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Land system science in Latin America: challenges and perspectives

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This article reviews the current status, trends and challenges of land system science in Latin America. We highlight the advances in the conceptualization, analysis and monitoring of land systems. These advances shift from a focus on the relationships between forests and other land uses to include a greater diversity of land cover and land-use types and the processes and interactions that link them. We then provide a biome-level typology of social-ecological land systems (SELS) as an approach to help connect local-level realities to regional processes and we discuss how this approach can help to design more socially inclusive land systems. We also discuss the increased role of distant socio-economic and ecological interactions that connect these SELS to global processes. Combined, these insights support a research agenda for land system science in the region that can develop more accurate and integrative monitoring of land change and their social and ecological consequences, better understand different stakeholder perspectives within a context of livelihood diversification, and encourage institutional feedbacks to govern land systems influenced by distant drivers.

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Introduction

Land System Science (LSS) is a recent integrative field of research and practice in the natural and social sciences that seeks to address the terrestrial components of the Earth System and design solutions for their sustainability [1]. The Global Land Programme (GLP), a core project of the Future Earth research programme on global sustainability, has identified key achievements, challenges and future prospects for LSS [2••]. Besides such global synthesis efforts, land system science has contributed to examining regional-level environmental change, the trade-offs and potential synergies between these changes, and potential scenarios and alternatives [3].

This article focuses on Latin America and has the objective of identifying the current status, trends, challenges and perspectives of LSS in the region. The further development of LSS entails understanding land changes in relation to social-ecological processes in order to contribute to develop solutions for the sustainability of land systems [2••]. We focus on key advances, challenges and perspectives in four key avenues related to these goals: (1) monitoring change in land systems, (2) conceptualizing social-ecological land systems, (3) designing socially inclusive land systems and (4) governing telecoupled (distantly interacting) land systems.

These four avenues are related to the unique characteristics of the region in terms of the diversity of its social-ecological systems, regional history, demographic patterns and connections to other global regions. Latin America harbors one fifth of the world's forests [4••], the greatest terrestrial biological diversity of ecosystems on Earth [5] and areas of crucial importance for carbon sequestration and climate regulation [6]. Latin America is also the largest world region with an overall positive bio-capacity reserve [7], namely the natural ability to provide the resources and ecosystem services that are consumed by people each year [8]. Agriculture is expanding rapidly, largely to supply increasing global demand (particularly from Asia) for calories and protein [9]. Livestock ranching also occupies an exceptionally large share of the landscape, with a general pattern of low animal density [10••]. Finally, the urbanization rate in Latin America is among the highest globally, with the rural population declining from 50% to 25% of total population between 1960 and 2000 [11].

Land change monitoring in Latin America has notably diversified its scope beyond binary forest/non-forest data (first section), opening up opportunities to address land change in relation to social-ecological processes made visible at the biome level (second section). On the other hand, transformation toward more sustainable land systems is challenged by rural economic changes, high urbanization and revalorization of land due to global demand. The challenges of designing and governing globally connected land systems in this context are discussed in third and fourth sections.

Monitoring change in land systems

In Latin America, monitoring of land change has historically concentrated on the forest/non-forest distinction using satellite imagery, particularly of the Landsat generation starting in 1972. The first large-scale monitoring system in the region was the Project for Estimating the Annual Gross Deforestation in the Brazilian Legal Amazon (PRODES), implemented in 1988 [12]. PRODES contributed to public awareness and policies by providing spatialized and quantitative data on deforestation [13••]. Monitoring of deforestation in near real time started in 2004 [14] and later included forest degradation estimates [15]. PRODES data were also combined with socio-economic data to assess the human drivers of deforestation [16]. Other tools, such as CLASlite, were developed to cover the whole Amazon region [17]. Recent studies have addressed land change processes across borders at the interface of forest with other land covers [18•]. The release of global high-resolution forest cover change data [19] has created opportunities for local, regional and global studies (e.g., Ref. [20••]). Challenges remain in terms of monitoring differences in forest cover types and transboundary land change [21•] and relationships between land change, biodiversity and ecosystem services (including their patterns and critical thresholds) [22]. The need for countries to assess and report on carbon emissions has led to advances in estimation and monitoring of biomass associated with different types of land cover [23]. Nevertheless, differences of up to 50% in biomass values across different density maps have led to uncertainties in carbon emissions assessment [24••].

Recent studies have produced data that go beyond binary forest/non-forest classifications. In Brazil, a broader array of land-use classes for deforested areas is being developed under the TerraClass project [25]. The ability of remotely sensed data to distinguish land cover types with similar structural features (and thus spectral signatures), but representing different land uses, such as different types of annual crops, intensively used grasslands versus natural grasslands, or forests versus agroforestry systems, perennial crops (oil palm, cocoa) and tree plantations, remains a key challenge. This is especially crucial in areas where intense land cover conversion is occurring [9]. Advances exist in assessing degradation in dry forests [26•] and the dynamics of croplands and pasturelands, including successional processes [27••]. Studies have improved knowledge of vegetation recovery, which occurs in contexts with divergent trajectories of intensification and forest transitions in most Latin American countries [9]. Nevertheless, these advances have yet to be integrated into official monitoring systems, complicated by the diverse and often inconsistent land-use and land-cover classification systems used among countries and even between agencies within a country [28]. This creates both opportunities (i.e., representation of diverse classifications and approaches) and limitations (i.e., difficulties with comparison and scaling). While the imposition of a unifying classification system is not desirable, better linkages between case and project specifics and agreed upon reference classification systems are needed.

Addressing land changes in the region also requires studies that focus on non-forest contexts. Urbanization is one key process driving land change in Latin America: cities cover a relatively small surface area, but they strongly influence land-use at the regional and global scales. Remote sensing of city locations and extent has been performed at a global scale [29] and provides a starting point to assess urbanization in the region. In general, fine-grain studies have greater potential to assess subtle changes and more complex landscapes not necessarily tied to forests. For example, a study at the level of individual fields in the Bolivian Andes linked agrobiodiversity dynamics with livelihood diversification [30••]. High-resolution studies are especially needed in mountainous and hilly environments, which are important for water provision and regulation, biological diversity and cultural diversity. In these places, rough topography, very heterogeneous landscapes and small-scale processes challenge continuous 'wall-to-wall' monitoring systems, visual and digital interpretation and multi-temporal approaches.

Understanding the links between land change and social-ecological interactions also requires close connections between remote sensing data, field observations and official statistics. This is still a challenge in the region, where spatial statistics about livestock distribution are scarce, agriculture statistics are rarely informed by remote sensing and mapping efforts are often based on limited training and validation data. The era of big data provides a much broader toolset to respond to the questions and needs of scientists, policy makers, civil society organizations, private industry and governments, which are as diverse as the regions they are mapping. In this context, the promotion of open access satellite data, currently controlled by governments and private companies, should continue to be a priority [31•]. The availability and use of satellite imagery for real-time land cover and land-use data [31•] has promoted research and applications in the public and private sectors and helped the involvement of stakeholders in the wider public to achieve a more complete understanding of land-use dynamics.

Conceptualizing social-ecological land systems

Understanding and assessing land change through a social-ecological systems perspective [32,33] is another key challenge for land system science in Latin America and elsewhere [2••]. We suggest 'social-ecological land systems' (SELS) as a unifying concept, with each SELS defined and characterized by its particular configurations of social and environmental conditions, settlement patterns, land-use dynamics and contextual factors. These are nested systems that can be analyzed from fine to intermediate to coarse grains. They may function as complex adaptive systems, with humans profoundly dependent upon constituent biomes and ecosystems while acting as principal agents of land transformation [34,35]. The SELS approach is intended to help bridge the divide between local and regional land change processes and inform regional to global interactions in land system science.

A simplified biome-level typology for Latin American SELS (Table 1) shows the processes, trends and characteristics, which shape their structure, functioning and dynamics. Each of these biome-level SELS types reflects change regimes tied to different geographies, settlement and economic histories, institutions, resource management practices and technologies and the differentiated influence of local to global forces [36,37]. Diverging land cover trends, including deforestation, forest stabilization and forest resurgence [9] are leading to processes of landscape hybridization, where traditional and modern land-use elements combine or overlap with processes of land cover fragmentation, simplification, or recovery. These are reflective of interactions among global financial markets, national governments' rural development policies and the livelihood choices of local land users [37]. Finally, the effects of climate change on biodiversity and agricultural production are felt differently among SELS according to geography, land-use context and the adaptive capacity of local societies [38].

An understanding of SELS patterns and dynamics requires knowledge of land tenure and acquisition processes. Land tenure issues have become particularly relevant in light of current revalorizations of land and the consequent potential for agrarian conflict [39]. While privatization and land concentration have historically been associated with European colonization and its appropriation of previously held commons [40], a new wave of enclosures has taken place in recent times, affecting larger areas than previously thought [41]. These enclosures are not only linked to agro-industrial expansion, but also non-food sectors such as mining [42••], industrial forestry [43], conservation, carbon storage and biofuels [44]. In some places, these processes have been resisted by social pressures and state promotion of devolution and decentralization policies [45]. This has permitted territorial control by indigenous groups and smallholders at an unprecedented scale [46] and limited land markets and land concentration, as evidently shown in countries with a strong 'agrarianism' tradition, such as Mexico, Guatemala, Peru and Bolivia [47••,48]. It remains to be seen whether local resistance will decrease in proportion to livelihood diversification, off-farm work and rural depopulation [48].

Table 1

A typology of biome-level social-ecological land systems (SELs) in Latin America

Biome-level social-ecological land systems (SELS) types	Main geographical areas	Main processes, trends and characteristics
South American Lowlands: new agropastoral areas.	Amazon; Chaco; Pantanal; 11 countries involved	Forested areas with relatively rapid rate of land-use change through demands of commodity markets. Cattle ranching and expansion of agricultural frontiers add to forest degradation due to logging. Shifting to larger management/production units in some areas, while in others a diversity of land systems dominates. Of specific concern to conservation planners due to high rates of deforestation, biodiversity loss and carbon emissions. New land uses in conflict with long-settled indigenous and local communities. Expansion of indigenous and protected areas, including sustainable use reserves. Chaotic urbanization and peri-urban expansion. Dramatic increases in the agricultural productivity have enhanced their contributions to national economic growth and global food security.
South American Plateau-Lowlands: agropastoral historical areas	Pampas grasslands of Argentina, Uruguay and Brazil; Brazilian Cerrado; Colombian and Venezuelan Llanos	Long history of cropland and ranching settlements. Significant expansion in recent decades of the size of agricultural and livestock farms and, in recent years, large-scale land acquisitions. High-tech agribusiness in the Cerrado (soybeans, maize and other grains and fibers) increasingly surrounding indigenous and conservation areas, contributing to pollution of rivers and wetlands and the fragmentation of habitats.
South American Highlands and Altiplano	Tropical Andes (northern and central sections of the Andes); Eastern Andean Foothills	High diversity of landscapes, most with long histories of human settlement. Characterized by small, subsistence-oriented management units, high cultural and agro-ecological diversity and limited mechanized agriculture. Relatively high levels of biodiversity and endemism found within anthropogenic landscapes. Increasing integration during the past half-century with lowland areas and urban centers, and elevated rates of rural out-migration as part of a general process of livelihood diversification. May become peripheral as political power and people move to the lowlands, while opened up to new wave of mining and tourism activities.
Mexican and Central American Highlands	Mesoamerican highlands; Mexican pine-oak forests	Similar characteristics and processes to those in South American Highlands and Altiplano SELS, but more integrated into global markets and increased livelihood diversification influenced by international markets, international migration and remittances, especially in Mexico and, to a lesser degree, Guatemala, Honduras and El Salvador. Home to many biodiversity hotspots and a priority for conservation planners due to concerns over fragmentation, poor landscape connectivity and small patch size.
Dry- and Mediterranean Lands	Northern and Central Chile; West of Argentina; North-Eastern Brazil (Caatinga); Chihuahuan and Sonoran deserts	Dominated by irrigated agriculture within large matrices of semi-arid shrublands, with extensive livestock grazing (particularly goats) and recent expansion of high capital crops (e.g., vineyards, olives, fruit orchards). Various degrees of urbanization. Conservation concerns due to high species endemism and extensive degradation driven by capital-intensive land-use and extensive cattle ranching.
Coastal Agricultural Lands with long colonization history	Atlantic Forest of Brazil. Pacific and Caribbean coastlines of Latin America	Long history of human occupation with mixed land and forest usages, characterized by highly degraded and threatened natural ecosystems (e.g., 'lomas costeras', dry tropical forests, wetlands). Traditional tropical crops such as sugar cane and coffee and expanding crops such as oil palm or eucalyptus. Important biomes such as Brazil's Atlantic forest have become highly fragmented. Some areas have shifted to export-oriented irrigated agriculture, large-scale land acquisitions for tourism and other developments. Home to high population densities (in major urban areas) and the concentration of political and economic power.
Southern Temperate Forests and Drylands	Patagonia of Chile and Argentina	Growing tourism and forestry plantations (based on exotic conifers); decreasing agriculture and livestock. Extensive formal conservation, largely due to high scenic value and relative low agriculture value.

Designing socially inclusive land systems

The design of 'optimal' land system architectures (i.e., that maximize positive trade-offs) has been identified as a particular problematic facing land system science [49]. However, as the complexity of regional landscape mosaics increases, so does the divergence in how these systems are perceived and valued by different land users and related stakeholders, making the definition and design of 'optimal' land systems a societal challenge.

The land optimization debate has been largely framed as a trade-off between a spatial integration of fragmented land uses and functions (the 'land sharing' model) and a spatial segregation of those in homogenous units (the 'land sparing' model) [50••,51]. Sparing models, which combine areas of intensive, capital-based agro-industrial production with areas excluded from productive uses, typically maximize economic returns per unit of land in use [52] and often offer the best alternative to balance agricultural production and biodiversity conservation. Land sharing arguments instead rely on connecting cultural and biological diversity [53••] to achieve landscape sustainability and thereby optimize social and environmental dimensions of land-use systems. This dichotomy, however, is over-simplistic [51]. Rather, the diversity of Latin American SELS requires more complex analytical frameworks, which acknowledge different spatio-temporal frames and trans-scale complexity in both natural and human ecosystems, non-linearity of SELS processes and the importance of ecosystem services assessed in light of stakeholder perceptions. A large part of Latin American food production will continue to be generated in low-diversity, mechanized agricultural systems. However, more efforts need to be directed to the efficient transfer of resources from these highly productive areas to the conservation of 'spared' ecosystems and to address the environmental costs of input-intensive production systems. On the other hand, many diverse agroecosystems, particularly in mountains, will continue to contribute to local food security and the maintenance of agrobiodiversity and ecosystem services. It becomes critical to acknowledge the value of livelihood diversification, dynamic landscape values and incorporate new social networks in decision processes and land optimization designs [54••].

Experiences with participatory appraisal in some areas of Latin America offer a starting point to address these goals by supporting negotiation among multiple stakeholder groups. Examples include territorial planning with Afro-Brazilian communities [55], place-based landscape ethnoecology [56] and the elaboration of participatory scenarios at multiple scales [57••]. Although imperfect [58], the recently implemented forest law of Argentina (Ley 26.331) produced a national forest zoning plan through a participatory process [59]. To develop more equitable, just and sustainable landscapes, participatory approaches must integrate stakeholder perceptions of ecosystem services and landscape values as they shift across time and space, and consider how institutions and markets translate these perceptions into economic decisions that can yield more desirable landscape configurations.

Livelihood diversification also calls for more explicit integration of urban economies into land system design. In Latin America, urban centers have a disproportionate influence in terms of population and political and economic power. However, with rare exceptions [60••], participatory initiatives have usually focused on small rural populations, neglecting the fact that decisions taken in cities are hugely influential on rural environments, both in terms of disrupting and stabilizing processes [61]. Understanding the mechanisms and pathways of these urban–rural connections (both domestic and international) is a major research focus for the region [62••].

Governing telecoupled land systems

LSS has also increased its focus on distant drivers from natural and human systems, including feedbacks that influence social-ecological systems. The telecoupling framework [63••] focuses on sending, receiving and spillover systems, flows, agents, causes and effects related to SELS. Telecouplings can broaden local options for capital and knowledge transfer, but also challenge governance in communities, local and national governments, especially when there are scale mismatches between local regulations, globalized drivers and feedbacks of land change [64••]. As major commodity and workforce exporters, some Latin American SELS are strongly affected by international global drivers and processes [65], with examples ranging from the effects of migrant remittances on Central America and Mexico [66], to the collapse of the Soviet Union on Cuba [67], the booming gold demand associated with financial crises [42••], the multiple impacts of growing demand for agricultural products (from industrial crops to niche crops), as well as international pressures for environmental conservation.

The long and highly influential history of distant social-ecological forces in Latin America (starting with colonial trade in the 16th Century) favors stakeholders who can mobilize large-scale capital for resource use [68]. Telecouplings challenge territory-based governance [39], even when users enjoy secure land rights, through spillover effects. Globalization can force rates of change that are difficult to adapt to, and produce unexpected shocks on local land users [67,69]. Even some SELS that are not directly affected by these drivers are characterized by significant out-migration [70••], resulting in a 'new rurality' [71] that creates opportunities for other stakeholders to emerge and fill any void, while also exacerbating chaotic urbanization and urban expansion [57••,60••].

An example of the importance of agricultural commodities for distant markets is the soybean-cattle ranching system in Brazil, Argentina, Bolivia and Paraguay, which has expanded to supply major markets such as China [68,72••]. Along with nationally driven development policies, this expansion made Latin America a global deforestation hotspot [19], affecting the Amazon rainforests [73], the Chaco and Chiquitania dry forests, the intensification of agriculture in the pampas [68] and catalyzing a new wave of conflicts involving traditional communities [59]. Because the export of agricultural commodities represents an important revenue for national economies, it can undermine local and national environmental regulations [74••], relegating initiatives such as the 'zero-deforestation' commitment in supply chains or the 'soy moratorium' in Brazil to non-binding agreements [75]. Territorial-based regulations are also challenged by novel agribusiness strategies, such as multi-location production, discontinuous land acquisitions, land leasing and high mobility with minimum fixed capital [72••,74••]. They are also challenged by the functional interdependence of biophysical systems [76]. For example, large-scale moisture transport in the atmosphere [77] ties land change and deforestation in Amazonia to the provisioning of water in highly urbanized centers in the south and southeast of Brazil [78]. The regulation of agro-industrial production could become a divisive policy issue if seen from the perspective of its contribution to water scarcity in large urban centers.

Regional integration initiatives such as trade agreements and trans-boundary infrastructure represent other forms of telecouplings. An example is the Inter-Oceanic Highway (IOH) in the southwestern Amazon, part of the Integration of Regional Infrastructure in South America (IIRSA), which links the Amazonian resource frontier to both Atlantic and Pacific ports. The opening of the IOH has increased migration from the Andes, gold mining and fruit production and accelerated forest loss [79]. Land governance has become particularly challenging at the tri-national frontier of Bolivia, Brazil and Peru. Grassroots environmental planning initiatives emerged under the 'Madre de Dios-Acre-Pando (MAP) Initiative' [80], which held public stakeholder forums on issues related to environmental conservation, economic development, social equity and public policies. The MAP initiative has helped foster inter-organizational and international collaboration [81]. The emergence of institutions as a feedback component of telecouplings can advance the multi-level governance of trans-boundary drivers of land change, such as cross-border infrastructure [81], and could be replicated elsewhere.

Conclusions

In this article, we focused on four avenues of land system science around which a regional research agenda for Latin America can be constructed: monitoring change in land systems, conceptualizing social-ecological land systems, designing socially inclusive land systems, and governing telecoupled land systems.

More accurate and integrative monitoring of land change and its social and ecological consequences is needed. Pragmatic approaches to deforestation analysis have aided our ability to assess the distribution and rate of change, and inform the public about the scale and consequences of forest clearance. Yet further monitoring tools are required that provide for a finer-grain discrimination across land-use/cover classes, including dry forests, grasslands, mountains and urban areas. This can be facilitated by open access to satellite-based data, national statistics and field surveys, thereby helping to expand the scope and detail of participatory assessments. Such outcomes are dependent upon improved coordination across all sectors involved in monitoring work.

Finding integrative sustainability solutions to complex land change processes also requires a better understanding of their interactions, so that policies and regulations seeking to address specific processes do not interfere with one another. The concept of SELS allows for a focus on the interactions among dynamic social and environmental processes and helps to connect local- with regional-level land change. The SELS concept also highlights the perspectives of diverse groups of stakeholders, which if properly harnessed can better inform land system analysis and contribute to a more democratic and robust planning and policy making process. Latin American researchers can build on a strong tradition of participatory assessment and planning to help achieve this goal, with care taken to encapsulate both rural and urban stakeholders, embrace multiple governance levels and address the spatio-temporal dimension of landscape values.

Finally, from colonial trade to contemporary global value chains, Latin America has been characterized by historically strong influences of distant socio-economic couplings on land governance. These telecouplings entail challenges to sustainable land governance, but also offer opportunities, through feedbacks, to improve scale matching in governing, regulating and sustaining local SELS.

By building upon the above-stated suggestions and insights, Latin American land system science may contribute to the collective understandings of land change processes and to the identification of the enabling policy conditions needed to secure ecologically sustainable and socially inclusive management systems for the region's terrestrial resources.

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