Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

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

Research
Environmental Engineering—Article

Divergent Changes in Vegetation Greenness, Productivity, and Rainfall Use Efficiency Are Characteristic of Ecological Restoration Towards High-Quality Development in the Yellow River Basin, China

Yang Yu [a,b,*], Ting Hua [c,d], Liding Chen [e], Zhiqiang Zhang [a,b], Paulo Pereira [f]

[a] *Jixian National Forest Ecosystem Observation and Research Station, National Ecosystem Research Network of China (CNERN), School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China*
[b] *School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China*
[c] *State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China*
[d] *Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China*
[e] *State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China*
[f] *Environmental Management Laboratory, Mykolas Romeris University, Vilnius 08303, Lithuania*

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Vegetation greenness
Vegetation productivity
Rainfall use efficiency
Sensitivity
Yellow River Basin

ABSTRACT

Globally, vegetation has been changing dramatically. The vegetation–water dynamic is key to understanding ecosystem structure and functioning in water-limited ecosystems. Continual satellite monitoring has detected global vegetation greening. However, a vegetation greenness increase does not mean that ecosystem functions increase. The intricate interplays resulting from the relationships between vegetation and precipitation must be more adequately comprehended. In this study, satellite data, for example, leaf area index (LAI), net primary production (NPP) and rainfall use efficiency (RUE), were used to quantify vegetation dynamics and their relationship with rainfall in different reaches of the Yellow River Basin (YRB). A sequential regression method was used to detect trends of NPP sensitivity to rainfall. The results showed that 34.53% of the YRB exhibited a significant greening trend since 2000. Among them, 20.54%, 53.37%, and 16.73% of upper, middle, and lower reach areas showed a significant positive trend, respectively. NPP showed a similar trend to LAI in the YRB upper, middle, and lower reaches. A notable difference was noted in the distributions and trends of RUE across the upper, middle, and lower reaches. Moreover, there were significant trends in vegetation–rainfall sensitivity in 16.86% of the YRB's middle reaches—14.08% showed negative trends and 2.78% positive trends. A total of 8.41% of the YRB exhibited a marked increase in LAI, NPP, and RUE. Subsequently, strategic locations reliant on the correlation between vegetation and rainfall were identified and designated for restoration planning purposes to propose future ecological restoration efforts. Our analysis indicates that the middle reach of the YRB exhibited the most significant variation in vegetation greenness and productivity. The present study underscores the significance of examining the correlation between vegetation and rainfall within the context of the high-quality development strategy of the YRB. The outcomes of our analysis and the proposed ecological restoration framework can provide decision-makers with valuable insights for executing rational basin pattern optimization and sustainable management.

1. Introduction

The restoration of degraded ecosystems and converted lands into healthy ecosystems, commonly referred to as ecological restoration, is a crucial social solution for addressing land degradation, preserving biodiversity, stabilizing the climate, enhancing ecosystem functioning, and providing ecosystem services to communities [1–3]. Numerous international and national political initiatives have recognized the importance of ecosystem restoration and have proposed a range of restorative agenda. Notably, the United Nations (UN) has officially designated the time spanning from 2021 to 2030 as the "UN Decade on Ecosystem Restoration", while Africa's Great Green Wall project aims to reforest a 7000 km

---

* Corresponding author.
E-mail address: yangyu@bjfu.edu.cn (Y. Yu).

https://doi.org/10.1016/j.eng.2023.07.012

Please cite this article as: Y. Yu, T. Hua, L. Chen et al., Divergent Changes in Vegetation Greenness, Productivity, and Rainfall Use Efficiency Are Characteristic of Ecological Restoration Towards High-Quality Development in the Yellow River Basin, China, Engineering, https://doi.org/10.1016/j.eng.2023.07.012

stretch south of the Sahara. Meanwhile, massive land-sustainability programs have been implemented in China to combat land degradation [4]. However, in regions with limited water resources, blind ecological restoration may exacerbate the tradeoffs between carbon and water, restricting restoration efficiency, effectiveness, and social well-being, which has sparked much debate [5,6].

Adequate water supply is a prerequisite for sustainable vegetation growth, and the interdependence between vegetation and water significantly impacts the exchange of water, carbon, and energy between the terrestrial and atmospheric systems [7–9]. The projected effects of global warming include increasingly severe water constraints on vegetation growth, attributable to heightened vapor pressure deficit and potential reductions in soil water content. Furthermore, satellite observations have detected a global greening trend, which indicates heightened water requirements for vegetation [10,11]. These constraints are particularly pronounced in water-limited regions, where water input relies heavily on precipitation and can significantly impact the efficacy of vegetation growth and restoration efforts [12–14].

Recent studies have predominantly concentrated on the correlation between vegetation and water, specifically examining the sensitivity of vegetation to water availability [15,16], the impacts of drought on the restoration of vegetation [17,18], and the resilience of vegetation in the face of drought [19,20], utilizing field experiments, remote sensing, and process-based models. Nevertheless, utilizing spatially explicit recognition of the vegetation-water relationship has yet to serve well for ecological restoration practice. Nonetheless, it can serve as a crucial point of reference for forest management, such as plant species selection, and facilitate informed decisions regarding the adaptability of vegetation to drought. To bolster ecologically significant restoration strategies, it is imperative to consider both rainfall use efficiency (RUE), defined as the ratio of vegetation productivity to rainfall input, and the sensitivity of vegetation to rainfall measured by sequential linear regression [14]. Furthermore, the extensively inconsistent change in vegetation greenness and productivity raises concerns about whether ecological restoration can improve ecosystem function to match the increase in vegetation greenness. Modis-based remote sensing data reveals that 45.6% of vegetated regions across the globe exhibited inconsistent trends in vegetation greenness and productivity [21], while the increase in the latter is lower than the rate of the former [22]. By increasing the amount of photosynthetically active radiation absorbed, vegetation greening can enhance productivity [8,23]. However, as reported in previous studies, this greening increase does not signify an improvement in ecosystem functioning, partly constrained by light-use and carbon-use efficiency or excessively dense leaf area [24,25]. As a result, targeted restoration and adaptation efforts need to involve vegetation greenness, vegetation productivity, and vegetation–water relation to guide sustainable restoration.

To combat extensive and dramatic land degradation, which has involved substantial economic costs, the Chinese government established several large-scale ecological projects [4,13,26]. Consequently, a noticeable greening trend was observed in the Yellow River Basin (YRB) [13,27,28]. It is a densely populated area with numerous ecological barriers and is also on the land route of the "One Belt One Road" initiative. The central government proposed to promote environmental protection and high-quality development of the YRB in 2019. It seeks to increase environmental protection and social advancement. However, scarce water resources and the fragile environment may compromise the government's greening strategy in the future [5]. Therefore, incorporating the understanding of vegetation-rainfall relationships into sustainable regional revegetation is imperative to comprehending the biophysical processes involved in the restoration and ensuring the longevity of ecological management [29,30].

To better understand the relationship between greening and stabilization in the YRB, this study analyzed the vegetation functioning and rainfall availability based on leaf area index (LAI), net primary production (NPP), and rainfall data between 2000–2018. The trend of NPP sensitivity to rainfall was assessed as well. The main aims of our study are: ① to detect the vegetation greenness and spatial productivity distribution in different parts of the YRB (upper, middle, and lower reaches); ② to compare the RUE in YRB upper, middle, and lower reaches; and ③ to identify the key areas for ecological restoration according to the trends of vegetation greenness and productivity and vegetation–rainfall relationship in the YRB.

2. Materials and methods

2.1. Study area

The Yellow River spans a total area of 7.95×10^5 km^2, flowing through nine provinces and regions, including Qinghai, Sichuan, Gansu, Ningxia Hui Autonomous Region, the Inner Mongolia Autonomous Region, Shaanxi, Shanxi, Henan, and Shandong. Kenli County of Shandong Province merges into the Bohai Sea (Fig. 1). The elevation is high in the west and low in the east. The Yellow River links the Qinghai–Tibet Plateau, the Loess Plateau, and the northern China plains. Water scarcity is vital in ecological security barriers, combating desertification and providing water supply. There is a continental climate in the area of the Yellow River. The region exhibits a semi-humid climate in the southeastern area, a semiarid climate in the central region, and an arid climate in the northwestern part [31]. As a result of the landforms and habitats of the YRB, a variety of plant species can flourish there. In the late 1990 s, the Chinese government carried out the "Grain for Green Program". 16 000 km^2 of rain-fed cropland were successfully converted to non-crop vegetation, resulting in a discernible trend of "greening" ([32,33], Fig. S1 in Appendix A). Over the past 20 years, toward restoring degraded landscapes, the "Grain for Green Program" implemented state-of-the-art management strategies and advanced technical innovations [34].

2.2. Datasets

LAI, NPP, rainfall, and administrative division data were used in this study. We used yearly NPP data between 2000 to 2018 obtained from the MOD17A3 product with a 1 km spatial resolution (unit: kg C·m^{-2}) from the Numerical Terra Dynamic Simulation Group (NTSG) and National Aeronautics and Space Administration (NASA), given data availability [35,36]. The MOD17 algorithm has been modified to correct the problem of cloud-contaminated MODIS LAI–fraction of photosynthetically active radiation inputs produced by the NTSG of University of Montana, USA. LAI data between 2000 to 2018 was obtained from the MOD15A2H V6 product (United States Geological Survey (USGS) Earth data[‡]) with a 500 m spatial resolution [37]. To mitigate the impact of atmospheric noise and cloud contamination, the LAI data was consolidated into yearly values using the maximum value composite technique [38]. The annual rainfall data between 2000 to 2018 from Climate Hazards Group Infrared Precipitation with Station data were resampled from the original resolution of 0.05 degrees to match the 1 km NPP data resolution [39].

[‡] https://lpdaac.usgs.gov/product_search/.

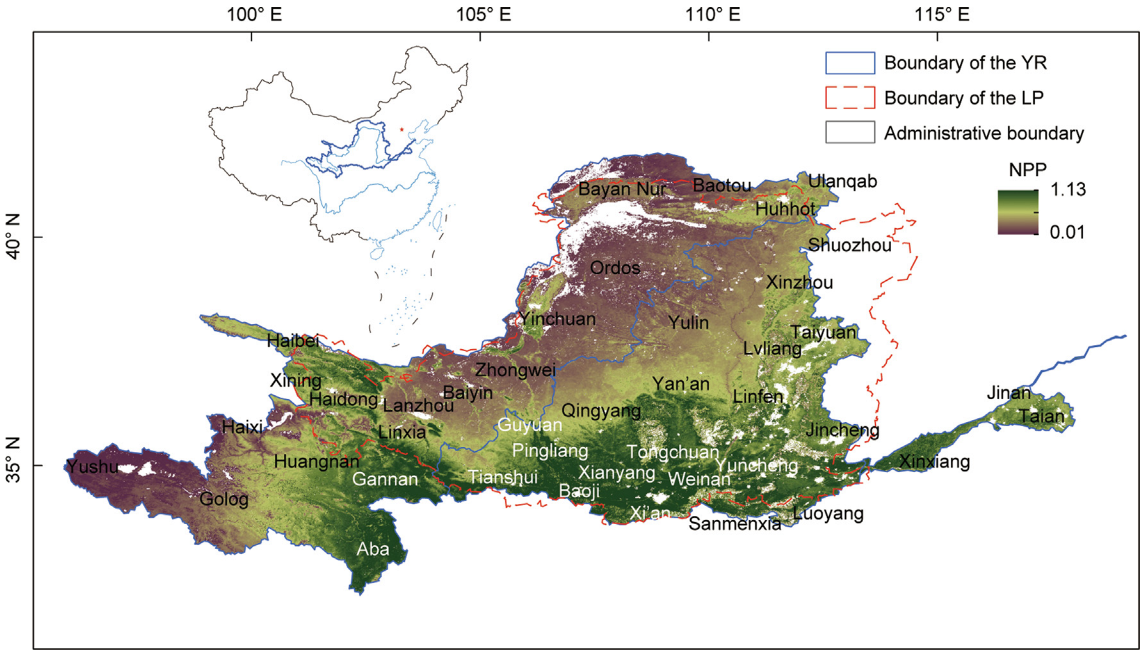

Fig. 1. Location of the YRB. YR: Yellow River; LP: Loess Plateau. The base map is NPP distribution (unit: kg C·m^{-2}).

2.3. RUE

The RUE is calculated by dividing NPP by rainfall as a proxy for the plant production response to rainfall (Eq. (1)).

$$\mathrm{RUE} = \frac{\mathrm{NPP}}{R} \tag{1}$$

where RUE (kg C·m^{-2}·mm^{-1}) denotes the rainfall use efficiency, and NPP and R are yearly data of NPP (kg C·m^{-2}) and rainfall (mm), respectively.

Rainfall is the primary climatic constraint on vegetation growth in arid and semiarid regions. Therefore, RUE can reflect ecosystem changes by describing the ecosystem-specific relationship between NPP and rainfall. Thus, RUE has been frequently used to evaluate ecosystem function and land degradation [40–42].

2.4. Sensitivity of NPP to rainfall

We described the vegetation–rainfall relation (the sensitivity of NPP to rainfall) by using a sequential regression method between rainfall and vegetation productivity (using NPP as a proxy) within a spatial–temporal window (Fig. 2) [14,43]. According to Ref. [43], the optimal moving window size is 7 × 7 pixels, and the optimal time step is four years (Fig. 2(b)). NPP and rainfall were regressed linearly for all pixels in the moving window (7 × 7) and over the selected period (four years) (Fig. 2(c)). In order to determine the sensitivity of the NPP to rainfall, the regression slope was applied to the moving window's center pixel (Fig. 2(d)). Thus, we can obtain the annual sensitivity of NPP to rainfall for each pixel (Fig. 2(e)). When more than two-thirds of the pixels had no data, the regression was not fitting, and the regression slope was not assigned to the center pixel. We were able to identify the pixel scale sensitivity of the whole study region as the window moved. NPP is highly sensitive to rainfall in the center pixel if the regression slope has a high absolute value. Normally, slopes greater than zero indicate positive and negative sensitivity if the slope is lower than zero. A positive sensitivity indicates that NPP will change direction with rainfall and vice versa. Alterations in the NPP–rainfall relationship may be indicated by changes in vegetation biophysical processes and ecosystem function concerning water availability [43].

2.5. Statistical analysis

Vegetation greenness was measured using LAI, and NPP was used to measure vegetation productivity. Some derivative indexes were applied based on vegetation indexes: RUE and sensitivity of NPP to rainfall. Those two derivative indexes' significantly positive/negative trends can be interpreted as an increase or decrease in unit productivity per unit rainfall, indicative of vegetation functioning changes. In order to simulate the trend of each pixel in these four indicators, linear regression analysis was used based on least-squares methods. Significant trends were considered at a $p < 0.05$. Vegetation indicators' trends were categorized into three groups according to significance level: significantly increased (+), significantly decreased (−), or no significant change (0). This procedure defined a significant trend as a significant pattern of vegetation characteristics (e.g., greenness, productivity, or efficiency) in any index (e.g., LAI, NPP, and RUE). Following the rules outlined above, the trend consistency was judged based on the three vegetation characteristics for each pixel. An ideal state would be one where LAI, NPP, and RUE all show a significantly positive trend, illustrating that the greenness, vegetation productivity, and RUE of regional vegetation are improving. A significant trend of sensitivity of NPP to rainfall is an auxiliary indicator. Changes in vegetation water usage and functioning, as illustrated by the sensitivity of NPP to rainfall, may indicate the changing sensitivity (that is, reduced or increased vegetation resistance) of vegetation to environmental stressors [44]. This section's state definition and consistency are described by Ref. [21].

3. Results

3.1. Spatial variation of vegetation greenness and productivity

Fig. 3 shows a combination of changes in the LAI and NPP of the YRB. Based on satellite data, the "greening" percentage in the YRB showed a significant increase since 2000. 34.53% of the YRB

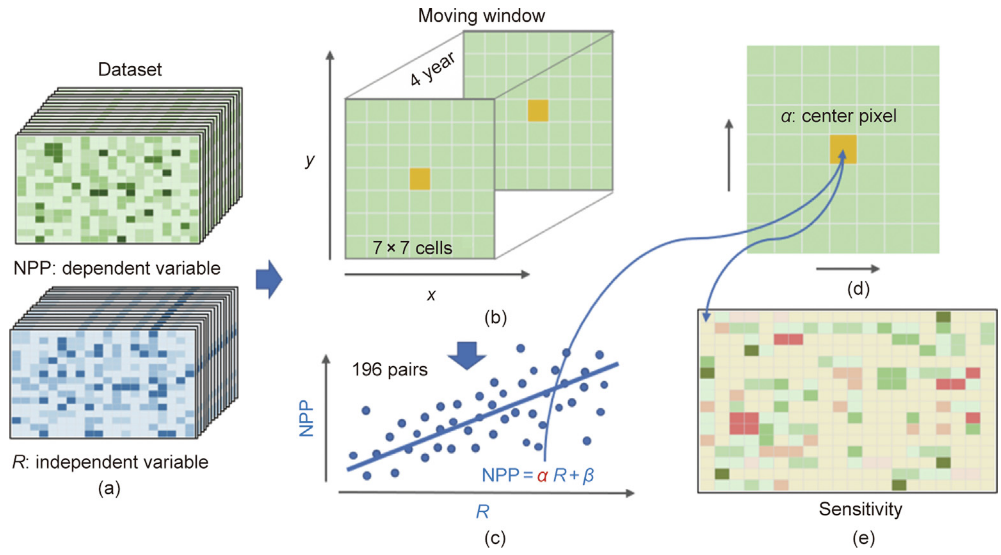

Fig. 2. Flow chart of the calculation of the sensitivity of NPP to rainfall. (a) input data for the method. (b) the size of the moving window. (c–d) show the method for calculating the sensitivity of NPP to rainfall based on moving window and linear regression. α is the regression slope between NPP and rainfall datasets, and β is regression intercept. (e) the annual sensitivity of NPP to rainfall for each pixel is determined by moving window.

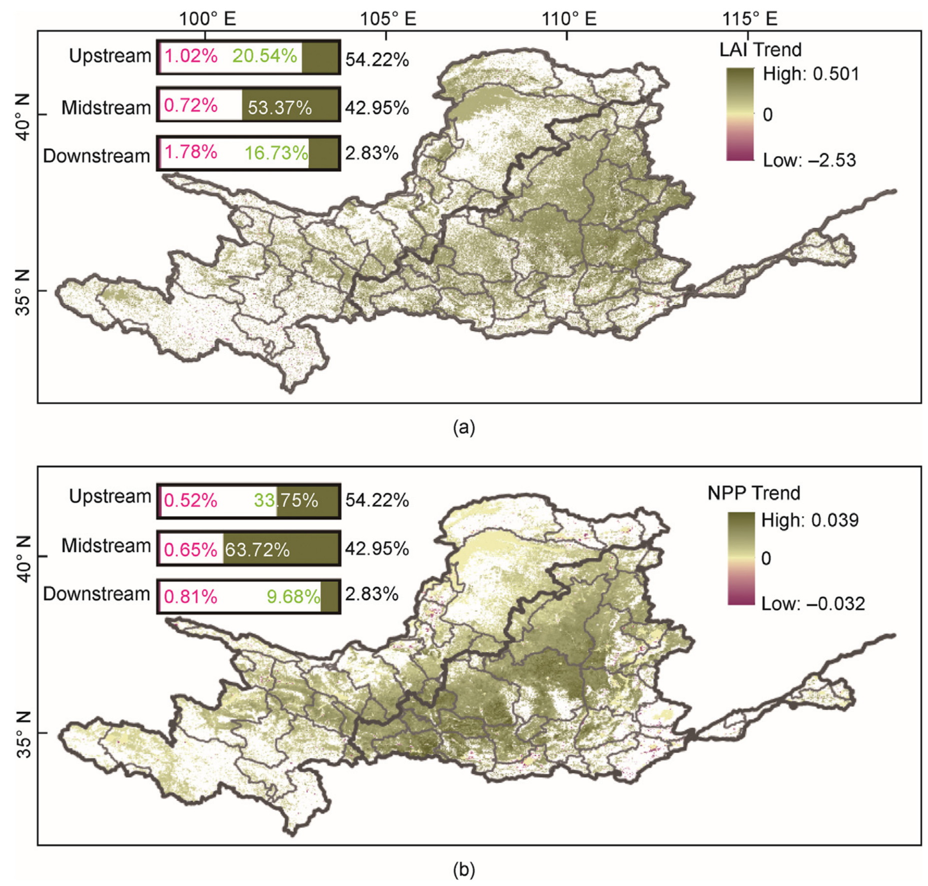

Fig. 3. Significant positive and negative trends in (a) LAI and (b) NPP (unit: kg C·m^{-2}) across the YRB and their distribution per the river basin in percentage. The proportion (%) of significantly positive (indicated in the color green) and significantly negative trends (purple) of vegetation greenness (i.e., LAI) and vegetation productivity (i.e., NPP) in the upper, middle, and lower reaches of the YRB is summarized. The percentage on the right of the bars shows the area proportion (%) of the upper, middle, and lower reaches of the YRB.

exhibited significant greening. Our analysis revealed that approximately 20.54% of the upper reaches of the YRB showed a significant positive trend, 53.37% and 16.73% in the middle and lower reaches of the YRB, respectively. The middle reaches of the YRB, which accounted for 42.95% of the whole YRB, including northern Shaanxi and east of Ordos in Inner Mongolia, showed a significant greening trend. Meanwhile, the variation trend of NPP in the upper, middle, and lower reaches of the YRB is consistent with LAI. In particularly, our results detected that nearly 65% of middle reaches show significant trends in NPP since 2000. This translates into 63.72% positive and 0.65% negative trends. It is important to note that the significant increase in the proportion of NPP in the upstream (33.75%) and middle reaches (63.72%) is higher than that of LAI (20.54% and 53.37%, respectively) but lower than that of LAI in the downstream (9.68% vs 16.73%).

3.2. RUE trend

Fig. 4 shows the trends of rainfall and RUE across the YRB. Except for a few areas, such as the upper reaches, western Ordos and northern Lanzhou, the majority of the YRB shows an increasing trend in rainfall (Fig. 4(a)). On average, the rainfall trend in the upper, middle, and lower reaches of the YRB is 2.38 $\mathrm{mm \cdot a^{-1}}$, 4.60 $\mathrm{mm \cdot a^{-1}}$, and 0.31 $\mathrm{mm \cdot a^{-1}}$, respectively. Our results also found that about 16% of middle reaches exhibit significant trends, translating into 15.09% positive and 1.29% negative trends. Compared with the middle reaches of the YRB, a smaller area of significant upstream and downstream changes was observed. For example, in the YRB's lower reaches, only about 2% exhibit significant trends, translating into 1.21% positive and 0.70% negative trends. In the upper reaches of YRB, approximately 12% exhibit significant trends, translating into 9.98% positive and 2.57% negative trends. Significant variations in the distribution and direction of trends were evident in the upper, middle, and lower reaches, with the midstream showing the largest positive trends (15.09%), followed by the upstream (9.98%) and downstream (1.21%). On the other hand, a greater fraction of negative trends was found in the northwest Sichuan Province of the upper reaches (Fig. 4(b-i)), followed by western Inner Mongolia (Fig. 4(b-ii)) and parts of Shanxi Province (Fig. 4(b-iii)) of the middle reaches of the YRB.

3.3. Upper–middle–lower reaches differences in vegetation–rainfall sensitivity

We observed an important upper–middle–lower difference in the distribution and direction of trends of vegetation–rainfall sensitivity (Fig. 5). Our results showed that in YRB's upper reaches, 19.66% show significant trends in vegetation–rainfall sensitivity, 16.90% of the trends are positive, and 2.76% are negative, while in the lower reaches of the YRB, only 4.98% show significant negative trends. However, our results show that the trends in vegetation–rainfall sensitivity of the middle reaches differ from those of the upstream and downstream. 16.86% of the middle reaches of the YRB show significant trends in vegetation–rainfall sensitivity, translating into 14.08% negative and 2.78% positive trends. In particular, the significant negative trends in the upper and lower reaches of the YRB were lower than in the middle reaches. Specifically, negative trends in vegetation–rainfall sensitivity of the upper reaches were mainly in the west of Qinghai Lake (Fig. 5(i)). In contrast, the middle reaches are mainly concentrated in northern Inner Mongolia (Fig. 5(ii)) and southeastern Shanxi, including Taiyuan, Linfen, and Yuncheng Cities (Figs. 5(iii)–(v)).

3.4. Key area identification in the combined vegetation–rainfall relationship

Comparing the changing directions of vegetation greenness, productivity, and RUE, we found pronounced regional differences in the distribution and direction across the YRB (Fig. 6). The areas with a consistently significant increase in vegetation greenness, productivity, and RUE accounted for 8.41% of the YRB, mainly distributed in the north of Yan'an and the south of Yulin City, Shaanxi Province of the middle reaches of YBR (Figs. 6(a-vii) and (a-viii)). Furthermore, the areas with increased greenness and productivity but unchanged RUE accounted for 16.55% of the YRB and were mainly concentrated in the eastern Gansu Province (Pingliang and Qingyang Cities, respectively) and southern Ningxia Hui Autonomous Region. Moreover, areas with an increase in vegetation greenness and no changes in productivity or RUE accounted for 9.23% of the YRB, indicating enhanced vegetation growth. Within the YRB's middle reaches, these areas were widely distributed, especially in the northwest of Shaanxi Province, and also located near areas with enhanced greenness and NPP. However, about 2.26% of the YRB consistently decreased in these three indicators. Such regions are mainly distributed in the northern Inner Mongolia and northern Ningxia Hui Autonomous Region (Figs. 6(a-i)–(a-iii)), the northwest Sichuan Province of the upper reaches and the Henan section in the YRB's lower reaches (Figs. 6(a-v) and (a-viii)). Overall, the regions exhibiting variations in vegetation greenness and productivity were predominantly located in the middle reaches of the YRB and were of considerable magnitude.

4. Discussion

4.1. Ecological engineering drives vegetation greenness and productivity improvement

Vegetation restoration is a critical and effective solution to prevent soil erosion and promote ecological management. As a pilot region, several large-scale and ambitious ecological restoration programs, including the "Grain for Green Project", "Natural Forest Land Resource Conservation Project", and "Three-North Shelterbelt Project", have been carried out in the YRB since 1998 to attain the target of conserving and expanding forests and mitigating soil erosion. Consequently, a greening trend has been widely detected, and human-induced ecosystem degradation has been greatly reduced [13,45,46]. Our study also generally showed a significant increasing trend of LAI and NPP in each reach of the YRB since 2000 (Fig. 3). This was consistent with that of Ref. [46], who reported a policy-driven massive greening in the Loess Plateau of China. The statistical book revealed that in Shanxi, Shaanxi, and Ningxia, a total area of $47.93 \times 10^3\ \mathrm{km}^2$ underwent afforestation [47,48]. Undoubtedly, ecological restoration has played a notable role in greening vegetation in the middle reaches of the YRB.

Furthermore, our findings indicate that the increase in the proportion of NPP was significantly greater than that of LAI in the upper and middle reaches of the YRB (Fig. 3), and Fig. 6 also shows inconsistent changes in LAI and NPP. The structure and function of an ecosystem will be directly affected when vegetation grows inconsistently in terms of greenness and productivity. By increasing vegetation leaf area, chlorophyll and photosynthetically active radiation are absorbed more efficiently, thus increasing vegetative productivity and respiration [23]. Nevertheless, photosynthesis slows down when vegetation leaves reach a specific area due to self-shadowing and nutrient limitation [24]. Differences in the driving factors for LAI and NPP are a possible explanation. LAI changes were primarily influenced by CO_2 fertilization, and climate change contributed less (8%), while the latter can explain 28.6% of productivity changes [8,49]. Previous research has reported a parabolic relationship between NPP and LAI in humid areas and the decoupling of greenness and productivity as aridity decreases [50,51]. It is related to the tradeoffs between ecosystem structure and physiology becoming stronger in more humid climates [50]. This decoupling of greenness–productivity may be further caused by environmental variables (e.g., solar radiation, water availability, and temperature) affecting light use efficiency [25,52]. Besides, evenness is regarded as a key factor mediating the relationship between forest productivity and richness [53]. In ecological

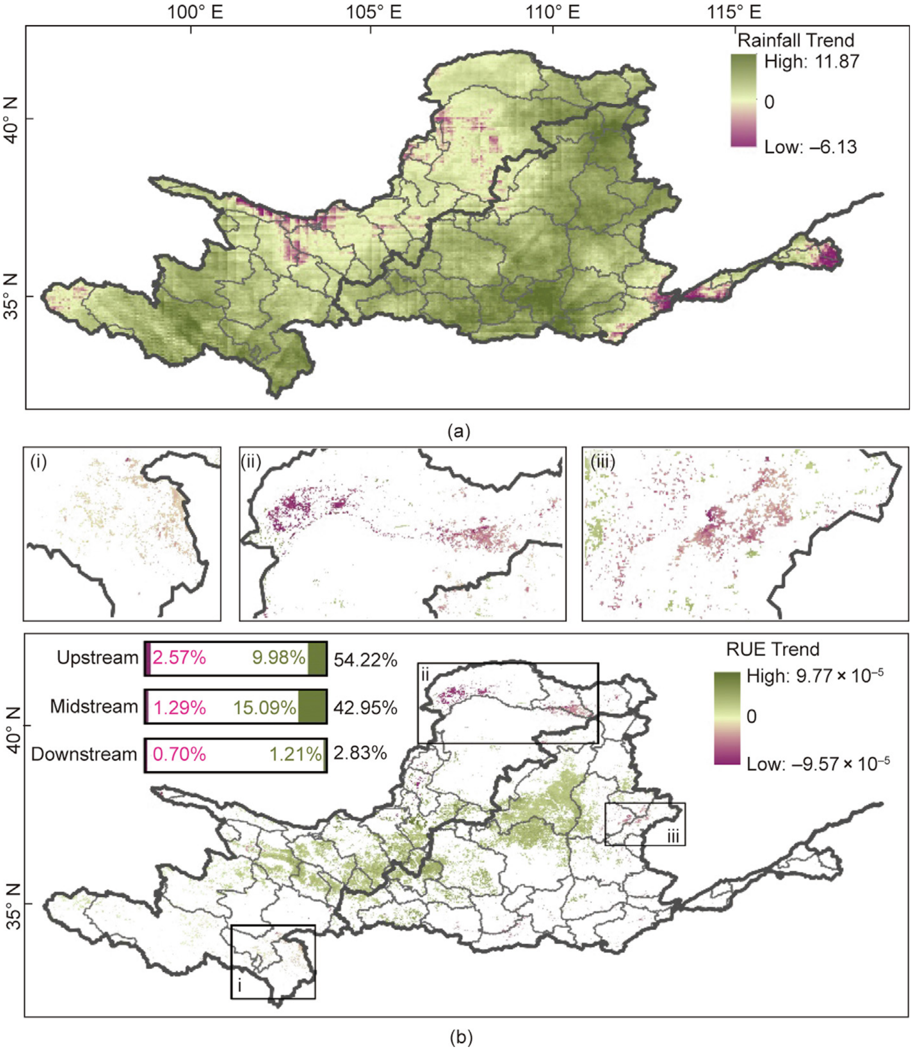

Fig. 4. Trends in rainfall and significant trends in RUE across the YRB. (a) is presented in the rain data's original resolution (0.05 degree). The proportion (%) of significantly positive (green) and significantly negative trends (purple) of RUE in the upper, middle, and lower reaches of the YRB was summarized. (b) The proportion of significant positive and negative RUE per the YRB is summarized in percentage. (i–iii) Typical areas of negative trends of RUE. The percentage on the right of the bars shows the area proportion (%) of the upper, middle, and lower reaches of the YRB.

restoration, a single tree species is often selected and planted uniformly, which limits community productivity. This conclusion also aligns with the differences between LAI and NPP of the YRB. On the other hand, despite plantations such as timber stands and tree crops increasing the vegetation greenness rapidly, the inconsistency also depends on the timeframe. For instance, many apple orchards are on the Loess Plateau, and aggressive expansion is planned. The fruits accounted for a certain percentage of apple trees and showed large seasonal variations.

Overall, the ecological restoration efforts have resulted in a notable augmentation of vegetation greenness and productivity in the YRB, with the middle reach exhibiting the most significant improvements. From 2000 onwards, the carbon sequestration potential in the Loess Plateau has increased by approximately one-third [48]. The vegetation restoration reduced soil erosion and sediment flow into the Yellow River, accounting for 57% of the total sediment reduction [54]. In addition to ecological benefits, ecological restoration promoted social benefits, including the advancement of agricultural transformation and the indirect promotion of emerging industries (e.g., ecotourism and folk tourism), as previous studies reported [48,55]. Increased farmer income resulted from implementing policies supporting ecological restoration, ecological compensation, and food subsidies [56]. According to the United Nations Sustainable Development Goals (SDGs) framework, ecological restoration in the YRB will promote multiple SDGs, including SDG1 (no poverty), SDG6 (clean water and sanitation), SDG13 (climate action), and SDG15 (life on land), through ecological restoration efforts in the YRB.

4.2. Inconsistent trends between vegetation–rainfall sensitivity and other vegetation indicators

The changes in greenness, productivity, RUE, and sensitivity showed the diversity of vegetation growth dynamics (Figs. 4 and 5). Numerous studies showed that massive greening drives the growth of water use efficiency or RUE, especially in the middle reach of the YRB. A significantly positive trend of RUE was generally found in regions of eastern Gansu and northwestern Shaanxi, respectively, where many plantations have been developed [57,58]. Sustained vegetation greening further enhances vegetation productivity, accelerating the process of vegetation photosynthesis to a large extent and triggering an essential response in the ecosystem through long-term greening, which means that the total transpiration and evaporation in land vegetation correspondingly increased to a certain degree [59]. The observed trends may be attributed to the implementation of extensive ecological

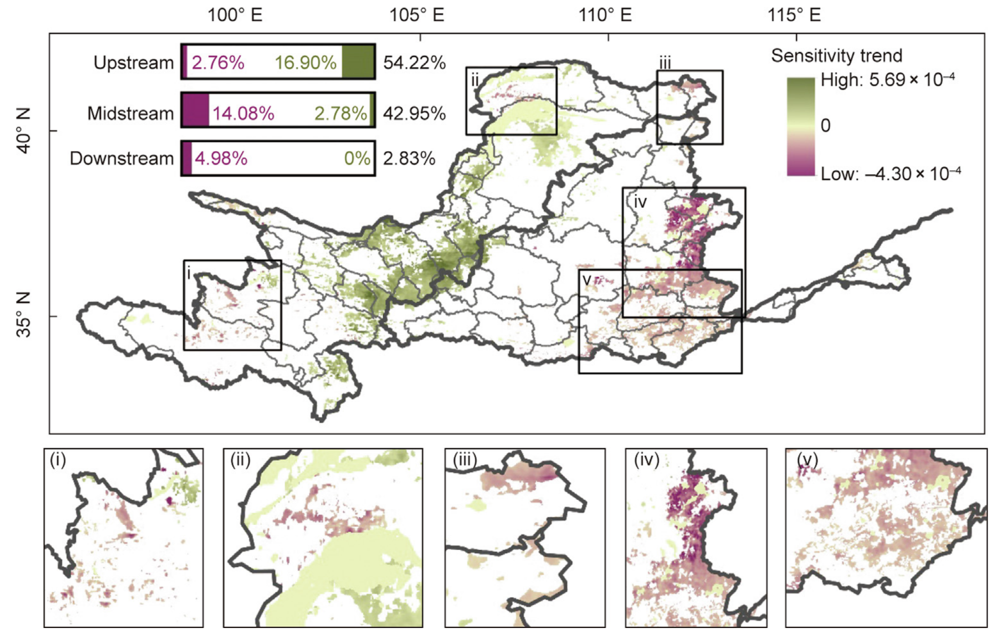

Fig. 5. Trends in vegetation–rainfall sensitivity across the YRB and their distribution per the basin in percentage. (i–v) are typical areas of a negative trend. The proportion (%) of significantly positive (green) and significantly negative trends (purple) of vegetation–rainfall sensitivity in the upper, middle, and lower reaches of the YRB is summarized. The percentage on the right of the bars shows the area proportion (%) of the upper, middle, and lower reaches of the YRB.

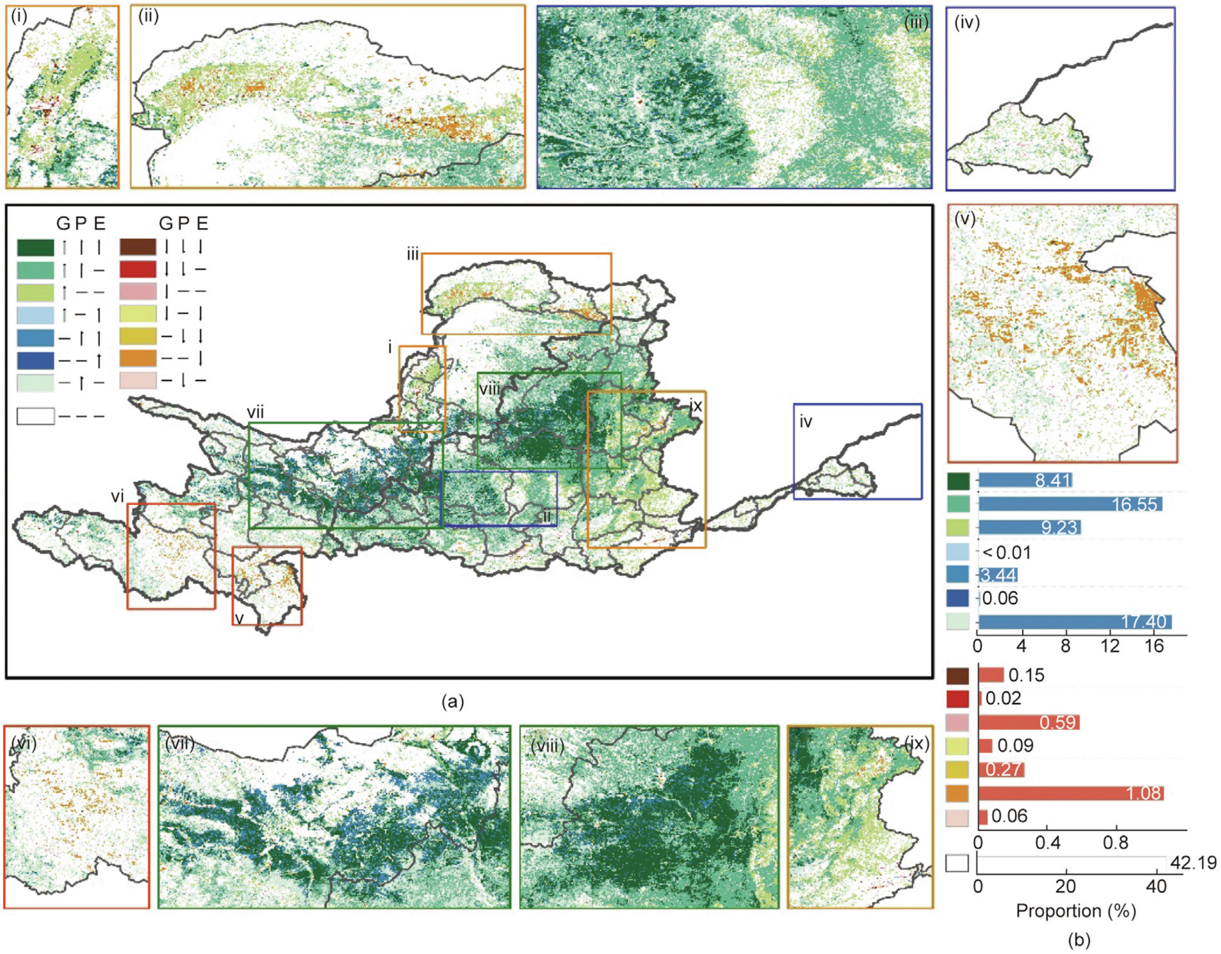

Fig. 6. (a) Combinations of trends in greenness (G), productivity (P), and RUE (E) across the YRB. The dash (–) means a non-significant change, while ↑ and ↓ indicate a significant increasing or decreasing trend. (i–ix) Representative regions with consistent increases or decreases are highlighted with rectangles in the YRB. (b) The area proportion with significant change trends, and the associate legend is shown in the top left of (a).

engineering practices, which have developed more productive systems. A notable illustration of this phenomenon is the expansion of Shaanxi Province's green map by 400 km towards the north. The regional ecological environment has changed from "overall deterioration and local improvement" to "overall improvement and local virtuous circle". On the other hand, our analysis found that the proportion of a significant increase in RUE (11.93%) is smaller than that of NPP (45.94%) and LAI (34.53%) (Figs. 3 and 4). In particularly, more than a quarter of pixels showed vegetation greenness significantly increased, and yet RUE did not increase (Fig. 6), suggesting that greening did not mean increased RUE.

Moreover, significant positive and negative trends were observed in vegetation–rainfall sensitivity across the YRB. Generally, the vegetation is becoming more responsive to rainfall over time due to positive trends. Negative trends indicate less-responsive vegetation and lower productivity per available unit of rainfall, demonstrating a shift towards vegetation that may be hindered in its functioning. As the primary driver for vegetation productivity, rainfall is the main water source for restoration. Our results further revealed that the greening of vegetation in the YRB's middle reaches is the most obvious. In contrast, the proportion of a significant decrease in sensitivity is higher than that of a significant increase, indicating that vegetation has a weak response to rainfall. The vegetation productivity per rainfall unit is low, meaning vegetation with lower RUE is concentrated. One possible explanation is that the rainfall input is sufficient for potential carbon sequestration in parts of the middle reaches of the YRB but still in great deficit. On the other hand, under equivalent precipitation, the sensitivity trend is spatially divergent between natural and artificial forests. Our results found that the areas with a significant negative trend of vegetation–rainfall sensitivity in the middle reaches of the Yellow River are mainly in the middle reach of Taihang and Lvliang Mountains of Shanxi, where an area of large-scale plantation construction with higher rainfall is located, indicating that this region is also the main one of vegetation with lower RUE distribution. Previous studies reported a positive trend in vegetation–rainfall sensitivity can be observed with a change in ecosystem composition [43], especially replacing large woody plants with shrubs. However, an open question is whether such a positive change would also result in sustainable environmental improvements, benefiting the ecosystem and people's livelihood. By studying the changing trend of sensitivity, we can also provide new thoughts on the transformation of inefficient forests and the optimization of landscape patterns for future vegetation restoration strategies, especially from the perspective of sustainable utilization of water resources, previous study also expressed the concern that the water constraint of ecological restoration in the Loess Plateau might reach the threshold [5].

4.3. Ecological restoration based on the vegetation–rainfall relationship

In practice, the relationship among LAI, NPP, and RUE provides an intuitive map for decision-making and ecological restoration planning for a high-quality development strategy of the YRB. Based on the changes in RUE trends, we can identify the key restoration areas under the background of high-quality development in the YRB. A reinterpretation of these three indicators can also help identify appropriate conservation strategies for given locations in the context of climate change. Conservation strategies may arise from an LAI perspective (monitoring and identifying present greening), an NPP perspective (impacts and improving lower productivity plantations), and/or an RUE perspective (enhancing ecosystems' capacity to recover from rainfall change). In regions with a consistent increase in LAI, NPP, and RUE, which account for 8.41% of the YRB, there is no need for additional adaptation measures or maintenance of the current status. This trend indicates a positive sign of ecological restoration in terms of habitat quality, carbon sequestration, and vegetation stability. However, nearly all significantly decreasing trends of LAI, NPP, and/or RUE mainly occurred in regions with rapid urbanization, such as Xi'an City, Xining City, and Yinchuan City. Consequently, balancing the tradeoffs between urbanization and ecosystem protection is necessary in areas where RUE and sensitivity showed a significant decreasing trend, for example, in the middle reaches of the Taihang and Lvliang Mountains of Shanxi Province. However, the rainfall is relatively stable, and inefficient forests (where vegetation utilization efficiency of rainfall is low) were widely distributed (Fig. 6(a-i)). Management practices should prioritize strengthening the forest quality and ecosystem service function, planting trees with particularly traits, and adapting to the land and trees to improve low-efficiency forests. Considering future climate change scenarios, transforming inefficient forests in the YRB, especially in the YRB's middle reaches, is still necessary.

Our findings have important implications for vegetation protection and ecological restoration in arid and semiarid ecosystems. High-quality development of the YRB is the current national strategy. Under the current vegetation greenness, productivity, and RUE, we distinguished the corresponding water conservation areas, key soil and water conservation areas, and biodiversity conservation areas in the upper, middle, and lower reaches of the YRB, respectively. Four highlighted recommendations, which may benefit vegetation restoration in practice, are stressed here (Fig. 7). First, based on our results, we recommend that areas with increased greenness and RUE maintain the current conditions. Special attention, therefore, should be paid to natural restoration planning and management strategies. For areas with declining RUE, valid measures should be taken to improve the forests with lower RUE, especially in the face of accelerated climate change. Furthermore, in areas where the greenness decreased but the RUE was maintained, suitable vegetation types should be carefully selected and planted according to sloping conditions for ecological restoration. Moreover, greater attention should be paid to weighing livelihood and eco-environmental improvement in areas where greenness and RUE are declining. Finally, continuous *in-situ* monitoring should be carried out for the areas where RUE and greenness are not changing significantly.

Satellite observations are becoming increasingly crucial for detecting vegetation changes, and uncertainty about regional ecosystem change might be exacerbated if studies rely on single indices to explore driving mechanisms. In summary, our study demonstrated that considering the trends of LAI, NPP, and RUE can be used to identify the regions that meet the requirements for ecological protection and high-quality development of the YRB. Based on the three indicators mapped in this study, it is possible to identify more appropriate adaptive conservation strategies to restore the YRB to its ecological health. It has been demonstrated that satellite-based data and statistical methods can be used to inform conservation planning and restoration prioritization based on vegetation–rainfall relationships at the YRB. Nevertheless, it should be noted that sensitivity assessments solely capture the vegetation's temporary reaction to climate disturbances within brief timeframes and are inadequate for representing the long-term ecosystem attributes in the future.

Our study identifies the biophysical constraints of ecological restoration based on the vegetation–water relationship, while practical restoration necessitates broadening the focus beyond the biophysical to economic constraints [60,61]. More than 45 billion CNY had been invested in the "Grain for Green program" in the Shanxi Province, Shaanxi Province, and Ningxia Hui Autonomous Region by 2014 [48]. In addition, several other restoration programs, such as the "Natural Forest Land Resource Conservation

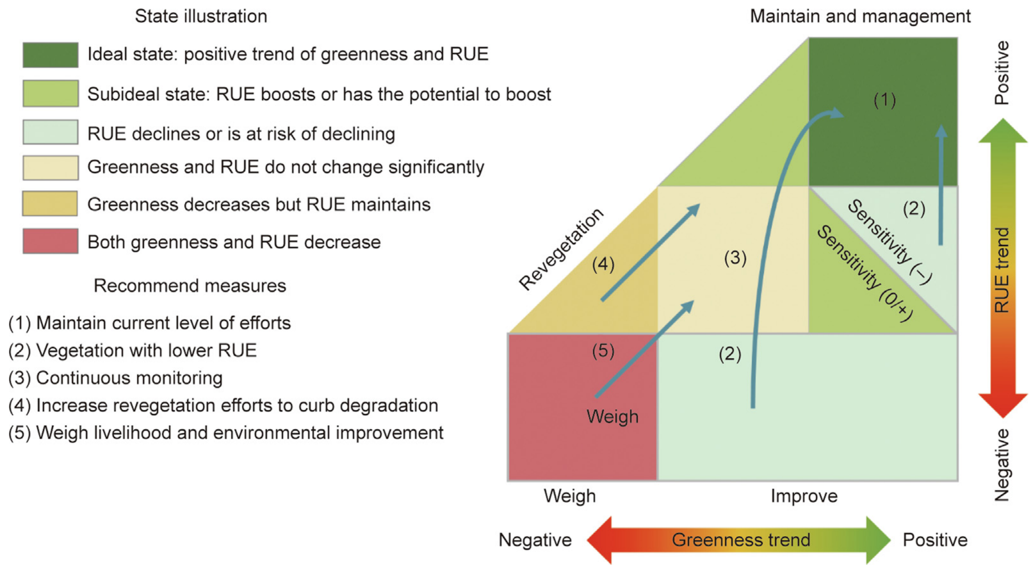

Fig. 7. A framework for ecological restoration based on the greenness, RUE, and sensitivity trends perspective.

Project" and "Three-North Shelterbelt Project" in the YRB, also involve huge amounts of economic investment [4]. These investments have also led to a large increase in gross ecosystem product and indirect social benefits [4,48]. Also, according to the experience gained from the African Great Green Wall, every USD invested in land restoration generates yields ranging from 1.1 to 4.4 USD across different scenarios. This is an optimistic sign, while it also relies on a well-developed carbon market to ensure sustainable restoration investments [62]. Although our study does not consider economic constraints, the biophysical constraints based on the vegetation–water relationship can clarify which areas of vegetation with lower RUE need to be further optimized and which areas need to be monitored more intensively. This could provide a significant reference for more economical ecological restoration practices.

4.4. Contributions, limitations, and uncertainties

This study used two indicators depicting the vegetation–water relationship, RUE and sensitivity of vegetation to rainfall, combined with LAI and NPP as the proxy of vegetation greenness and productivity to spatially explicitly guide ecological restoration. The present study underscores the significance of examining the correlation between vegetation and precipitation within the context of the high-quality development strategy of the YRB. The outcomes of our analysis and the proposed ecological restoration framework can provide decision-makers with valuable insights for executing rational basin pattern optimization and sustainable management. Our analytical framework is transferable to other regions that have implemented or plan to implement large-scale ecological restoration programs worldwide.

However, there were still some limitations. On the one hand, the mechanisms of the inconsistencies among LAI, NPP, and RUE need to be further monitored or detected, particularly for the disparities among different vegetation types, and supported by field monitoring. On the other hand, the influences of social and economic factors (e.g., population pressure or urbanization development) on the vegetation–rainfall sensitivity need to be considered. Although positive trends have been observed, specific ecosystem properties, such as biodiversity loss or impact on groundwater, have not been considered. Moreover, our proposed restoration strategy is based on the relationship between vegetation and rainfall but needs to consider the needs of agricultural and domestic water. Regarding the datasets used in this research, the LAI datasets' resolution differs from that of the NPP datasets, which may lead to some uncertainties. Previous studies have identified these problems and limitations [63]. Consequently, detailed studies of the driving factors need to be conducted to fully understand the mechanisms behind the inconsistencies in vegetation growth to provide references for the ecological protection and high-quality development of the YRB.

5. Conclusions

Given the constraints of water availability on ecosystem functioning in water-limited ecosystems, restoration planning should consider the long-term functional response of vegetation productivity to rainfall. Extensive ecological initiatives (e.g., afforestation) facilitated the substantial proliferation of greenery and enhanced vegetation productivity in most of the YRB, particularly in its middle reaches. However, the proportion of significant positive trends of RUE is far lower, suggesting that massive greening did not equal an overall increase in RUE. Furthermore, a large negative trend in vegetation–rainfall sensitivity was observed, particularly in northern Inner Mongolia and southeastern Shanxi, pointing towards less vegetation productivity per available unit of rainfall. This indicates the possible presence of inefficient forests and functional degradation risks for the ecosystem, highlighting the urgency of strengthening forest management and incorporating vegetation–water relations into conservation/restoration planning. In combination with the above indicators, an intuitive map for vegetation restoration planning and decision-making for the high-quality development strategy of the YRB was provided. Management priorities should be given to the middle reaches of the Taihang and Lvliang Mountains of Shanxi and optimizing the inefficient forests for the observed negative trends of RUE and vegetation–rainfall sensitivity. This study provides comprehensive insights for understanding structural and functional vegetation changes and their functional response to rainfall, which is helpful for optimizing ecological restoration in conditions of limited water availability.

Acknowledgments

This study was supported by the Fundamental Research Funds for the Central Universities (QNTD202303), the National Natural Science Foundation of China (42177310, 42377331), and the National Key Research and Development Program (2022YFF1300803). Yang Yu received the Outstanding Chinese and Foreign Youth Exchange Program supported by China Association for Science and Technology (2020–2022).

Compliance with ethics guidelines

Yang Yu, Ting Hua, Liding Chen, Zhiqiang Zhang, and Paulo Pereira declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2023.07.012.

References

[1] IPBES. The assessment report on land degradation and restoration. Report. Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES); 2018.
[2] Strassburg BBN, Iribarrem A, Beyer HL, Cordeiro CL, Crouzeilles R, Jakovac CC, et al. Global priority areas for ecosystem restoration. Nature 2020;586(7831):724–9.
[3] Sasmito SD, Basyuni M, Kridalaksana A, Saragi-Sasmito MF, Lovelock CE, Murdiyarso D. Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. Nat Ecol Evol 2023;7(1):62–70.
[4] Bryan BA, Gao L, Ye Y, Sun X, Connor JD, Crossman ND, et al. China's response to a national land-system sustainability emergency. Nature 2018;559(7713):193–204.
[5] Feng X, Fu B, Piao S, Wang S, Ciais P, Zeng Z, et al. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat Clim Chang 2016;6(11):1019–22.
[6] Wang X, Ge Q, Geng X, Wang Z, Gao L, Bryan BA, et al. Unintended consequences of combating desertification in China. Nat Commun 2023;14(1):1139.
[7] Novick KA, Ficklin D, Stoy P, Williams C, Bohrer G, Oishi A, et al. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. Nat Clim Chang 2016;6(11):1023–7.
[8] Huang K, Xia J, Wang Y, Ahlström A, Chen J, Cook RB, et al. Enhanced peak growth of global vegetation and its key mechanisms. Nat Ecol Evol 2018;2(12):1897–905.
[9] Jiao W, Wang L, Smithm WK, Chang Q, Wang H, D'Odorica P. Observed increasing water constraint on vegetation growth over the last three decades. Nat Commun 2021;12:3777.
[10] Huang J, Yu H, Guan X, Wang G, Guo R. Accelerated dryland expansion under climate change. Nat Clim Chang 2016;6(2):166–71.
[11] Yuan W, Zheng Y, Piao S, Ciais P, Lombardozzi D, Wang Y, et al. Increased atmospheric vapor pressure deficit reduces global vegetation growth. Sci Adv 2019;5(8):eaax1396.
[12] Zhu Z, Piao S, Myneni RB, Huang M, Zeng Z, Canadell JG, et al. Greening of the Earth and its drivers. Nat Clim Chang 2016;6(8):791–5.
[13] Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi RK, et al. China and India lead in greening of the world through land-use management. Nat Sustain 2019;2(2):122–9.
[14] Abel C, Horion S, Tagesson T, De Keersmaecker W, Seddon AWR, Abdi AM, et al. The human–environment nexus and vegetation–rainfall sensitivity in tropical drylands. Nat Sustain 2021;4(1):25–32.
[15] Li W, Migliavacca M, Forkel M, Denissen JMC, Reichstein M, Yang H, et al. Widespread increasing vegetation sensitivity to soil moisture. Nat Commun 2022;13(1):3959.
[16] Zhang Y, Gentine P, Luo X, Lian X, Liu Y, Zhou S, et al. Increasing sensitivity of dryland vegetation greenness to precipitation due to rising atmospheric CO_2. Nat Commun 2022;13(1):4875.
[17] Konings AG, Saatchi SS, Frankenberg C, Keller M, Leshyk V, Anderegg WRL, et al. Detecting forest response to droughts with global observations of vegetation water content. Glob Chang Biol 2021;27(23):6005–24.
[18] Dong B, Yu Y, Pereira P. Non-growing season drought legacy effects on vegetation growth in southwestern China. The Science of the Total Environment 2022;846:157334.
[19] Anderegg WRL, Konings AG, Trugman AT, Yu K, Bowling DR, Gabbitas R, et al. Hydraulic diversity of forests regulates ecosystem resilience during drought. Nature 2018;561(7724):538–41.
[20] Yao Y, Liu Y, Zhou S, Song J, Fu B. Soil moisture determines the recovery time of ecosystems from drought. Global Chang Biol 2023;29(13):3562–74.
[21] Ding Z, Peng J, Qiu S, Zhao Y. Nearly half of global vegetated area experienced inconsistent vegetation growth in terms of greenness, cover, and productivity. Earth's Futur 2020;8(10):1–15.
[22] Zhang Y, Song C, Band L, Sun G. No proportional increase of terrestrial gross carbon sequestration from the greening Earth. Journal of Geophysical Research – Biogeosciences 2019;124(8):2540–53.
[23] Piao S, Wang X, Park T, Chen C, Lian X, He Y, et al. Characteristics, drivers and feedbacks of global greening. Nat Rev Earth Environ 2020;1(1):14–27.
[24] Street LE, Shaver GR, Williams M, Van Wijk MT. What is the relationship between changes in canopy leaf area and changes in photosynthetic CO_2 flux in arctic ecosystems? J Ecol 2007;95(1):139–50.
[25] Walther S, Guanter L, Heim B, Jung M, Duveiller G, Wolanin A, et al. Assessing the dynamics of vegetation productivity in circumpolar regions with different satellite indicators of greenness and photosynthesis. Biogeosciences Discuss 2018;15(20):6221–56.
[26] Lü Y, Fu B, Feng X, Zeng Y, Liu Y, Chang R, et al. A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. PLoS One1 2012;7(2):e31782.
[27] Tian F, Liu L, Yang J, Wu J. Vegetation greening in more than 94% of the Yellow River Basin (YRB) region in China during the 21st century caused jointly by warming and anthropogenic activities. Ecol Ind 2021;125:107479.
[28] Zhang W, Wang L, Xiang F, Qin W, Jiang W. Vegetation dynamics and the relations with climate change at multiple time scales in the Yangtze River and Yellow River Basin, China. Ecol Ind 2020;110:105892.
[29] Ding Z, Zheng H, Wang J, O'Connor P, Li C, Chen X, et al. Integrating top-down and bottom-up approaches improves practicality and efficiency of large-scale ecological restoration planning: Insights from a social-ecological system. Engineering 2022 [In press].
[30] Zhao F, Wu Y, Yin X, Alexandrov G, Qiu L. Toward sustainable revegetation in the Loess Plateau using coupled water and carbon management. Engineering 2022;15:143–53.
[31] Lan H, Peng J, Zhu Y, Li L, Pan B, Huang Q, et al. Research on geological and surficial processes and major disaster effects in the Yellow River Basin. Sci China Earth Sci 2022;65(2):234–56.
[32] Li J, Peng S, Li Z. Detecting and attributing vegetation changes on China's Loess Plateau. Agric For Meteorol 2017;247:260–70.
[33] Li Y, Zhang L, Qiu J, Yan J, Wan L, Wang P, et al. Spatially explicit quantification of the interactions among ecosystem services. Landsc Ecol 2017;32(6):1181–99.
[34] Yu Y, Zhao W, Martinez-Murillo JF, Pereira P. Loess Plateau: from degradation to restoration. Sci Total Environ 2020;738:140206.
[35] Zhao M, Running SW. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 2010;329(5994):940–3.
[36] Running S, Zhao M. MOD17A3HGF MODIS/Terra net primary production gap-filled yearly L4 global 500 m SIN Grid V006 [Data set]. Sioux Falls: NASA EOSDIS The Land Processes Distributed Active Archive Center (LP DAAC); 2019.
[37] Myneni R, Knyazikhin Y, Part T. MOD15A2H MODIS/Terra leaf area index/FPAR 8-Day L4 Global 500m SIN Grid V006. 2015.
[38] Huete A, Didan K, Miura H, Rodriguez EP, Gao X, Ferreira LF. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens Environ 2002;83(1–2):195–213.
[39] Funk C, Peterson P, Landsfeld M, Pedreros D, Verdin J, Shukla S, et al. The climate hazards infrared precipitation with stations-a new environmental record for monitoring extremes. Sci Data 2015;2(1):150066.
[40] Fensholt R, Rasmussen K, Kaspersen P, Huber S, Horion S, Swinnen E. Assessing land degradation/recovery in the African Sahel from long-term Earth observation based primary productivity and precipitation relationships. Remote Sens 2013;5(2):664–86.
[41] Horion S, Prishchepov AV, Verbesselt J, de Beurs K, Tagesson T, Fensholt R. Revealing turning points in ecosystem functioning over the Northern Eurasian agricultural frontier. Glob Chang Biol 2016;22(8):2801–17.
[42] Bernardino PN, De Keersmaecker W, Fensholt R, Verbesselt J, Somers B, Horion S. Global-scale characterisation of turning points in arid and semiarid ecosystem functioning. Glob Ecol Biogeogr 2020;29(7):1230–45.
[43] Abel C, Horion S, Tagesson T, Brandt M, Fensholt R. Towards improved remote sensing based monitoring of dryland ecosystem functioning using sequential linear regression slopes (SeRGS). Remote Sens Environ 2019;224:317–32.
[44] Hodgson D, McDonald JL, Hosken DJ. What do you mean, 'resilient'? Trends Ecol Evol 2015;30(9):503–6.
[45] Cai H, Yang X, Xu X. Human-induced grassland degradation/restoration in the central Tibetan Plateau: the effects of ecological protection and restoration projects. Ecol Eng 2015;83:112–9.
[46] Cao Y, Xie Z, Woodgate W, Ma X, Cleverly J, Pang Y, et al. Ecohydrological decoupling of water storage and vegetation attributed to China's large-scale ecological restoration programs. J Hydrol 2022;615:128651.
[47] Wu D, Zhao X, Liang S, Zhou T, Huang K, Tang B, et al. Time-lag effects of global vegetation responses to climate change. Glob Chang Biol 2015;21(9):3520–31.
[48] Wu X, Wang S, Fu B, Feng X, Chen Y. Socio-ecological changes on the Loess Plateau of China after Grain to Green Program. Sci Total Environ 2019;678:565–73.

[49] Chen JM, Ju W, Ciais P, Viovy N, Liu R, Liu Y, et al. Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink. Nat Commun 2019;10(1):4259.

[50] Hu Z, Piao S, Knapp AK, Wang X, Peng S, Yuan W, et al. Decoupling of greenness and gross primary productivity as aridity decreases. Remote Sens Environ 2022;279:113120.

[51] Pan N, Wang S, Wei F, Shen M, Fu B. Inconsistent changes in NPP and LAI were determined from the parabolic LAI versus NPP relationship. Ecol Ind 2021;131:108134.

[52] Yan D, Scott RL, Moore DJP, Biederman JA, Smith WK. Understanding the relationship between vegetation greenness and productivity across dryland ecosystems through the integration of PhenoCam, satellite, and eddy covariance data. Remote Sens Environ 2019;223:50–62.

[53] Hordijk I, Maynard DS, Hart SP, Lidong M, ter Steege H, Liang J, et al. Evenness mediates the global relationship between forest productivity and richness. J Ecol 2023;111(6):1–19.

[54] Wang S, Fu B, Liang W. Developing policy for the Yellow River sediment sustainable control. Natl Sci Rev 2016;3(2):162–4.

[55] Li Y, Zhang X, Cao Z, Liu Z, Zhi L, Liu Y. Towards the progress of ecological restoration and economic development in China's Loess Plateau and strategy for more sustainable development. Sci Total Environ 2021;756:143676.

[56] Chen D, Wei W, Chen L. Effects of terracing practices on water erosion control in China: a meta analysis. Earth Sci Rev 2017;173:109–21.

[57] Tian F, Yang J, Du R, Lin Y, Chen M, Wu J. Sustained vegetation greening enhanced ecosystem water-use efficiency in the Loess Plateau of China in recent 20 years. Ecol Eng 2022;184:106768.

[58] Zheng H, Lin H, Zhu X, Jin Z, Bao H. Divergent spatial responses of plant and ecosystem water-use efficiency to climate and vegetation gradients in the Chinese Loess Plateau. Glob Planet Change 2019;181:102995.

[59] Li T, Xia J, Zhang L, She D, Wang G, Cheng L. An improved complementary relationship for estimating evapotranspiration attributed to climate change and revegetation in the Loess Plateau, China. J Hydrolo 2021;592:125516.

[60] Luedeling E, Börner J, Amelung W, Schiffers K, Shepherd K, Rosenstock T. Forest restoration: overlooked constraints. Science 2019;366(6463):315.

[61] Zeng Y, Sarira TV, Carrasco LR, Chong KY, Friess DA, Lee JSH, et al. Economic and social constraints on reforestation for climate mitigation in Southeast Asia. Nat Clim Chang 2020;10(9):842–4.

[62] Mirzabaev A, Sacande M, Motlagh F, Shyrokaya A, Martucci A. Economic efficiency and targeting of the African Great Green Wall. Nat Sustain 2022;5 (1):17–25.

[63] Gomes E, Inácio M, Bogdzevič K, Kalinauskas M, Karnauskaitė D, Pereira P. Future scenarios impact on land use change and habitat quality in Lithuania. Environ Res 2021;197:111101.