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Nature-based Solutions can help restore degraded grasslands and increase carbon sequestration in the Tibetan Plateau

Jian Sun[1]✉, Yingxin Wang[1,2], Tien Ming Lee[3], Xiaowei Nie[1], Tao Wang[1], Eryuan Liang[1], Yafeng Wang[1], Lin Zhang[1], Jun Wang[4], Shilong Piao[1,5], Fahu Chen[1] & Bojie Fu[6,7]

The Tibetan grassland ecosystems possess significant carbon sink potential and have room for improved carbon sequestration processes. There is a need to uncover more ambitious and coherent solutions (e.g., Nature-based Solutions) to increase carbon sequestration. Here, we investigated the rationale and urgency behind the implementation of Nature-based Solutions on sequestering carbon using literature review and meta-analysis. We also project the changes in terrestrial carbon sink of Tibetan Plateau grassland ecosystems using model simulations with different future emissions scenario. The results show that the Nature-based Solution projects are expected to increase the carbon sink of Tibetan Plateau grassland ecosystems by 15 to 21 tetragrams of carbon by 2060. We defined a conceptual framework of Nature-based Solutions that integrates initiatives for the restoration of degraded grasslands and carbon sequestration. Our framework consists of four stages: theory, identification, practice, and goal. Traditional Tibetan knowledge plays an important role in reframing the proposed Nature-based Solutions framework. We also apply this framework to optimize ecological restoration techniques and projects and to evaluate the annual changes in the carbon sink under different socioeconomic pathway scenarios.

By the end of 2020, several countries in the world have successively proposed carbon-neutral targets. Among them, the major economies in the world, such as the United States, the European Union, have proposed to achieve carbon-neutral targets by 2050[1]. As one of the world's largest economies, China has committed to reaching the peak of CO_2 emissions by 2030 and attaining carbon neutrality by 2060[2,3]. Balancing carbon absorption and emission (i.e., net-zero emissions) is a critical strategy for mitigating the impacts from global climate change[4]. Research indicates that a complete energy transition to renewable energy sources in manufacturing and power generation, coupled with the gradual phase-out of fossil fuels, has the potential to significantly reduce greenhouse gas emissions[5,6]. Additionally, carbon-removal technologies such as carbon capture, utilization, and storage could contribute to the generation of negative emissions[7,8]. Notably, the natural ecosystems play a crucial role in tackling the climate crisis, as sustainable ecosystems store a significant amount of carbon in soils, sediments, and vegetation[9,10].

The terrestrial natural ecosystem in China serves as carbon sinks across nearly all major biome types[11]. For instance, forests, grasslands, and shrublands contained ~30.8, 6.7, and 25.4 Pg C, respectively[12]. Notably, the Tibetan Plateau (TP), which accounts for about a quarter of China's total land area, hosts diverse ecosystems with significant carbon sink potential[13]. The regional carbon sink in the TP was systematically assessed at 33.12 to 37.84 Tg C year^{-1} based on the inventory method, ecosystem modeling simulation, and atmospheric inversion[14]. The carbon storage in vegetation and soil at ~32 Pg C and 16 Pg C, respectively[15]. Ecoregions of shrubland and grassland are estimated to store about 7.17–9.66 Pg C[16], while the soil

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[1]State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, 100101 Beijing, China. [2]Research Institute of Ecological Conservation and Restoration, Chinese Academy of Forestry, Beijing, China. [3]School of Life Sciences and School of Ecology, State Key Lab of Biological Control, Sun Yat-sen University, Guangzhou, China. [4]Land Consolidation and Rehabilitation Center, Ministry of Natural Resources, Beijing, China. [5]Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing, China. [6]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China. [7]State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing, China. ✉e-mail: sunjian@itpcas.ac.cn

organic carbon in permafrost regions of the TP is estimated to be 19.0 Pg C to a depth of 2 m[17]. The resilience and adaptability of grassland (1.33×10^8 ha, which accounts for 60% of TP) to climate change (e.g., warming, drought, and fire), coupled with the ability of storing belowground carbon, helped to preserve the sequestered carbon[18]. Also, innovative managements and restoration approaches could further boost soil health and increase carbon stocks of degraded grasslands. Comparatively, degraded grasslands have experienced a significant decline of 42% in soil organic carbon storage as compared to non-degraded grasslands[19].

Since the 1970s, numerous ecological restoration practices have been implemented to alleviate the degradation of grasslands on the TP[20,21]. Initially, these restoration efforts focused on rehabilitating specific degraded sites but have since evolved into broader objectives (e.g., enhancing biodiversity, improving soil quality, and increasing carbon sequestration)[21]. A substantial body of research has investigated the drivers of grassland degradation, explored the benefits of restoration practices, and highlighted their detrimental impacts[22,23]. Presently, there is an urgent need to raise awareness and to adapt more ambitious and coordinated approaches to restore degraded grasslands[24], particularly to achieve carbon neutrality. In this context, Nature-based Solutions (NbS) have emerged as powerful tools due to their ability to address multiple long-term challenges, such as climate change, food security and disaster risk reduction[25,26]. NbS has gained widespread acceptance as a measure for addressing environmental challenges globally, and its application has rapidly expanded[26]. It was widely employed to restore vegetation, mitigate soil degradation, and enhance carbon sequestration[27]. NbS interventions, such as protecting intact ecosystems, managing working lands, and restoring degraded cover, have the potential to save ~10 gigatons of CO_2 equivalent per year[28]. Holden et al.[29] demonstrated that the implementation of NbS, specifically the clearing of invasive alien trees, could effectively mitigate the negative effects of anthropogenic climate change on drought streamflow in South Africa. The removal of invasive alien trees has the potential to alleviate the reduction in streamflow by 3–16 percentage points when there is moderate invasion[29]. Meanwhile, Turner et al.[30] established a framework to clarify how social-ecological interactions produced nature's contributions to adaptations, to explore a small set of mechanisms that enabled these interactions, and to test them in a small number of case studies. Moreover, the Natural Climate Solutions World Atlas identified 15 specific NbS pathways, including reforestation, grazing management, and ecosystem restoration, which could significantly reduce China's annual carbon emissions by 2.08 billion tonnes CO_2 equivalent, equivalent to about one-fifth of the total greenhouse gas emissions (11.7 billion tonnes) in 2018[28].

Currently, NbS are beginning to emerge in China, but their application in grassland ecosystems, especially in the TP, is relatively limited. In the past, the natural rule-based four-season grazing system in the TP was mostly carried out collectively by pastoralists on shared pastures, but in recent years, shared pastures on the plateau have become scarce, and many have been contracted out or banned from grazing due to serious ecological problems such as grassland degradation[31]. In fact, the indigenous Tibetan local culture, which constitutes the dominant group in the TP, has long recognized the indispensable relationship between human beings and nature[26,32]. The survival of the Tibetan people is entirely reliant on the Earth's natural resources. Furthermore, Tibetan herders are perceived as both guardians of the grasslands and local experts, thus playing a vital role in the conservation of the environment[32]. Carbon sequestration projects involving NbS are considered to have substantial prospects and potential in the TP, owing to its unique geographical and cultural characteristics[33]. Consequently, conceptual, and quantitative research to assess the potential and synergies of NbS are urgently needed to provide essential data and guidance to inform policy decisions concerning the TP.

To address these gaps, in this research, we synthesize the role of NbS on restoring degraded grasslands and sequestering carbon in the TP. In the following sections, we first demonstrate the rationale and urgency behind the implementation of NbS on sequestering carbon in the TP using literature review and meta-analysis. We then define and elaborate on a conceptual framework of NbS that integrates initiatives for the restoration of degraded grasslands and carbon sequestration. Finally, we apply this framework to optimize grassland ecological restoration techniques and projects and to evaluate the annual changes in the carbon sink in the TP under various NbS projects and different socioeconomic pathway scenarios.

Results and discussion

Rationale and urgency behind the implementation of NbS on sequestering carbon in the TP

Potential of restoration of degraded grassland in improving carbon sink. Human activities, including overgrazing and climate change, have led to the extensive degradation of grasslands, thereby resulting in soil erosion and carbon loss[22,34]. Currently, ~40% of the grasslands in the TP have been degraded to varying degrees. The proportions of degradation in Tibetan grasslands are as follows: heavy degradation—8%, moderate degradation—10%, and light degradation—18% (Fig. 1a). Massive losses of soil nutrients and carbon in the degraded area have reversed grassland from carbon sink to carbon source[35]. Consequently, the degradation has led to the loss of 1.01 Pg of soil carbon since the 1980s, which is twice of the potential carbon accumulation resulting from climate change and elevated CO_2 concentration[36]. Most of the soil carbon are presently stored in water-stable aggregates and will be released as they fall apart with grassland degradation. In addition, the decline in plant production may reduce the carbon input to the soil via photosynthetic assimilation[37].

Restoration is a process of reversing grassland from degradation to the recovery of ecological functionality[34]. Numerous studies have demonstrated that restoration practices significantly increase plant coverage and productivity, accelerate the plant community succession, and subsequently enhanced CO_2 sequestration in grasslands[38]. In the TP, restored grasslands exhibit, on average, 0.14 kg C/m^2 (29.2%) higher plant biomass carbon and 1.15 kg C/m^2 (12.3%) higher soil organic carbon density compared to degraded grasslands[39]. Furthermore, restoration efforts, such as grazing exclusion and artificial grassland establishment, are estimated to contribute to a carbon sink potential of ~49.87 Tg C/year and 34.33 Tg C/year, respectively[40]. Our meta-analysis indicates that heavy grazing exerts a negative impact on soil organic carbon and aboveground biomass. However, root biomass remains unaffected (Fig. 2). On the other hand, grazing exclusion significantly enhances carbon storage in litter mass, aboveground, and belowground biomass, as compared to grazing (Fig. 2). Carbon sequestration in artificial grasslands is facilitated by both the absorption of CO_2 during plant growth and carbon transport from plants to the soil (Fig. 2).

Uncertainties and challenges hindering restoration projects. To maximize the potential of restoration projects, it is crucial to identify, assess, and address the existing uncertainties and challenges associated with the restoration process. This knowledge should then be applied to enhance the outcomes of restoration initiatives, particularly in relation to carbon sequestration[41]. Currently, the two crucial issues are that (1) there is a dearth of comprehensive methods for effectively evaluating the implemented restoration projects, and (2) a substantial gap exists in our understanding of the degraded state of grassland, owing to the utilization of disparate data sources and inconsistent methodologies (Fig. 1).

The central government of China and local Tibetan authorities have implemented four distinct categories of ecological restoration projects, which encompassed grassland ecological projects, forest ecological projects, initiatives to combat sand desertification, and projects focused on soil erosion control (Fig. 1b). These restoration endeavors are context-specific and often entail considerable time investment. Overlapping of different projects has been observed in certain areas (Fig. 1b), complicating the assessment of benefits and impacts due to the divergent needs of stakeholders involved in the project[21,42]. Furthermore, the decentralized administration of grassland restoration has led to the involvement of numerous stakeholders, contributing to a widespread radicalization of ecological issues[43].

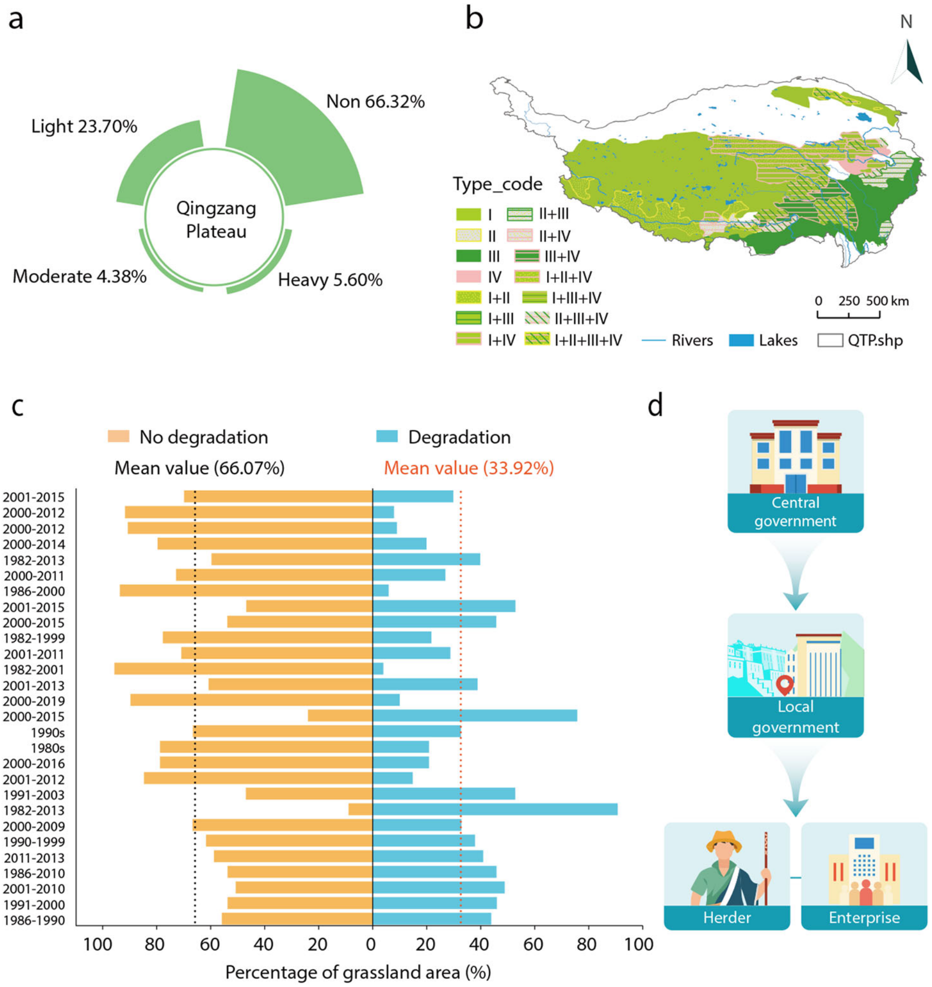

Fig. 1 | The basis and urgency of implementing NbS for improving carbon sink via restoration project. The proportion of grassland degradation in the TP (**a**). Distribution and location of the ecological restoration engineering of TP (**b**). The figure shows the location of the Grassland ecological engineering (I), Sand source control project (II), Forest ecological project (III), and Soil erosion control project (IV). Almost all restoration project takes a top-down design and approach (**c**). Percentage of no degraded and degraded grassland area in the TP during past decades from different studies (**d**). Every element of the image was created by us and our co-authors.

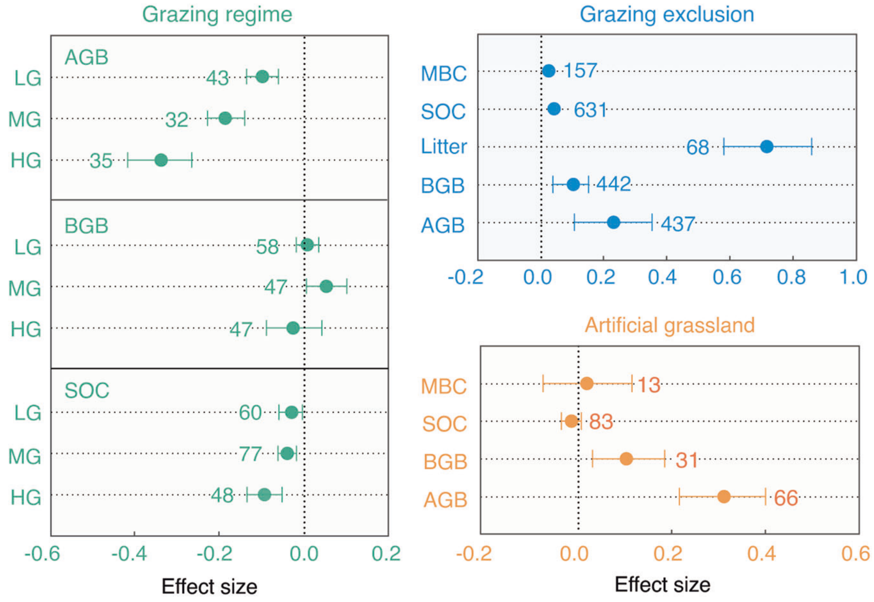

Fig. 2 | Response ratios of plant and soil carbon under grazing exclusion compared with grazing sites, artificial grassland compared with natural grassland, and different grazing regimes using a meta-analysis approach. LG light grazing, MG moderate grazing, HG high grazing, AGB aboveground biomass, BGB belowground biomass, SOC soil organic carbon, Litter plant litter biomass, MBC microbial biomass carbon. The analysis involved data extracted from 284 published articles (see Supplementary Table 4).

Accurately assessing the extent of degraded grassland of TP remained a critical challenge. Remote sensing methods offer distinct advantages over traditional ground-based observation approaches, as they enable the assessment of large geographical areas with multiple spatial, spectral, and temporal resolutions[44]. However, discrepancies in the estimation of grassland degradation have been evident in previous studies, with reported values ranging from 50%, 40%, to as low as 33%, derived from vegetation cover assessments using remote sensing imagery[45,46]. Furthermore, inconsistent assessment criteria for degradation persist due to inadequate sample sizes, multiple data sources, and varied methodologies (Fig. 1c and Supplementary Table 1). For example, the limitations of remote sensing in capturing detailed information such as soil water content, soil nutrient availability, and plant composition have contributed to uncertainties in distinguishing different degradation levels of vegetation coverage[23]. Additionally, controversies surrounding the reasons for grassland degradation in the TP persist among scientists, government policymakers, and local herders, primarily due to the absence of long-term practical experiments[47].

Engaging the local herders during the implementation of restoration projects. While the integration of local herders' culture and knowledge to inform decision-making in restoration projects is crucial, conflicts persist between herders and the implementation of such projects (Fig. 1d). The majority of restoration projects in the TP followed a top-down approach, prioritizing short-term outcomes and neglecting the interests of local herders[48]. Consequently, certain grassland ecological restoration projects lacked support from local herders and faced obstacles in successful implementation. For example, local herders strongly opposed grazing exclusion in certain high-quality grasslands, considering it a waste of natural resources[24]. In some cases, local herders were compelled to abandon their traditional way of life due to ecological-based migration policies. Moreover, the benefits of ecological restoration are not immediate and the local herders did not have the patience to wait. The misalignments between the local government policies and national ecological projects often led to protracted disputes, heightening misunderstandings among local herders about the objectives of the projects[49]. Ironically, local herders possess extensive knowledge and experience in safeguarding and utilizing their grasslands, derived from years of observation, grazing practices, and intergenerational transmission[50].

Conceptual framework of the contribution of NbS to restore degraded grasslands and sequester carbon in the TP

Ecological restoration measures play a crucial role in the restoration and management of grasslands in the TP[51]. However, these measures face various challenges, including our limited understanding of ecosystem mechanisms, an excessive reliance on project-based approaches, and inadequate management policies[24,43]. The current challenge lies in recognizing and addressing these problems and uncertainties, particularly due to the unsystematic nature of projects and the continuous evolution of our understanding of the restoration processes[52–55]. To tackle these challenges, NbS are often thought as "no-regret" options that incorporate local traditional knowledge, and the approach used in the implementation allowed uncertainties could be considered[56]. NbS emphasize the significance of restoration practices that strive to return ecosystems to their natural or near-natural states[25,57]. Here, we present a conceptual framework adapted from the IUCN Global NbS Standards, which includes eight specific criteria and 28 detailed indicators. It utilizes the principles and logical framework of NbS to protect, manage, and restore grasslands on the Tibetan Plateau, with the aim of increasing carbon storage (Fig. 3).

The proposed conceptual framework consists of four stages: theory, identification, practice, and goal, as illustrated in Fig. 3. Firstly, "theory", NbS aligns with the Chinese governance model of "community of life of mountains, rivers, forests, fields, lakes, grass and ice" and the 3-C approach (classification-coordination-collaboration systematic approach)[22]. The restoration of degraded grassland requires a comprehensive approach that involves local herders, scientists, politicians, and the international organizations. Collaboration between multiple stakeholders is hence crucial for the success of NbS. Among these stakeholders, the traditional knowledge of the local herders is indispensable and needs to be at the core of NbS (Box 1 and Supplementary Fig. 2). Namely, NbS is a place-based partnership between people and nature, and it is not just another top-down approach implemented on a larger scale. Governments should ensure that local herders' land tenure rights are upheld and provide funding, appropriate policies, and support for community-based organizations to ensure the success of restoration projects with NbS (Fig. 3). Theories, and knowledge should be acquired through the monitoring of the projects and social policies and translated into the restoration policies and program redesigns. Secondly, "identification", policymakers and local herders can utilize three categories-grassland types, drivers of degradation, and stages of degradation-to further categorize grassland ecosystems based on NbS (Fig. 3). Grassland types can be classified into various categories, namely alpine meadows, alpine grasslands, and alpine desert grasslands. The degradation of these grassland ecosystems is driven by multiple factors, such as overgrazing, excessive land use, climate change, and improper management practices. Identifying the stages of degradation relies on indicators including vegetation cover, soil quality, loss of biodiversity, and soil erosion. The amalgamation of these categorizations enables policymakers and local herders to gain a comprehensive understanding of the current state of grassland ecosystems and implement suitable measures for their protection and restoration, thus enhancing carbon storage (Fig. 3). Thirdly, "practice", NbS is committed to developing more suitable management plans to protect and restore degraded grassland, while simultaneously aiming to increase carbon sink and build a socio-ecological grassland system. To effectively enhance carbon sink through restoration efforts, we suggest three approaches utilizing NbS: (1) Conservation of non-degraded and lightly degraded grasslands: this approach aims to prevent further carbon release by implementing measures to protect and maintain the existing carbon stocks in these grassland areas. (2) Improved management practices for moderately degraded grasslands: this approach focuses on reducing greenhouse gas (GHG) emissions from grasslands that have experienced moderate levels of degradation. (3) Restoration of heavily degraded grasslands: this approach targets the rehabilitation of grasslands that have undergone significant degradation (Fig. 3). And ultimately, "goal", the goals of NbS conceptual framework are to support sustainable development, includes long-term carbon storage increase while simultaneously providing benefits for human well-being (Fig. 3).

Conceptual framework applications

Optimizing grassland restoration techniques with NbS framework. In the TP, numerous restoration practices have been conducted, including the establishment of fences, exclusion of livestock from degraded areas, adoption of rotational grazing, and cultivation of favorable forage grasses and legumes[58]. However, the application of grassland restoration technology is mostly policy-orientated, lacking a comprehensive design and classification under new ecological concepts. Here, we have developed a systematic classification of grassland restoration techniques based on the NbS pathway being employed, specifically categorized as protection, improved management, or restoration (Fig. 4 and see Supplementary Table 2). The systematic classification incorporates several key features. Firstly, it adopts a hierarchical structure to depict the NbS features of restoration techniques within three distinct levels: protect, manage, and restore. Secondly, the classification system provides comprehensive coverage of grassland restoration techniques specific to the TP[59]. Thirdly, it places local traditional knowledge at the core of the classification system. Lastly, it offers detailed documentation, including descriptive profiles accompanied by illustrations, for a total of 19 restoration techniques (see Supplementary Table 2). This classification system delineates the following three pathways. The protection pathways encompass targeted grazing, litter

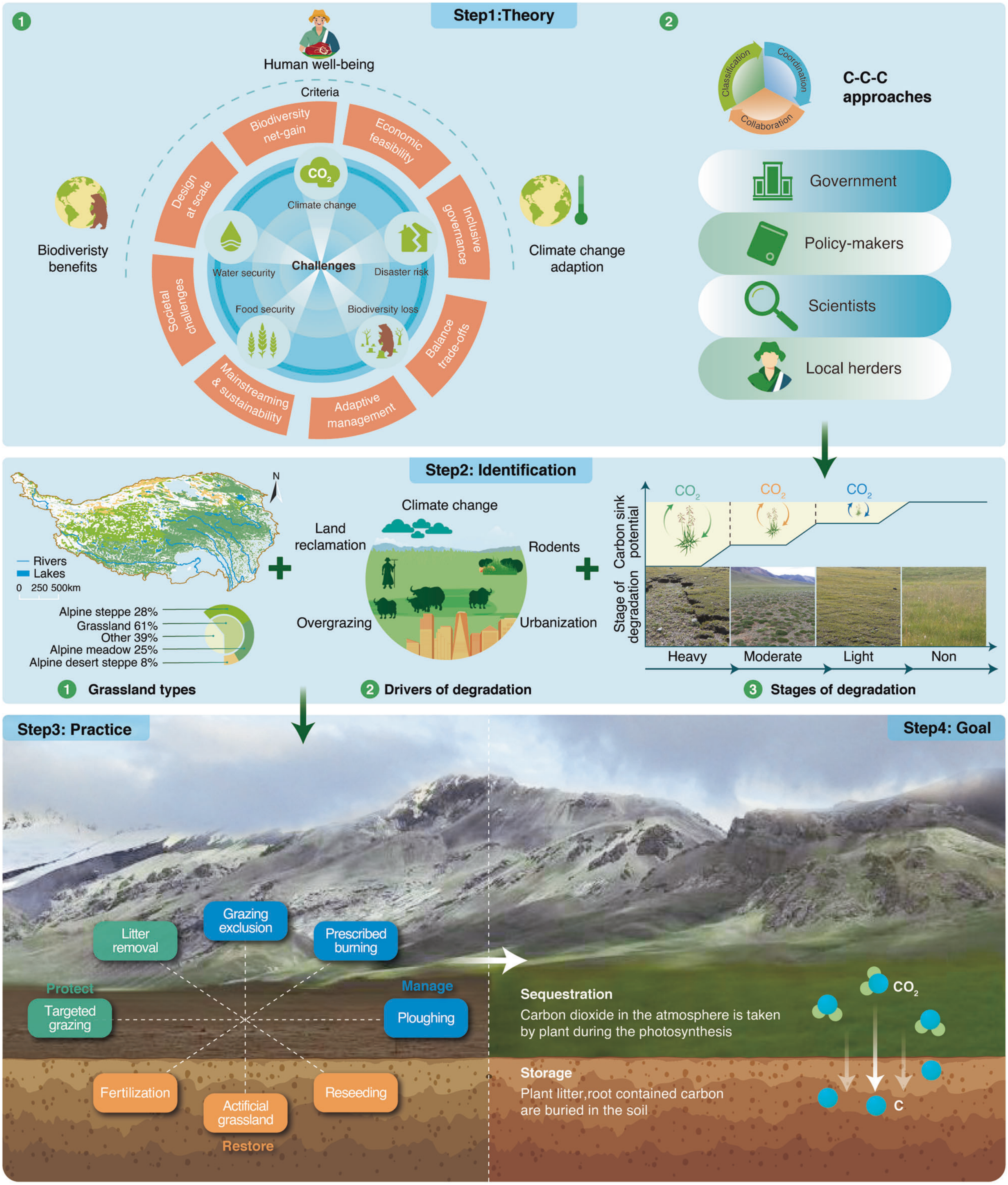

Fig. 3 | Conceptual framework of the application NbS to enhance carbon sequestration through the restoration, management, and protection of degraded grassland in the TP. The conceptual framework encompasses four stages: theory, identification, practice, and goal. The NbS approach emphasizes the safeguarding of intact systems in accordance with the mitigation hierarchy. Grassland types within this framework include alpine steppe, alpine meadow, alpine desert, and alpine wetland. Degradation of grasslands is attributed to various factors, including overgrazing, climate change, urbanization, and the proliferation of invasive species. Every element of the image was created by us and our co-authors.

removal, weed control, root cutting, microbial inoculation, and prescribed burning. The improved management pathways include techniques such as grazing exclusion, rodent control, mowing, plowing, and grazing chickens. Lastly, the restoration pathways comprise artificial grassland establishment, no-tillage reseeding, topsoil removal, straw checkerboard barrier implementation, irrigation, fertilization, and sward ripping (Fig. 4).

Optimizing grassland restoration projects with NbS framework. The integration of NbS assessment into the dynamic adaptive management

Box 1 | Knowledge co-production with local Tibetan herders on grassland restoration with NbS

An effective "solution" should be grounded in the specific needs and perspectives of local Tibetan herders, rather than relying on external factors such as governments, NGOs, and corporations[73]. In the long term, NbS will increase the probability of success for several reasons, including local Tibetan herders holding unique and rich knowledge that is integral to grassland management, local traditional knowledge in the TP usually emerges from the close contact with land, and passed on for generations, which often manifest in culture, practice, and beliefs of local herders[74,75]. Local traditional knowledge helps to reframe NbS based on five crucial contributions (see Supplementary Fig. 2) as following:

- Holistic: the local Tibetan knowledge-led NbS can simultaneously address several societal challenges. Based on long-term and empirical observations on grassland, local Tibetan herders can take the complex interactions with pastures, livestock, communities, and policies in the system into account, and make more comprehensive decisions[48].
- Legitimate: NbS in local Tibetan herders' grassland rely on locally-established authority systems with agreed customary norms and rules to manage natural grassland resources. Local Tibetan herders have established a relatively complete decision-making process and an open consultation platform, which village leaders are all elected by the herders as a collective group[74].
- Enduring: local traditional knowledge-led NbS are embedded in communities' livelihood and long-term land management. Herders do have sophisticated practical knowledge when it comes to managing their land, such as diversified grazing, nomadic grazing, and the indispensability of the humus layer[73,74].
- Culturally driven: the local traditional knowledge-led NbS acknowledge the interdependence between nature and the social system. In the "taboo and worship" culture of local Tibetan herders, protecting the natural environment and maintaining normal food chain of the ecosystem are the most important components.
- Locally-owned: NbS with local traditional knowledge are inspired by values embedded in local authority systems and could respond to specific conditions and needs. NbS restoration projects should display both leadership and ownership of the local communities that have a deep cultural attachment, customary custodianship, and the sustainable governance of their grasslands[74].

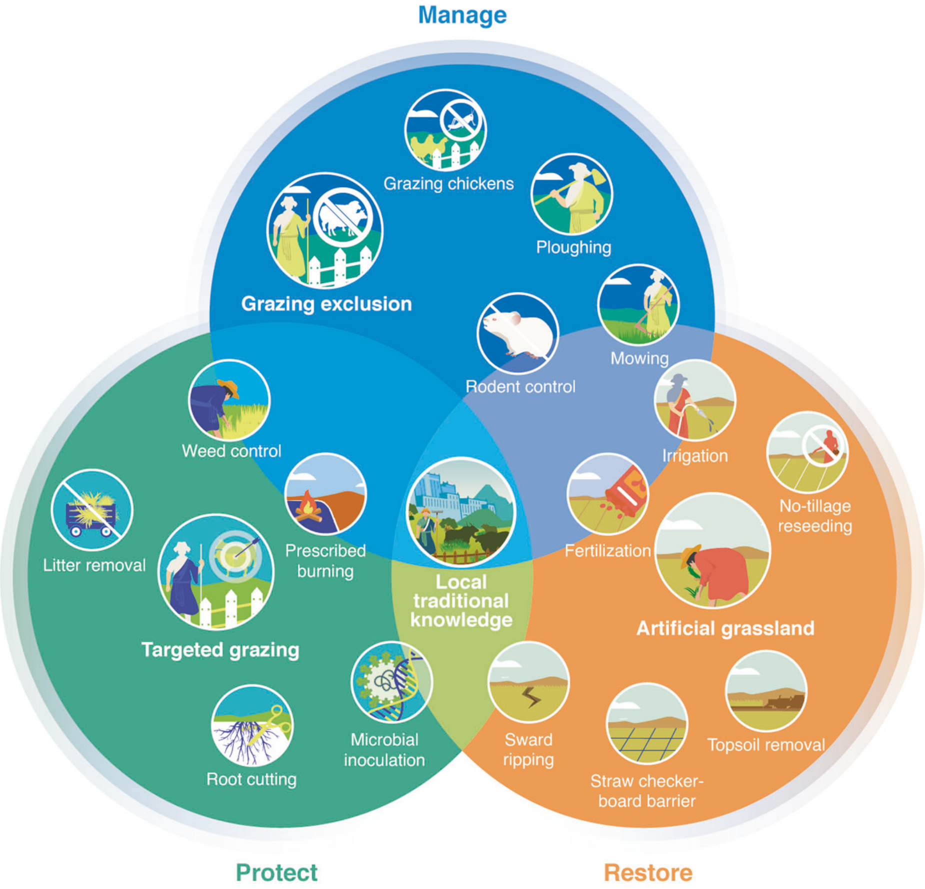

Fig. 4 | Grassland ecological restoration techniques are classified into three groups (protect, manage, and restore) with NbS. In this classification system, the "protect" pathways include targeted grazing, litter removal, weed control, root cutting, microbial inoculation, and prescribed burning; the "managed" pathways consist of grazing exclusion, rodent control, mowing, plowing, and grazing chickens; and the "restore" pathways contain artificial grassland, no-tillage reseeding, topsoil removal, straw checkerboard barrier, irrigation, fertilization, and sward ripping. Every element of the image was created by us and our co-authors.

of grassland restoration projects during the stages of project planning, design, and implementation provides a comprehensive approach[60,61]. With the NbS approach, the advantages and disadvantages of specific grassland restoration projects are clearly, intuitively, and vividly reflected, enabling continuous adjustment of intervention measures as necessary[61]. Based on the literature review and existing NbS projects, a five-step framework for monitoring and evaluating implemented projects in the TP has been identified (Fig. 5). The process commences with the identification of the current state (existing conditions), followed by the determination of requisite inputs and outputs necessary to achieve short-term and

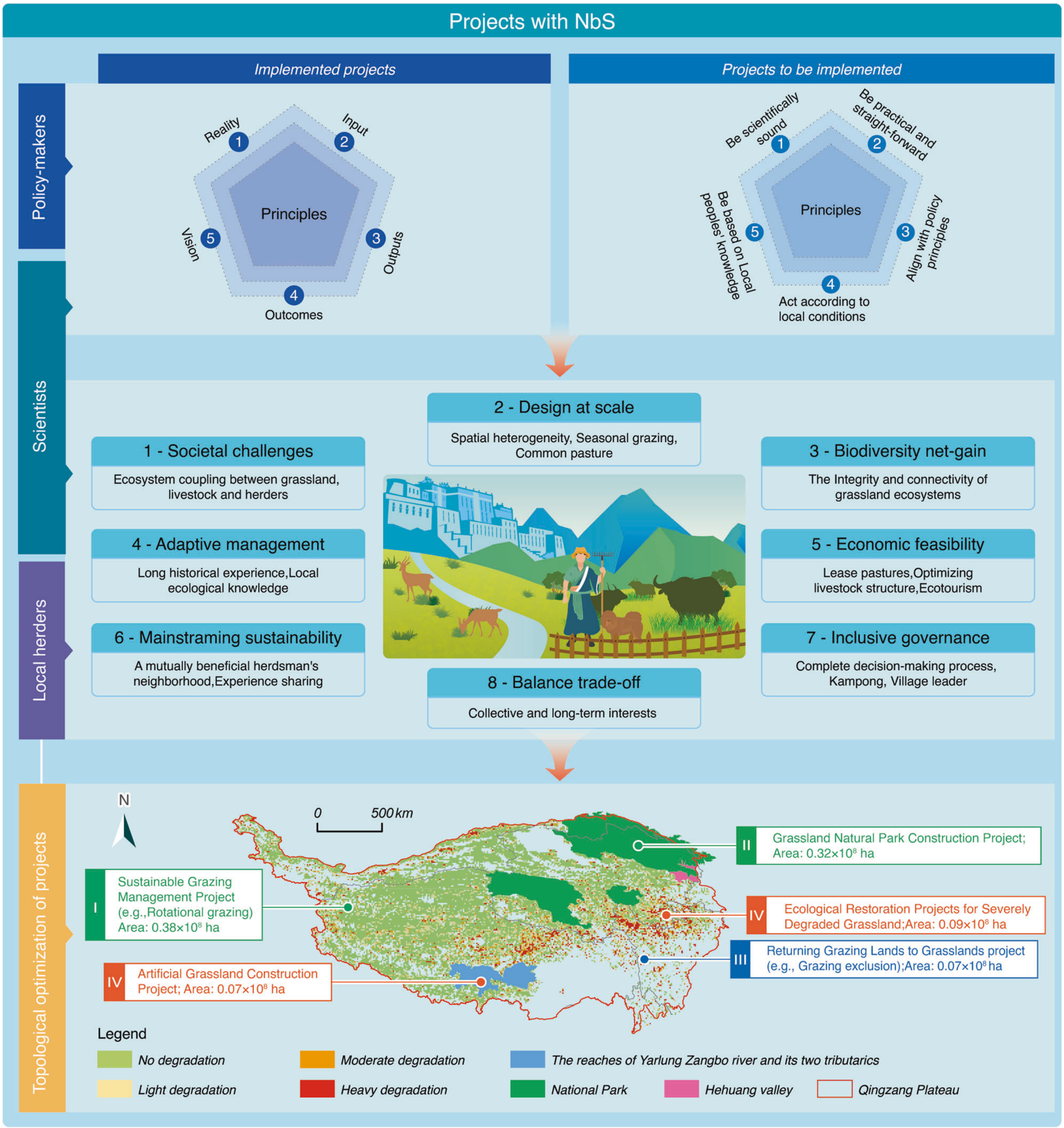

Fig. 5 | The roadmap for optimizing grassland ecological restoration projects using NbS conceptual framework. The collaborative effort among policy-makers, scientists, and local herders for ensuring the effectiveness and sustainability of NbS projects. Distribution map of three categories (protect, manage, and restore) of NbS projects on the Tibetan Plateau. Each element of this image is copyrighted by us.

intermediate outcomes that align with the desired long-term vision (Fig. 5). Additionally, pilot NbS projects play a crucial role in expanding the concept and knowledge of NbS related to the effectiveness of grassland restoration practices as a mitigation strategy for carbon sequestration. Evaluation plans and principles for pilot NbS projects should: (1) be scientifically robust; (2) be practical and simple; (3) align with policy principles; (4) be context-specific; and (5) encompass long-term commitments integrating scientific and local/traditional knowledge (Fig. 5). Successful implementation of NbS policies and pilot projects hinges on fostering collaboration among policy-makers, scientists, and local herders. Therefore, disseminating knowledge on NbS projects among local herders is essential to ensure successful implementation (Fig. 5).

Here, a new optimization scheme has been developed and delineates three categories of NbS projects across TP (Fig. 5 and Supplementary Table 3). (1) Projects with a "protect" approach encompass sustainable grazing management projects in lightly degraded grassland (0.38×10^8 ha) and grassland national park projects in the Sanjiangyuan and Qilian Mountain (0.32×10^8 ha). (2) Projects with a "manage" approach include returning grazing lands to grasslands project for moderately degraded grassland (0.07×10^8 ha). (3) Projects with a "restore" approach comprise ecological restoration projects for severely degraded grassland (0.09×10^8 ha) and artificial grassland construction projects in the Hehuang valley and the reaches of Yarlung Zangbo River and its two tributaries (0.07×10^8 ha).

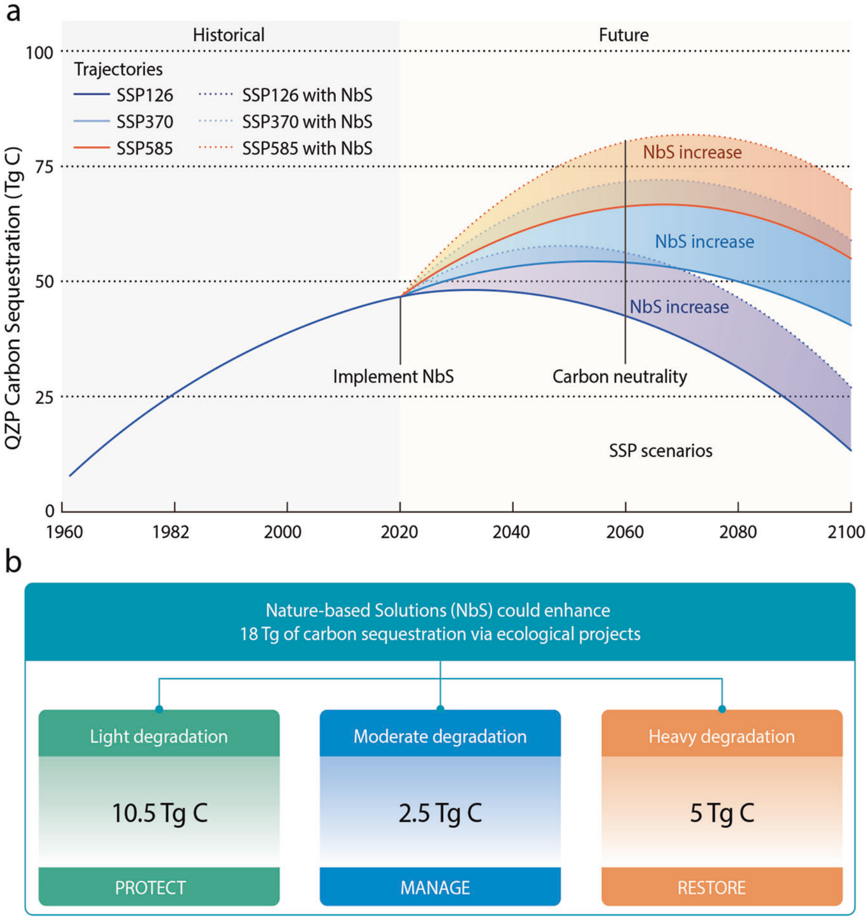

Fig. 6 | Projection of carbon sequestration of TP per year in the Shared Socioeconomic Pathways (SSPs) without (solid lines) and with (dotted lines) NbS projects. Three SSPs scenarios are SSP1-2.6 (sustainable development pathway), SSP3-7.0 (uneven development pathway), and SSP5-8.5 (rapid development pathway) (**a**). Three steps to enhance carbon sequestration via ecological projects under the guidance of NbS, including protecting light degraded grassland, managing moderate grassland, and restoring heavy grassland with NbS projects (**b**).

Projected changes of carbon sink under different NbS and SSP scenarios. The natural recovery of carbon in degraded grassland ecosystems is a protracted process, often spanning several decades or even centuries, and the eventual restoration outcome is contingent upon the prevailing condition of the grassland ecosystem[14]. To assess the potential capacity for carbon sequestration in restored degraded grasslands, an initial evaluation of the projected long-term trends in total carbon storage in the TP was conducted in the absence of NbS. For NbS, it was posited that ecological interventions aligned with three distinct approaches would be progressively implemented across all degraded grasslands commencing from 2020. It is anticipated that by 2060, these degraded grasslands will have undergone restoration to their optimal state, characterized by maximal carbon sequestration capacity, thus attaining carbon neutrality.

In the absence of NbS projects, the projected carbon sink of the TP in 2060 (the target year for carbon neutrality) is estimated to be 41 Tg C, 62 Tg C, and 70 Tg C per year for the SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios, respectively (Fig. 6a). With the inclusion of NbS projects, the carbon sink in 2060 is expected to increase by 21 Tg C under the SSP1-2.6 scenario, 18 Tg C under the SSP3-7.0 scenario, and 15 Tg C under the SSP5-8.5 scenario (Fig. 6a). Specifically, our analysis reveals the specific contributions of different NbS projects to carbon sequestration. The protection of lightly degraded grasslands through measures such as optimizing grazing regimes has the potential to sequester 10.5 Tg C per year. The improved management of moderately degraded grasslands through actions like grazing exclusion can contribute to a carbon sequestration potential of 2.5 Tg C per year. Additionally, the restoration of heavily degraded grasslands via initiatives such as artificial grassland construction has the potential to sequester 5.0 Tg C per year (Fig. 6b).

The way forward

Currently, there are many successful examples on the applications of NbS worldwide[62,63], which demonstrate the promises of NbS in addressing ecological issues. Therefore, it is crucial to develop a conceptual framework for the restoration of degraded grasslands and enhancement of carbon sinks in the TP based on NbS. This is essential for promoting the widespread adoption of NbS and maximizing its ecological benefits. Consequently, future endeavors are necessary to refine and evaluate the approach in diverse contexts and across various scales.

In particular, we require extensive and quantitative research, encompassing modeling and meta-analysis based on observational data, to explore the potential and synergies of NbS. The technical and institutional framework for carbon storage and grassland restoration projects utilizing NbS must be established and integrated. Specifically, this involves (1) coordinating with the functional zoning of an ecological barrier in the TP; (2) optimizing the scale and timing of ecological project; (3) leveraging Tibetan historical and cultural inheritance, innovations, and technologies; and (4) implementing long-term ecosystem monitoring to facilitate investment in NbS projects.

Finally, it is necessary to validate and implement the conceptual framework underpinning NbS for carbon sequestration on a large scale, thereby establishing characteristic NbS cases specific to the TP. Throughout the implementation process, several fundamental principles must be clearly defined[64]: (1) NbS should not be considered as a standalone substitute for decarbonization measures; (2) NbS ought to prioritize the protection, restoration, and interconnectivity of expansive ecosystems; (3) It is hence imperative for NbS initiatives to respect and incorporate indigenous knowledge systems; (4) The integration of NbS practices must actively support and facilitate biodiversity conservation efforts.

Methods

Meta-analysis

The meta-analysis conducted in this study here focused on evaluating key grassland restoration techniques, specifically the impacts of optimizing grazing regimes, implementing grazing exclusion, and constructing artificial grassland in the TP. To gather quantitative data on the effects of these restoration techniques on carbon stock, we employed the use of two search engines, namely Google Scholar (http://scholar.google.com/) and China National Knowledge Infrastructure (http://www.cnki.net/), to search relevant publications (i.e., article, thesis, and monograph) in English and Chinese, respectively. The following keywords were used to screen the literatures: "grazing", "grazing system", "grazing exclusion", "fencing", and "artificial grassland"[65,66]. Literature selection was based on the following criteria (1) the inclusion of field trial data collected from the TP, specifically pertaining to grazing, grazing management, grazing exclusion, and artificial grassland experiments; (2) studies measured any of the following variables: aboveground biomass (AGB), belowground biomass (BGB), soil organic carbon (SOC) stock, plant litter biomass, and soil microbial biomass carbon (MBC) content; (3) no other measures (e.g., fertilization or reseeding) were conducted in the study sites; (4) each preliminary study provided the mean, standard deviation (SD) and/or standard error (SE), and confidence intervals for grazing, grazing exclusion, artificial grassland and control conditions. Ultimately, our analysis involved data extracted from 284 published articles (see Supplementary Table 4).

The MetaWin 2.1 software[67] was used for meta-analysis. The response ratio (RR) of response variables (i.e., AGB, BGB, SOC, MBC and plant litter biomass) to different grassland restoration techniques was calculated as follows:

$$\mathrm{RR} = \ln\left(\overline{X_t}/\overline{X_c}\right) \tag{1}$$

where X_t and X_c represent the treatment and control groups, respectively. The variance (v) of the RR was calculated by:

$$v = \frac{s_t^2}{n_t \bar{X}_t^2} + \frac{s_c^2}{n_c \bar{X}_c^2} \tag{2}$$

where n_t and n_c symbolize the sample sizes, s_t and s_c are the SDs of the corresponding variables in the treatment and the control groups, respectively.

The inverse of the variance is deemed to be the weight (W) of each RR. The mean response ratio (RR_{++}) is calculated from the individual RR of each paired comparison between the control and treatments, RR_{ij} ($i = 1,2,3\ldots, m$; $j = 1,2,3\ldots, k$), with the weight of each RR. We calculated RR_{++} and the 95% bootstrap confidence intervals (CIs) for the entire dataset. Significant responses were identified if all values in the CIs of the RR_{++} were on the same side of zero (either all positive or all negative). The RR_{++} are computed as follows:

$$\mathrm{RR}_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}\mathrm{RR}_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}} \tag{3}$$

where m refers to the number of groups, and k is the number of comparisons.

Definition of grassland degradation types

This study aimed to quantify the classification of grassland degradation in the TP. Initially, the research utilized Google Earth Engine (GEE, https://code.earthengine.google.com/) to acquire the Normalized Difference Vegetation Index (NDVI) for the growing seasons spanning from 1982 to 2020. The specific NDVI dataset used was the GIMMS NDVI From AVHRR Sensors (3rd Generation) available at https://nex.nasa.gov/nex. Subsequently, the slope of the NDVI time-series data was calculated using Sen's tendency estimation method[68,69] as follows:

$$\mathrm{Slope} = \mathrm{median}\left[\frac{x_i - x_j}{i - j}\right], \forall j > I \tag{4}$$

where Slope is the tendency of NDVI time series, and x_i and x_j are the values at moments i and j, respectively. Mann–Kendall (M-K) significance test was performed on the results of tendency analysis to determine the classification of grassland degradation[68,69]. The M-K significance test is performed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{vra}(S)}}, S>0, \\ 0, S = 0, \\ \frac{S+1}{\sqrt{\mathrm{vra}(S)}}, S<0, \end{cases}$$

$$S \sum_{j=1}^{n-1} \sum_{i=j=1}^{n} \mathrm{sgn}\left(\mathrm{NDVI}_j - \mathrm{NDVI}_i\right),$$

$$\mathrm{sgn}\left(\mathrm{NDVI}_j - \mathrm{NDVI}_i\right) = \begin{cases} 1, \mathrm{NDVI}_j - \mathrm{NDVI}_i = 0, \\ 0, \mathrm{NDVI}_j - \mathrm{NDVI}_i > 0, \\ -1, \mathrm{NDVI}_j - \mathrm{NDVI}_i < 0, \end{cases}$$

$$\mathrm{vra}(S) = \frac{n(n-1)(2n+5)}{18} \tag{5}$$

where NDVI_i and NDVI_j are the pixel values in the ith and jth years, respectively, while n denotes the length of the time series. The significance of the linear trend was determined using a statistical test, represented by the variable Z. A significant linear trend at the 0.01 level ($p < 0.01$) was indicated by $|Z| > 2.58$. Similarly, a linear trend was considered statistically significant at the 0.05 level ($p < 0.05$) if $|Z| > 1.96$. Overall, the classification of grassland degradation was explored according to the criteria presented in the table below.

Determining the carbon sequestration in the optimum state of grassland

Net ecosystem productivity (NEP) was used to calculate carbon sequestration, which was expressed as follows:

$$\mathrm{NEP} = \mathrm{NPP} - \mathrm{Rh} = \mathrm{GPP} - \mathrm{Ra} - \mathrm{Rh} \tag{6}$$

where NPP is net primary productivity, GPP is gross primary productivity, Ra is autotrophic respiration, and Rh is heterotrophic respiration. NEP quantifies carbon accumulation or loss, and a positive value of NEP indicates carbon sink of the ecosystem while a negative value indicates a carbon source.

The NEP data were obtained from the NESDC website (http://www.nesdc.org.cn). The data were generated using the Boreal Ecosystem Productivity Simulator (BEPS), a process-based ecological model employed to simulate global GPP/NPP/NEP data from the years 1981 to 2019[70].

The carbon sequestration in the optimal state of grassland ($C_{\max}$) was defined as the maximum NEP for 1981–2019:

$$C_{\max} = \max_{1981}^{2019}\left(\mathrm{NEP}_i\right), 1981 \leq i \leq 2019 \tag{7}$$

Projection of carbon sequestration

We initially evaluated the future trends of total carbon sequestration in the TP in the absence of NbS. To achieve this, the outputs of climate forcing data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b, https://www.isimip.org/), were used to drive the Land Surface Process

Model (ORCHIDEE-MICT), across various Shared Socioeconomic Pathways (SSPs) scenarios spanning the period from 1960 to 2100. The ORCHIDEE-MICT is a recent version of ORCHIDEE with improved the interaction between carbon and temperature. Notably, the model encompasses the integration of plant and soil carbon pools, while also incorporating processes related to permafrost carbon cycling[71].

In this study, we examined three distinct socioeconomic pathways: SSP1-2.6 (sustainable development pathway), SSP3-7.0 (uneven development pathway), and SSP5-8.5 (rapid development pathway). The simulations for these SSPs were performed using corrected downscaled future predicted climate data generated by the ISIMIP3b. These climate projections were derived from predictions provided by five Earth System Models (ESMs), namely GFDL-ESM4, IPSL-CM6A-LR, UKESM1-0-LL, MPI-ESM1-2-HR, MRI-ESM2-0. Specifically, the ORCHIDEE-MICT model was driven by daily mean temperature, precipitation, downgradient shortwave radiation, downgradient longwave radiation, wind speed, atmospheric pressure, and specific humidity. Furthermore, the model simulations accounted for variations in atmospheric CO_2 concentrations[72].

For NbS, we assumed that ecological initiatives corresponding to the three pathways will be progressively implemented across all degraded grasslands, commencing in 2020. The degraded grasslands are anticipated to be restored to an optimal state, characterized by maximum carbon sequestration (A), by the year 2060, resulting in carbon neutrality. Furthermore, they are expected to remain in this optimal state thereafter. The potential carbon sequestration in degraded grasslands, based on the NbS pathways (ΔC_NbS), was defined as follow:

$$\Delta C_{\mathrm{NbS}} = C_{\max} - C_{2060} \tag{8}$$

where C_{2060} denotes the simulated carbon sequestration in 2060 for the corresponding grasslands in the absence of NbS implementation.

To quantify the total potential carbon sequestration achieved through the implementation of NbS, the sum of the potential carbon sequestration for each pathway is calculated as the total potential carbon sequestration by NbS ($\Delta \mathrm{TC}_{\_\mathrm{NbS}}$). The annual potential carbon sequestration (ΔC_i) can be expressed as follows:

$$\Delta C_i = \frac{i-2020}{40} \times \Delta \mathrm{TC}_{\mathrm{NbS}}, 2021 \le i \le 2060 \tag{9}$$

$$\Delta C_j = \Delta \mathrm{TC}_{\mathrm{NbS}}, 2061 \le j \le 2100 \tag{10}$$

Finally, to capture the future carbon sequestration dynamics in the TP under the implementation of NbS, the simulated total carbon sequestration in the absence of NbS was incorporated together with the potential carbon sequestration achieved through NbS.

Data availability

The NEP data were obtained from the NESDC website (http://www.nesdc.org.cn/). The climate projection of ISIMIP3b is available from https://www.isimip.org/. The dataset used for Meta-analysis (Fig. 2) of this study is available from https://doi.org/10.11888/Terre.tpdc.301114. The model projection from ORCHIDEE-MICT used to create Fig. 5 of this study is available from https://cstr.cn/18406.11.Terre.tpdc.301114.

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Author contributions

J.S. and Y.W. formulated the research. J.S., Y.W., T.W., X.N., E.L., Y.W. and L.Z. performed the analyses and drafted the figures. J.S., Y.W., T.L. and J.W. wrote the first draft. E.L., S.P., F.C. and B.F. reviewed and edited the manuscript. All authors contributed to the discussion of contents.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Jian Sun.

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