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The sustainable management of land systems

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1. Introduction

Human activities and global climate change have imposed dual stress on the Earth's surface ecosystems, resulting in rapid changes in land use and land cover at different spatial and temporal scales. These changes have increased the vulnerability of ecosystems, making land use and land cover an important element in global change and sustainability research (Foley et al., 2005; Liu and Deng, 2010). Over the past three decades, researchers from various disciplines have conducted numerous studies on land use/cover change (LUCC) processes and simulations at different spatial and temporal scales, analysis of driving mechanisms, ecological and environmental effects, and sustainable management (Verburg et al., 2002; Turner et al., 2007; He et al., 2022). A series of international programs have also been launched to promote the progress of LUCC-related research.

In 1995, the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) jointly initiated the LUCC project. The project aimed to establish predictive, ecological and environmental outcome simulation and decision support models by understanding the mechanisms of interaction between "human driving forces, land use/cover change, global change, regional response, and environmental feedback." The Global Land Project (GLP), launched in 2005 as a follow-up to the LUCC project, aimed to measure, model, and understand coupled human-environment systems, identify changes and impacts of coupled human-environment systems on land from a systems analysis perspective, and understand the vulnerability and sustainability of coupled human-environment systems. In 2014, organizations such as the International Council for Science (ICSU) and the International Social Science Council (ISSC) launched the 10-year Future Earth program. Under the influence of this program, LUCC-related research began to focus on the coupling relationships between LUCC processes, ecosystem services, and human wellbeing at different scales, thereby enhancing global sustainability. At the same time, the second phase of the GLP was officially renamed the Global Land Programme, becoming a global research network within Future Earth. It continues to serve as a platform for networking, synthesis, and agenda-setting, connecting the scientific and practice communities.

LUCC represents the most direct signal of the impact of human activities on the Earth's surface. It is also an essential process of interaction between human socio-economic activities and the natural environment. To address the challenges posed by global change, conserve biodiversity, mitigate climate change, and enhance human wellbeing, it is crucial to understand the progress and shortcomings of LUCC research in the areas of biodiversity and ecological security, food security, climate change and United Nations sustainable development goals (SDGs) realization (Figure 1).

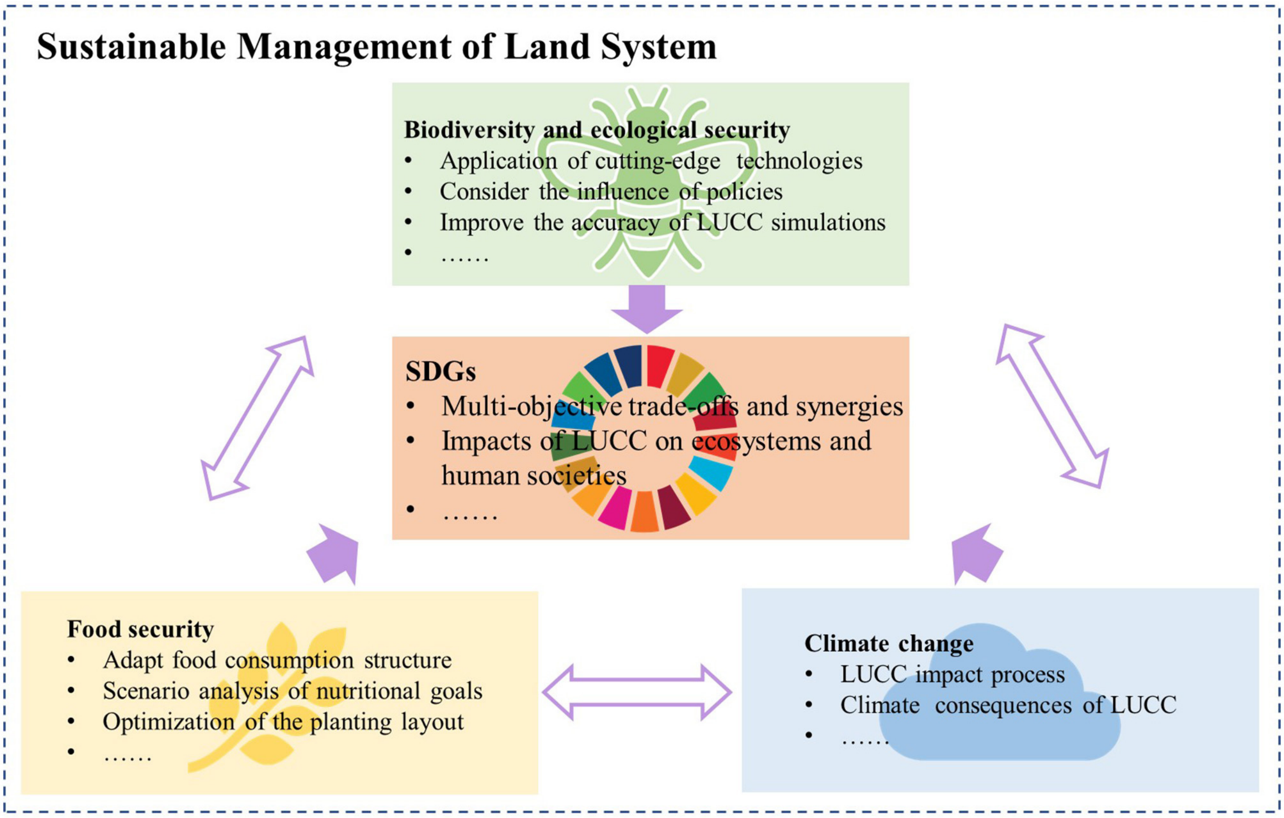

FIGURE 1
Sustainable management of land system.

2. Biodiversity and ecological security

Ecological security refers to the state of a healthy and intact ecosystem capable of providing ecosystem services that fulfill human wellbeing needs. It also encompasses the ability of the ecosystem to meet human development requirements and sustain social sustainable development, even when facing pressures, disturbances, and disruptions caused by human activities, climate change, and other factors (Xiao and Chen, 2002; Fan and Fang, 2020; Li S. et al., 2023). The preservation of biodiversity is vital for the wellbeing and survival of humanity, serving as the cornerstone for ensuring ecological security. The influence of LUCC on biodiversity and ecological security is critical (Li Y.et al., 2023), particularly the reduction of forests, expansion of agriculture, urbanization, and desertification, which impose significant pressures on ecological integrity. These land use changes can reduce the ability of ecosystems to cope with extreme events, leading to global or local biodiversity loss and degradation of ecosystems services, thus threatening ecological security. Preventing the threats of LUCC to ecological security and optimizing regional ecological security pattern have gradually become a research hotspot.

The ecological security pattern employs simulations of species movement to identify crucial ecological nodes (pinch points), ecological corridors, and ecological sources (Peng et al., 2018a). The ecological security pattern, as an effective measure to protect biodiversity and ensure ecological security, has been widely recognized and applied. The paradigm of constructing the ecological security pattern involves identifying ecological sources, establishing resistance surfaces, and extracting corridors (Peng et al., 2018b). This approach aims to optimize ecosystem patterns and enhance the integrity and sustainability of regional ecosystems. However, the ecological security pattern constructed based on the existing land use pattern often fails to reflect the future impacts of both human activities and natural factors on landscapes. Current research mainly focuses on the prediction of LUCC and the simulation of ecological security pattern, combining LUCC simulation with the evaluation of ecological security pattern (Li D. et al., 2020). Through LUCC, ecological security can be reflected. In recent years, some studies have conducted dynamic predictions of ecological security based on LUCC simulations, such as cellular automata (CA), agent-based models (Teng et al., 2011), CA-Markov (Kang et al., 2019), conversion of land use and its effects (CLUE) model (Zhou et al., 2016), the future land use simulation (FLUS) model (Zhang et al., 2020), and the patch-generating land use simulation (PLUS) model (Liang et al., 2021). Due to the inherent uncertainties in LUCC simulation and the evaluation of ecological security patterns, it is crucial for future research to incorporate more evaluation indicators and consider the influence of policies on LUCC. This will enhance the accuracy of the evaluation and increase its practical significance.

3. Food security

In recent years, there has been a growing global concern on food security, with zero hunger (no hunger) being one of the UN Sustainable Development Goals. Research indicates that by 2050, the global food demand is expected to increase by 70 to 100% (Godfray et al., 2010), and it has become a major challenge to balance the growing food demand of the society and the regional sustainable development (Foley et al., 2011). To tackle this problem, scholars have been trying to combine LUCC data and different models to evaluate and simulate food security. Schneider et al. (2022) predicted global future cropland resources under different climate paths based on existing LUCC data; Li S. et al. (2023) built an analysis network based on LUCC data to assess regional grain production changes, and found that urbanization of the Loess Plateau will not endanger local food security; Sun et al. (2023) built an early warning system for cultivated land resources based on LUCC data in order to achieve the sustainability of food security, economic development and ecological protection.

Other than directly being linked to LUCC, food security is often used as a land use change scenario to predict future regional land use. For example, Gomes et al. (2020) and Wang et al. (2023) considered ensuring food security as one of the future scenarios, and predicted future land use changes in the study area as such respectively. In addition, LUCC could also be used as the basis data for trade-offs between ecological security and food security, e.g., Wang et al. (2022) provided a basis for trade-offs/synergies between farmland and ecological land by quantifying the evolution of landscape gradients of ecological land and agricultural land under different scenarios. Overall, most of the current studies link food security with cultivated land or farmland resources. However, Zhu et al. (2023) pointed out that with the change of dietary structure, the single food supply mode relying on cultivated land resources needs to be replaced by those relying on multiple types of land resources (such as forest land, grassland and lakes). Considering the fact that current research based on LUCC rarely takes into account the changes in dietary structure and the balance of multi-nutrient, it is needed for future research consider the changes in food consumption structure in different regions, and set up different nutritional structure scenarios for different land use types, in order to provide a more in-depth and comprehensive scientific basis for promoting food security.

4. Climate change

While LUCC has brought benefits to mankind, the expansion of farmland, pastureland, plantation forests and cities has also brought many problems such as ecosystem degradation and loss of biodiversity, of which the impact of LUCC on climate has also received widespread attention worldwide (Liu et al., 2014). Global climate change has become the major and most pressing global environmental issue in recent years (Deng et al., 2013). The Sixth Assessment Report (AR6) illustrates that global temperatures have risen by 1.1°C and that all regions of the world are facing unprecedented changes in the climate system, from rising sea levels and frequent extreme weather events to the rapid melting of sea ice (IPCC, 2022). Further increases in temperature will further exacerbate these changes. For example, for every 0.5°C increase in global temperature, extreme heat, heavy rainfall and regional droughts will become more frequent and more severe.

LUCC has played a crucial role in contributing to regional and global climate change since the industrial era by driving surface energy flows and material exchange (Salazar et al., 2015). Human-involved changes in land use change, such as over-exploitation of forests, agricultural intensification and urbanization, have not only accelerated global warming through increased greenhouse gas emissions but have also caused irreversible biodiversity loss on a global scale in general (Song et al., 2009). Changes in land use can affect climate through biogeochemical and biophysical processes. The effects of LUCC are evident in two key processes: atmospheric and surface radiation/energy exchange, and carbon regulation. LUCC significantly impacts the global climate through greenhouse gas emissions, which are well-documented. On one hand, it alters the carbon cycle by emitting or absorbing atmospheric greenhouse gases (Li et al., 2017). Consequently, biogeophysical processes may lead to similar or greater regional climate change. On the other hand, changes in surface albedo and roughness resulting from LUCC affect the surface heat budget and vertical water vapor transport (Liu et al., 2016). These changes influence temperature, humidity, wind speed, evapotranspiration, and other factors, thus impacting climate through a range of biophysical processes. LUCC modifies the surface pattern of sensible and latent heat entering the atmosphere, which depends on factors such as temperature, precipitation, soil moisture content, and surface albedo (Mas et al., 2014). Thus, considering these biophysical processes can alter and sometimes reverse the relative values of ecological zones. Current literature emphasizes the feedback between climate and LUCC, extending beyond land use changes (Li Z. T. et al., 2020). However, quantifying the positive and negative effects of human activities on regional climate change remains an open question. Future research should examine the impact of LUCC on temperature and energy flux at different scales.

5. SDGs

LUCC is closely related to current economic, social, and environmental challenges, and is the core of various sustainable development goals. McElwee et al. (2020) conducted a review indicating that various land use type, such as farmland, pasture, and forestry, have more or less positive or negative impacts on most SDGs. Although LUCC such as deforestation and expansion of biomass plants are often seen as negative, "beneficial land use change" can simultaneously promote most SDGs (Englund et al., 2020). Specifically, agricultural land, as the basic guarantee of human nutrition supply, provides employment and income for the agricultural population, and is beneficial to many SDGs, including clean energy (SDG7), clean water (SDG6), and biodiversity conservation (SDG15). The intensification and sustainability of agricultural land play a crucial role in eradicating hunger and poverty, improving human wellbeing, and reducing environmental impacts (Kanter et al., 2018), thereby contributing to multiple SDGs. In addition, with the expansion of urban and construction land, the disproportionate relationship between land use efficiency and population growth has also had a new impact on SDG11 (Estoque et al., 2021).

The global optimization of land use change scenarios further enriched the relationship between land use change and multiple SDGs, explored potential synergies and trade-offs between SDGs caused by future land use changes in different countries, and extracted SDGs that urgently need to be strengthened in the future (Heck et al., 2018). Stehfest et al. (2019) predicted future global land use development and found that land use will have multiple impacts on biodiversity, food security, or climate related factors, revealing the transformation of future land use patterns involves multiple specific goals such as SDG1, SDG2, SDG13, SDG14, and SDG15. Besides land use change, the management of land use such as afforestation have a positive impact on SDG13, but the types of impacts on other SDGs varied (Smith et al., 2019).

LUCC management regulations and behavior of consumption have great potential to affect future land use cover/change, which are crucial for SDGs. As a central element of sustainable development strategies, research on their potential is not representative in current models and should receive more attention in future evaluations. Moreover, different land use transformations can lead to interactions between land system elements, resulting in heterogeneity of potential benefits and trade-off among negative impacts, leading to heterogeneity of potential benefits and tradeoffs between negative impacts, resulting in uncertain heterogeneity for multiple SDGs. The balancing analysis of multiple objectives in land use systems has become an increasingly important field.

6. Conclusion

Future LUCC research should embrace cutting-edge technologies like big data and artificial intelligence, while incorporating a wider range of evaluation indicators and considering the influence of policies. These efforts will significantly improve the accuracy of LUCC models and predictions. Moreover, a comprehensive understanding of the environmental consequences of LUCC is imperative. Ultimately, striking a balance between multiple objectives and trade-offs, such as ecological preservation and sustainable socio-economic development, becomes paramount within the constraints of limited land resources. Pursuing these research directions will provide a vital scientific basis for better comprehending the impacts of LUCC on ecosystems and human societies, while offering guidance and decision-making support toward achieving a sustainable future for humanity.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

JZ declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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