Toward a sustainable grassland ecosystem worldwide

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Globally, grasslands, covering about 40% of the Earth's land area, are vital for supporting important ecosystem functions, services, and livelihoods of millions of humans. Currently, grassland degradation is a major threat to the maintenance of ecological services,[1] food security, and sustainable development, and directly hinders the global efforts with meeting goals and targets such as the The UN Decade on Ecosystem Restoration and Sustainable Development Goals (SDGs).

Remote sensing approaches have the advantages of spanning large geographical areas with multiple spatial, spectral, and temporal resolutions. In global scale, remote sensing methods used normalized difference vegetation index to determine net primary productivity (NPP), which still is the effective method to indicate grassland conditions. To master the general situation of grassland, we analyzed the global spatial-temporal variation of NPP from 2001 to 2019 at the pixel level across the globe. As presented in Figure 1A, the NPP values of global grasslands showed an obvious variation trend, which indicated a considerable distribution pattern of spatial heterogeneity. The decreasing and increasing trend in grassland NPP covered approximately 25.3% and 74.5% of the total grassland area, respectively. We observed the highest proportion of degradation in Australia (45.5%). Conversely, 73.7% of the total grassland area revealed an increasing NPP trend, especially in Canada (86.4%). These changes are predicted to have huge effects on biodiversity and the livelihoods of approximately 1.5 billion people who rely on grassland ecosystem services and sustainability.

In general, current grassland degradation research explicitly links climate change and human activities to landscape patterns, soil properties, community traits, and ecosystem functions. While previous studies provide a theoretical basis for grassland degradation,[2] they use different definitions and classifications, which is a barrier to comprehensive global utilization.

Our understanding of the concept of grassland degradation has evolved in the past 100 years (1919–present) through three stages: biotic/abiotic indicators, ecosystem functions, and ecosystem services (Figure 1B). Before the 1990s, soil organic carbon was used as an index, likely representing the first discussion about grassland degradation. In 1979, the Food and Agriculture Organization (FAO) defined grassland degradation as a "process which lowers the capability of soils to produce food and fodder.". Then, during the 1990s, grassland degradation is defined as the reduction in the capacity of grasslands to carry out their key ecosystem functions (Figure 1B). The United Nations (UN) Convention to Combat Desertification paid more attention to the loss of biological or economic productivity and diversity of grassland ecosystem. Since the 20th century, some researchers have begun to define grassland degradation as the long-term loss of ecosystem function and services caused by disturbances from which the system cannot completely recover, following which the FAO also clarified in 2014 degradation as a reduction in the ability of grassland to provide ecosystem goods and services (Figure 1B).

To summarize, in the past century, scientists have accumulated a more concrete understanding of grassland degradation, from the change in visible indicators to the alteration of deep-seated social goods, functions, and services. Any definition of grassland degradation is essentially a grassland sustainability problem.

Due to the inconsistent definition of grassland degradation, different assessment indicators emerged across various countries, bringing challenges to grassland sustainability research. To standardize the degradation measure and achieve large-scale evaluation, based on remote sensing methods, some assessments have used vegetation index or NPP, which could reflect grassland degradation through calculating the slope or index. However, due to the limitations of associations between satellites and unobservable variables (e.g., soil nutrient status), the use of remote sensing for the assessment of grassland degradation has been impeded. Therefore, others have opted to use the ecosystem function of carbon and nutrient cycling and the remote sensing of fractional surface cover to estimate degradation. In addition, field investigation is necessary to address issues related to grassland restoration and sustainability, soil/site stability, hydrologic function, and biotic integrity. Phyto-ecological indicators were used for the quantitative assessment of grassland degradation. Socioeconomic factors are emerging to be key; more surveys of changing rangelands areas, degradation index, and data gathered from ranchers and range management experts are leading to a qualitative change in grassland degradation assessment. The Visual Soil Assessment was developed in New Zealand to provide a simple method to assess soil and plant quality semi-quantitatively, quickly, and effectively. This method is based on a weighted additive model, which includes indicators of soil quality (both static and dynamic) and plant performance. Moreover, since 2008, this method has been recommended by the FAO to herdsmen and scientists for its simplicity. Accordingly, grassland degradation assessment has progressed from a single factor to multiple factors, and from large scale to pasture level, which all point to the evaluation of grassland sustainability.

Obviously, limiting the grassland deterioration and achieving its sustainability requires all relevant stakeholders to work together to reach a consensus and consider all aspects for its key role in global climate change and human welfare.[3] To achieve sustainable development of the grassland ecosystem, there is a fundamental need to define and assess the extent of grassland degradation and unravel the causes and processes of grassland degradation. Accurately

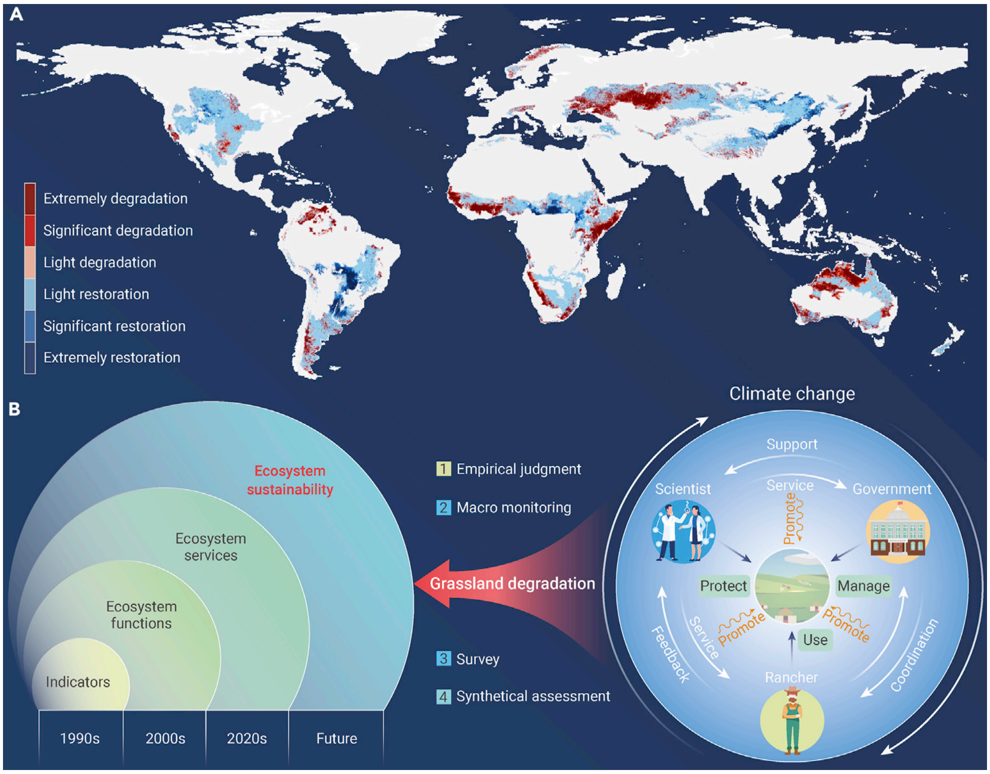

Figure 1. Toward a sustainable grassland ecosystem worldwide (A) Global trends of grassland degradation and restoration. The significance of the grassland dynamics was determined by the F-test to represent the confidence level of variation. Then, the variation trend in grassland NPP was classified into the following 6 categories based on the F-test: ED (extremely significant degradation, slope < 0, $p < 0.01$); SD (significant degradation, slope < 0, $0.01 < p < 0.05$); LD (light degradation, slope < 0, $p > 0.05$); LR (light restoration, slope > 0, $p > 0.05$); SR (significant restoration, slope > 0, $0.01 < p < 0.05$); and ER (extremely significant restoration, slope > 0, $p < 0.01$). (B) Grassland degradation definitions and grassland sustainability assessment.Different colors represent the focus of different periods of grassland degradation definitions from biotic/abiotic indicators to ecosystem sustainability. Collaborations and mutual relationship of policymaker-performer-evaluator (e.g., government, scientist, rancher). Comprehensive assessment of grassland sustainability from indicators, functions, services, and establish links with climate, soil and grassland conditions, livestock management and trades, herder economics, and effectiveness of policy.

assessing grassland ecosystem sustainability will require us to understand the impact of grassland degradation in the social-ecological system. Here, we defined grassland sustainability as the resistance, resilience, and recovery of complex social-ecological-bioeconomic system, which involves the background of habitat, available resource, practical patterns, livestock production, and financial and political influence.

Consequently, the essence of measuring grassland degradation is to evaluate whether the grassland ecosystem is sustainable. Nevertheless, the assessment of grassland degradation is a challenge because of the complexity of methods, criteria, habitats, management, tenure, policies, and culture. Therefore, developing a uniform conceptual model and methodology to assess grassland sustainability is of high importance. In our paper, we conceptualize a framework for grassland sustainability that is coupled with policymaker-performer-evaluator and evaluation system combined with ecosystem indicators, functions, services, and social systems, which ultimately attempts to achieve a grassland sustainability assessment (Figure 1B). To quantify grassland sustainability, we introduced the StageTHREE sustainable grasslands model,[4] which developed as part of the Australian Centre for International Agricultural Research (ACIAR) project in 2020.

Specifically, a grassland sustainability assessment should also consider the stakeholders, collaborations, and mutual relationships among different administrative departments (e.g., government, scientist, rancher). Through the understanding of the process and challenges of grassland degradation, we would be able to carry out grassland sustainability assessment. Grassland degradation is often accompanied by the change in basic indicators (e.g., coverage, water infiltration rate, plant biomass), which are components or measures of environmentally or ecologically relevant phenomena used to depict or evaluate environmental or ecological conditions. Through the observation of a series of key indicators, we can analyze different ecosystem functions of grassland such as carbon sequestration, nitrogen cycling, and microbial activity,[2] which reflect the biotic and abiotic processes that may contribute to ecosystem services either directly or indirectly. Considering the benefits humans obtain from grassland ecosystems, the cultural, provisioning, regulating, and supporting ecosystem services are key to establishing ecological-social system relations, and assessing grassland sustainability from a human-nature relationship perspective.[1] Most important, in addition to the above assessment, determining the sustainability of grassland ecosystem must integrate various factors such as policy and market,[5] which influence how herdsmen make decisions about using and managing grasslands via household strategies and, more broadly, community institutions.

Urgent action is needed to halt grassland degradation processes and to restore its sustainability, which requires the topic of grassland sustainability to be given a global priority that helps to alleviate poverty, and to increase carbon sink so as to attain zero net degraded land goal and SDGs. Therefore, authoritative, frequent assessments of type, standard definition, classification, trends, driving factors, and policy challenges of grassland degradation become crucial. Based on the above consensus, for the social attributes linked with livelihoods and poverty, a standardized methodology of grassland sustainability is needed rather than only grassland degradation. Considering effective assessment, such a methodology could effectively disseminate practical knowledge of restoration, and ensure that governments promote grassland sustainability for the benefit of their residents and all humankind. Therefore, building a grassland sustainability framework and action plan should be incorporated into the work of multilateral environmental agreements and organizations, such as the Convention on Biological Diversity, the UN Framework Convention on Climate Change, and the content of the UN's post-2015 development agenda oriented toward the achievement of the global SDGs. If the degraded grassland ecosystem restoration and sustainability can be broadly prioritized in countries and the world, then it could attract strong political support and commitment, thereby improving the livelihood of people living in rural areas around the world.

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DECLARATION OF INTERESTS

The authors declare no competing interests.