J.K., Guérin, M., Humphrey, V., Seneviratne, S., Zhang, Y., Zhou, S., 2019. Coupling between the terrestrial carbon and water cycles—a review. Environ. Res. Lett. 14, 083003.

Huang, M., Lu, Z., Jacques, G., 2003. Runoff responses to afforestation in a watershed of the Loess Plateau, China. Hydrol. Process. 17 (13), 2599–2609.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K. A., Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310, 1944–1947.

Jia, X.X., Shao, M.A., Zhu, Y.J., Luo, Y., 2017. Soil moisture decline due to afforestation across the Loess Plateau, China. J. Hydrol. 546, 113–122.

Jin, T.T., Fu, B.J., Liu, G.H., Wang, Z., 2011. Hydrologic feasibility of artificial forestation in the semi-arid Loess Plateau of China. Hydrol. Earth Syst. Sci. 15, 2519–2530.

Knapp, A., Carroll, C., Fahey, T., 2014. Patterns and controls of terrestrial primary production in a changing world. In: Book Ecology and the Environment, ISBN 978-1-4614-7500-2.

Li, Y., Piao, S.L., Li, L.Z.X., Chen, A.P., Wang, X.H., Ciais, P., Huang, L., Lian, X., Peng, S. S., Zeng, Z.Z., Wang, K., Zhou, L.M., 2018. Divergent hydrological response to large-scale afforestation and vegetation greening in China. Sci. Adv. 4 https://doi.org/10.1126/sciadv.aar4182 eaar4182.

Li, J., Wang, Y., Liu, L., 2020. Responses of the terrestrial ecosystem productivity to droughts in China. Front. Earth Sci. 8, 1–13.

Lohse, K.A., Brooks, P.D., McIntosh, J.C., Meixner, T., Huxman, T.E., 2009. Interactions between biogeochemistry and hydrologic Systems. Annu. Rev. Environ. Resour. 34 (1), 65–96.

Lu, Y., Ranjitkar, S., Harrison, R.D., Xu, J., Ou, X., Ma, X., He, J., 2017. Selection of native tree species for subtropical forest restoration in southwest China. PLoS One 12 (1), e0170418.

Lv, M.X., Ma, Z.G., Li, M.X., Zheng, Z.Y., 2019. Quantitative analysis of terrestrial water storage changes under the Grain for Green Program in the Yellow River basin. J. Geophys. Res. Atmos. 124, 1336-135.

Ma, M., Yuan, F., Cui, H., Ren, L., Liu, Y., 2020. A comprehensive analysis of meteorological drought stress over the Yellow River basin (China) for the next 40 years. Int. J. Climatol. 41 (Suppl. 1), E2927–E2948.

Ministry of Water Resources of the People's Republic of China (MWRC), 2019. China's Irrigated Area Reaches 1.11 Billion Mu, Ranking First in the World. Government Information Broadcast.

Ochoa-Tocachi, B.F., Wouter, B., Bert, D.B., Rolando, C., Patricio, C., Marcos, V., Carlos, A.L., et al., 2016. Impacts of land use on the hydrological response of tropical Andean catchments. Hydrol. Process. 30 (22), 4074–4089.

Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y., Rao, E., Jiang, L., Lu, F., Wang, X., Yang, G., Gong, S., Wu, B., Zeng, Y., Yang, W., Daily, G.C., 2016. Improvements in ecosystem services from investments in natural capital. Science 352, 1455–1459.

Quiggin, J., 2001. Environmental economics and the murray–darling river system. Aust. J. Agric. Resour. Econ. 45, 67–94.

Reyer, C.P., Leuzinger, S., Rammig, A., Wolf, A., Bartholomeus, R.P., Bonfante, A., de Lorenzi, F., Dury, M., Gloning, P., Jaoudé, R.A., Klein, T., Kuster, T.M., Martins, M., Niedrist, G., Wohlfahrt, G., de Angelis, P., de Dato, G., François, L., Menzel, A., Pereira, M., 2013. A plant's perspective of extremes: terrestrial plant responses to changing climatic variability. Global Change Biol. 19 (1), 75–89.

Wang, Y., Jiang, Q., Yang, Z., Sun, W., Wang, D., 2015. Effects of water and nitrogen addition on ecosystem carbon exchange in a meadow steppe. PLoS One 10 (5), e0127695.

Xiao, J.F., 2014. Satellite evidence for significant biophysical consequences of the "grain for green" program on the Loess Plateau in China. J. Geophys. Res. Biogeosci. 119, 2261–2275.

Xu, X., Liu, J., Zhang, S., Li, R., Yan, C., Wu, S., 2018. Remote Sensing Monitoring Data Set for Land Use and Cover in China. Data Registration and Publishing System of Resource and Environment Science Data Center of Chinese Academy of Sciences. DOI:10.12078/2018070201. http://www.resdc.cn/.

Yang, G., Shao, W., Wang, H., Han, D., 2016. Drought evolution characteristics and attribution analysis in northeast China. 12th International Conference on Hydroinformatics (HIC 2016). Procedia Eng. 154, 749–756.

Yang, Z., Hou, F., Cheng, J., Zhang, Y., 2021. Modeling the effect of different forest types on water balance in the three gorges reservoir area in China, with CoupModel. Water 13 (5), 654.

Zastrow, M., 2019. China's tree-planting could falter in a warming world. Nature 573, 474–475.

Zhang, J., Luo, M., Yue, H., Chen, X., Feng, C., 2018a. Critical thresholds in ecological restoration to achieve optimal ecosystem services: an analysis based on forest ecosystem restoration projects in China. Land Use Pol. 76, 675–678.

Zhang, S.L., Yang, D.W., Yang, Y.T., Piao, S.L., Yang, H.B., Lei, H.M., Fu, B.J., 2018b. Excessive afforestation and soil drying on China's Loess Plateau. J. Geophys. Res. Biogeosci. 123 (3), 923–935.

Zhang, Z., Shi, M., Chen, K., Yang, H., Wang, S., 2021. Water scarcity will constrain the formation of a world-class megalopolis in North China. Nat. Partn. J. (npj), Urban Sustain. 1, 13.

Zheng, C., Wen, Z., Liu, Y., Guo, Q., Jiang, Y., Ren, H., Fan, Y., Yang, Y., 2021. Integrating habitat suitability and the near-nature restoration priorities into revegetation plans based on potential vegetation distribution. Forests 12, 218.

Zhao, F., Wu, Y., Sivakumar, B., Long, A., Qiu, L., Chen, J., Wang, L., Liu, S., Hu, H., 2019. Climatic and hydrologic controls on net primary production in a semiarid loess watershed. J. Hydrol. 568, 803–815.