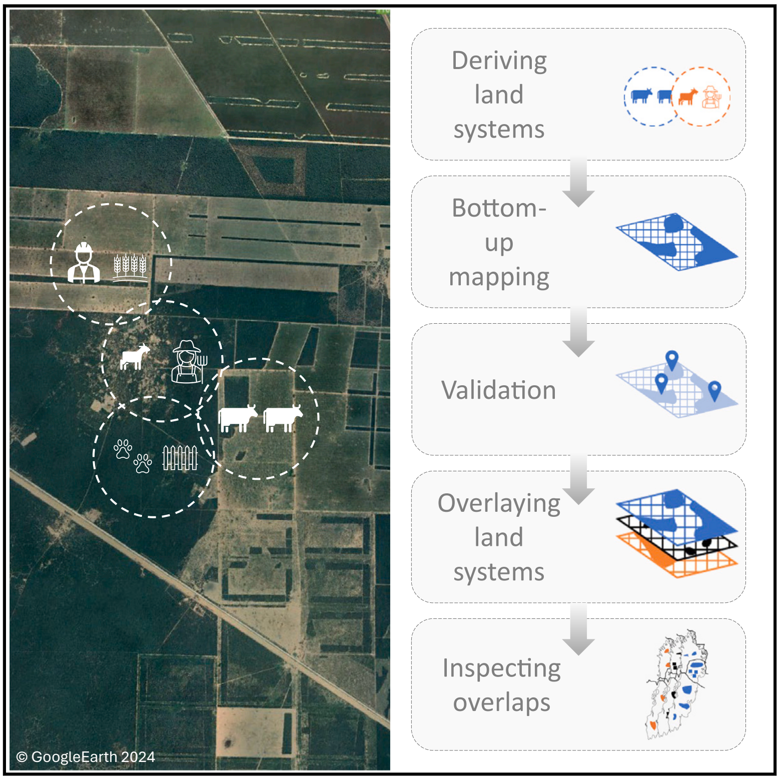
One Earth

Article

Considering land use complexity and overlap is critical for sustainability planning

Graphical abstract



Highlights

- Our approach allows mapping of the complex and contested nature of land use
- Our maps visualize land use actors that are often underrepresented or marginalized
- 35% of the area has overlapping land uses, possibly indicating land competition
- The main overlaps occur between capitalized and smallholder land uses

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In brief

Land use is often oversimplified in broad-scale sustainability assessments despite being central to many sustainability challenges. We developed a new approach that maps land use as social-ecological systems that can overlap in space. Our maps revealed typically overlooked actors, such as forest-dwelling smallholders, and highlighted substantial overlap between actors, particularly between smallholders and agribusinesses. This overlap can indicate land competition and potential conflicts, posing a risk to marginalizing smallholders.

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Article

Considering land use complexity and overlap is critical for sustainability planning

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SCIENCE FOR SOCIETY Although land use is both a driver and a lever of sustainability challenges, like biodiversity loss, climate change, and food security, it is often oversimplified in spatial planning. Most importantly, the diversity of land users is frequently ignored; for example, by overlooking forest-dwelling communities that are harder to detect in broad-scale data than large-scale agriculture. This can lead to ineffective and inequitable sustainability planning. We developed an approach to address this risk of oversimplification and underrepresentation. Our maps reveal the spatial footprint of typically overlooked people, such as Indigenous communities or smallholders, and uncovers substantial overlaps between different land uses, particularly between smallholders and agribusinesses. Our study shows how ignoring the diversity of land users can hide competing interests and conflict over land, which, in turn, can perpetuate or introduce injustices and miss opportunities for co-benefits.

SUMMARY

Land use is both a driver and a lever to address sustainability challenges like biodiversity loss, climate change, and food security. Yet, it is often oversimplified in sustainability planning, ignoring the diversity of actors or the multiple claims on land. We developed an approach to capture the complex and contested nature of land use by mapping it as social-ecological systems that can overlap in space. Demonstrating our approach for the Dry Chaco and Chiquitano forests in South America revealed three main insights. First, we mapped actors that are typically overlooked, such as forest-dwelling smallholders. Second, substantial land use overlap, particularly between smallholders and agribusinesses, signals land competition that risks marginalizing smallholders. Third, our maps showed conservation areas overlapping with other land systems, highlighting opportunities for co-benefits but also competition. Overall, our transferable approach captures land use complexity and visualizes often overlooked actors, thereby potentially contributing to more just and effective sustainability planning.

INTRODUCTION

While considerable efforts have been made to evaluate and map the ecological value of landscapes across the globe,[1,2] less attention has been given to understanding and representing social diversity and human-nature interactions in sustainability planning, such as conservation or land use planning.[3,4] This is particularly the case at broad geographic extents, for which data that adequately describe people, their relations to the environment and, more generally, social-ecological conditions are often lacking.[5,6] Given the increasingly broad-scale nature of sustainability assessments, better representing people in them is critically important.[7]

Land use is pivotal in this context. Although land use underpins global and local food security, it is also a main driver of the biodiversity crisis and climate change.[8,9] Addressing how we use land thus constitutes a major opportunity for addressing these intertwined sustainability challenges.[8,10] This is increasingly recognized, as ambitious visions of how to use land more sustainably, how to protect remaining natural areas, or how to restore degraded lands are formulated, such as in the context of the Montreal-Kunming targets of the Convention on Biological Diversity, the United Nations Decade of Restoration, the Bonn Challenge, the Glasgow Forest Declaration, or the Half-Earth Proposal.[11–13] Translating such visions and policies into action and changing land-use patterns on the ground, however, require sustainability planning and prioritization, including land use planning, conservation planning, and restoration planning.

Such planning has so far often treated the diversity of land use in overly simplistic ways, particularly at broad geographic scales, raising concerns about whether planning outcomes will be effective and just.[14–16] First, the diversity of land use actors has often been overlooked, although they are the ones making decisions over land and the ones being most directly impacted by land use planning, especially when they live in landscapes of high conservation value.[7,17] Overgeneralization of actor diversity can lead to ineffective sustainability policies[18,19] and agendas misaligned to local needs, which often results in conflict and conservation failure.[4] Second, the diversity of land use activities has often been reduced to just agriculture. This falls short of representing the various agricultural practices leading to different levels of land use intensity and manifold impacts on nature. Furthermore, it also neglects a wide range of non-agricultural activities, such as hunting, mining, or conservation. Third, assessments and planning often fail to capture the complex reality of co-occurring, interacting, and sometimes conflicting land uses in the same landscape. Planning exercises typically assume that a piece of land serves a single purpose and is used by a single actor or actor group. Such categorizations can be problematic where land uses overlap (e.g., smallholders embedded in landscapes dominated by agribusinesses and Indigenous people using forests that are inside protected areas), effectively masking out interacting or competing land uses, and thus power imbalances or land use conflicts.[20,21] This is particularly important as a large proportion of land globally is characterized by shared, unclear, or contested claims on land.[22,23]

At least three main factors have contributed to persistent oversights of the diversity and complexity surrounding land use in sustainability planning. First, land use continues to be approximated by land cover, particularly at broader scales for which high-quality land use data are scarce.[16,24] Second, actor diversity is overgeneralized too often[25,26] or altogether ignored when relying on crude proxies, such as population density or generalized opportunity costs, which inadequately capture the sociocultural reality on the ground.[27,28] And third, hegemonic theoretical and analytical underpinnings of mapping efforts have usually produced categorical representations of land use, overlooking the diversity of multiple, potentially co-occurring land uses that are hidden within broad categories (e.g., cropland and forest).[29,30]

Considering these challenges, we developed an approach to better represent land use diversity and complexity in sustainability planning, such as conservation or restoration planning. Conceptually, we built on a hierarchical, expert-based land system typology that structures the diversity of land use actors and activities in a bottom-up manner.[31] Land systems are here defined as typical combinations of land use actors and their activities. Although our approach is principally generic, we here focus on (sub)tropical dry forests, woodlands, and savannas (hereafter called tropical dry woodlands). Despite being among the most threatened ecoregions globally, dry woodlands have often received less attention from policymakers, funders, and the public compared to tropical rainforests.[32,33] This is especially alarming, as high and rising pressure, including from industrial agricultural expansion, not only puts at risk the unique endemic biodiversity harbored and carbon stored in tropical dry woodlands[34,35] but also undermines the livelihoods of millions of rural people in some of the world's poorest areas.[36–38] Effective and fair planning for such socially and ecologically vulnerable regions requires data on land use actors and processes, which, unfortunately, is rare or lacking for most tropical dry woodland regions

Here, we develop and demonstrate an approach to represent and visualize the diverse, co-occurring, and potentially competing land uses in a region instead of producing a map where every mapping unit (e.g., grid cell or administrative unit) is, by design, allocated to a single category of land use. We demonstrate this for the vast Dry Chaco and Chiquitano forests extending from Bolivia to Paraguay and into Argentina (950,826 km^2). This region faces some of the highest deforestation rates globally, making it a major source of carbon emissions, a hotspot of biodiversity loss, and a hotspot of conflict over land.[39–41] Specifically, our research questions were as follows:

(1) What is the spatial distribution of diverse land use actors and their activities in the Dry Chaco and Chiquitano forests?
(2) Which land uses co-occur, and what are typical configurations of overlapping, interacting, or conflicting land uses?

By mapping land systems from the bottom up, based on the identification of specific land use patterns associated with different land use actors, through expert knowledge and observation, we were able to reveal (1) actors that are typically hidden or systematically underrepresented, such as forest-dwelling smallholders, and (2) substantial overlaps among land systems, especially between smallholders and agribusinesses, signaling land competition that risks marginalizing smallholders. Overall, our approach provides a transferable and scalable pathway to capturing land use complexity in sustainability planning. It brings into focus overlooked actors, hard-to-map land use aspects, and contested land claims, contributing to more just and effective sustainability planning.

RESULTS

By mapping land systems individually and from the bottom up, we were able to create independent spatial representations

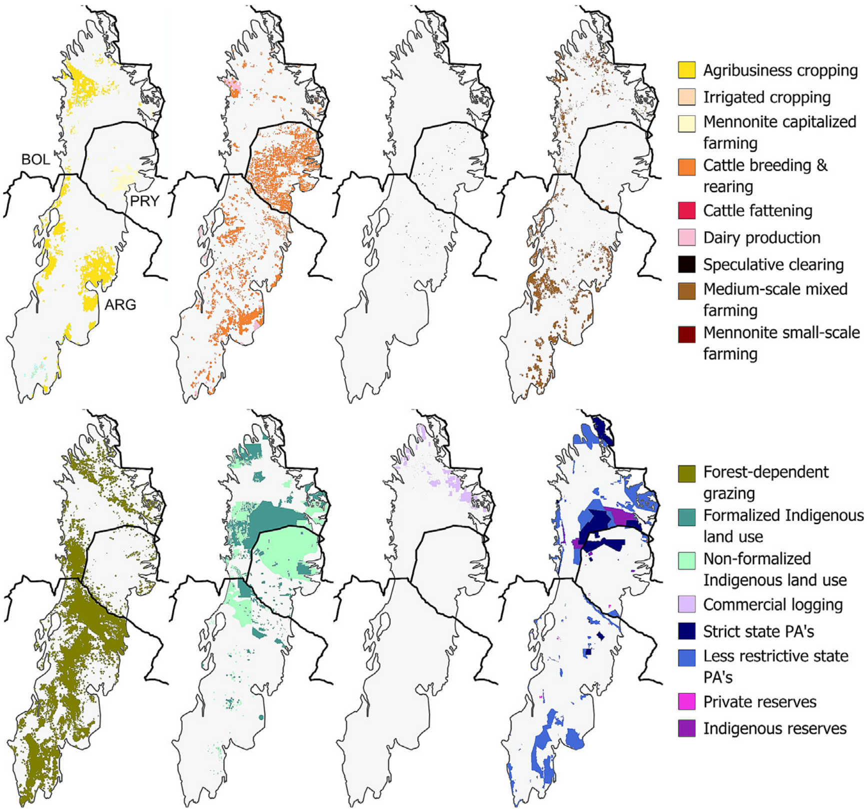

Figure 1. Maps depicting individual land systems grouped according to the overarching system from the global typology

Mining is not shown because it covers a negligible area. The black lines represent state borders.

that theoretically can, and often do, overlap in space. Our approach, based on identifying distinct land use patterns associated with different land use actors and their activities, resulted in plausible representations of land systems in the Dry Chaco and Chiquitano forests (Figure 1). Furthermore, our validation, using interview data, revealed an average agreement of 91% (Methods S3). Most land systems had agreement rates above 75%, with conservation, Indigenous, and Mennonite systems achieving 100% accuracy, followed by forest-dependent grazing (95%) and agribusiness cropping (88%). The lowest agreement rate was for cattle fattening (44%), which was frequently mapped as cattle breeding and rearing or sometimes as agribusiness cropping. Our point-based evaluation thus provides a robust method for validating land system maps but relies on extensive prior research and interview data. We note that we lacked such data for the Paraguayan part of the study region.

The most widespread land system we mapped was forest-dependent grazing, extending over 361,000 km^2, predominantly in the Argentinian and Bolivian Chaco and Chiquitano forests. This was followed by non-formalized Indigenous land use (155,000 km^2), with the largest contiguous area located in the northern Paraguayan Chaco, and cattle breeding and rearing (151,000 km^2), which appeared in all three countries but was particularly prevalent in the Paraguayan and Argentinian Chaco (Figures 1 and 2). The least widespread land systems, each covering <1,000 km^2, were mining, Mennonite small-scale farming, and speculative clearing. Further, 5.8% of the study area remained without any land system mapped (Figure 2), primarily comprising woodland-covered areas in the northeastern Chiquitano and Paraguayan Chaco, mountainous regions, and salt plains in the southern Argentinian Chaco (Figure 3). These unassigned areas are not necessarily unused but, rather, were not assigned to a system based on our decision criteria and available data. For instance, the forest-dependent grazing system was defined based on distances of forest use around homesteads, as documented in the literature.[42,43] Similarly, some of the datasets we used were potentially incomplete (for instance, on areas used informally by Indigenous people) or missing, such as forestry concessions for Argentina. More complete data would likely assign some currently unassigned areas to one of our systems.

Our land systems had diverse land cover compositions (Figure 2). While woodland and other natural vegetation cover fractions were highest in conservation, Indigenous, and smallholder land systems, interestingly, even industrialized land systems contained considerable shares of natural vegetation. In turn, conservation land systems also entailed some areas classified as cropland or pasture. Unassigned areas mainly comprised natural vegetation cover.

Our mapping approach revealed considerable spatial overlap among our 18 region-wide land systems (Figure 3). In total, 35% (334,000 km^2) of the study area had more than one system mapped, and 3% (37,700 km^2) and 0.2% (2,200 km^2) had more than two and three systems mapped, respectively (Figure 3A). The systems overlapping most with other systems were forest-dependent grazing, non-formalized Indigenous land use, and cattle breeding and rearing (Figure 3). We found considerable overlap between smallholder-related land systems and capitalized ones, specifically medium-scale mixed farming, small-scale Mennonite farming, forest-dependent grazing, or (non-)formalized Indigenous land use overlapping with agribusiness cropping, irrigated cropping, Mennonite capitalized farming, cattle breeding and rearing, cattle fattening, dairy production, speculative clearing, or mining (>108,000 km^2, 11.3% of the study area; Figure 3B). This type of overlap was especially prevalent in regions of expanding commodity frontiers, such as Santa Cruz, the central Paraguayan Chaco, Tartagal, Bandera, Córdoba, and San Luis. Similarly, we found substantial overlap between different conservation systems and other land systems in all three countries, both in less restrictive or private protected areas (9,800 km^2) and in strict state protected areas (PAs) (4,200 km^2) (together, 14.7% of the study area) (Figure 3B). Most of the overlaps correspond to smallholder land systems overlapping with

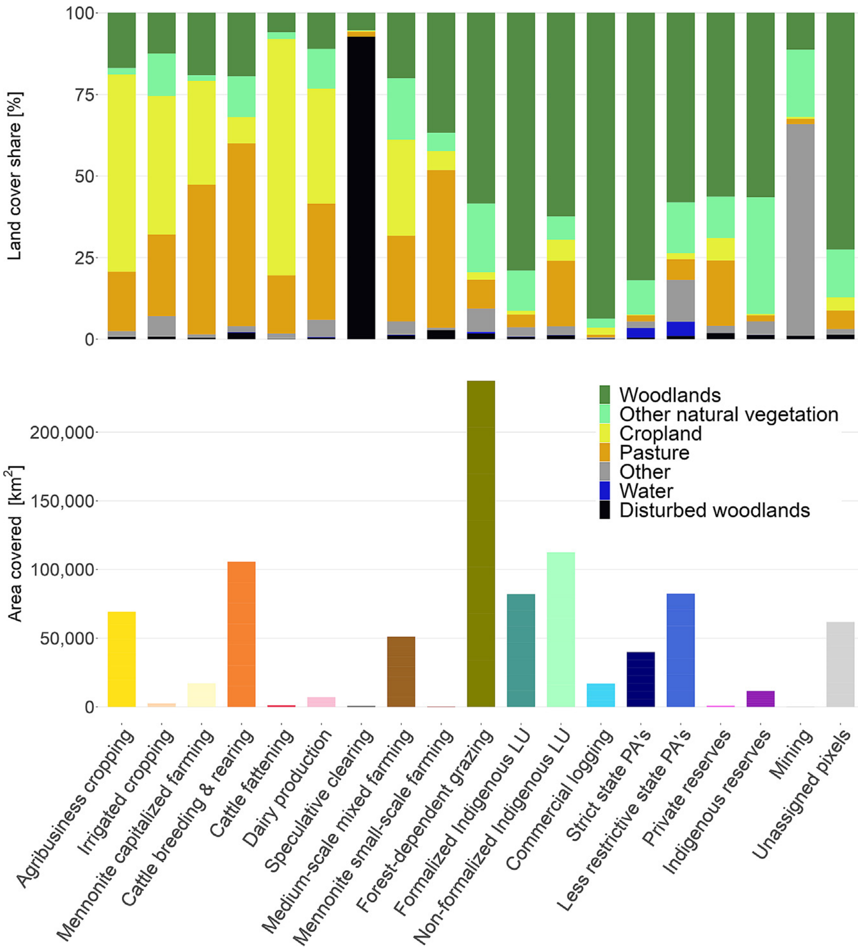

Figure 2. Land cover distribution and area covered by our 18 land systems and unassigned areas

The color panel refers to the first row (land cover share). The colors in the second row correspond to the land systems displayed in Figure 4.

conservation systems (13,400 km^2), but we also found overlap of conservation with industrialized land systems (1,200 km^2), mostly in less restrictive state PAs and private reserves. We found the strongest overlaps, relative to their area, between integrated or synergistic land systems, such as Indigenous reserves and formalized Indigenous land use (99%) or cattle fattening and agribusiness cropping (69%) (Figure 3C).

DISCUSSION

Land use is tightly connected to many of the most critical sustainability problems of our times, including biodiversity conservation, climate change, food security, and poverty alleviation, and land use is therefore also key to addressing these issues.[8,44] Despite its importance, land use is often overgeneralized and oversimplified in broad-scale sustainability planning, in particular through weak consideration of land use actors and their diverse activities or prevailing misconceptions of land as being "unused" due to inappropriately equating land cover with land use.[16,23] Poorly capturing the real-world complexity, context specificity, and often contested nature of land use results in hiding both social-ecological impacts and potential solutions to sustainability problems.[19,45,46] Yet, how to better capture and map the real-world complexity of land use while avoiding getting trapped in case specificity remains a major challenge. Here, we develop an approach to do so and demonstrate it for the 1 million-km^2 Dry Chaco and Chiquitano forests of South America, a global hotspot of deforestation, defaunation, and competition for land. Three main insights emerged from this exercise.

First, representing land use by land systems can put land use actors and practices on the map that are typically invisible in land cover-based, broad-scale assessments.[15,31] Most notably, forest-dependent grazing was the most widespread land system in our study. Relying on land cover maps would have "masked" these systems, as satellites cannot reliably distinguish and inhabited woodlands.[47] Likewise, land tenure data would not have adequately captured these actors, as many of them do not have formalized land rights (and because tenure data are often unavailable). As a result, in our region and elsewhere, forest-dwelling smallholders or pastoralists are often systematically underrepresented in large-scale planning.[20,21,48] For the Dry Chaco and Chiquitano forests, our systems can capture the extent of forests used for grazing, which is important for estimating the impact of smallholders (e.g., overgrazing), to understand the footprint of their resource use and livelihood foundations and, thus, to develop policies to encourage sustainable forest use.[49]

Furthermore, all of our systems contained major shares of natural vegetation, which challenges simplistic land cover/use relations and production-conservation dichotomies and highlights the importance of considering the ecological value of agroecosystems.[46] For example, many smallholders practice farming in multifunctional mosaic landscapes that are locally less ecologically damaging than industrialized agriculture,[45,50] but these systems are often either not differentiated from industrialized agriculture[28] or viewed as marginal and underutilized.[51,52] Our typology and associated maps can move beyond such fallacies. Generally, our land systems capture several additional aspects of social-ecological systems that are typically hard to map, such as indirect threats to biodiversity through land use (e.g., subsistence hunting or retaliatory killing of carnivores,[53] the multidimensional nature of land use intensity,[24] or coupled land uses, such as co-occurring industrialized cropping and ranching in our case.[54]

Our second main finding was that our maps revealed substantial overlap between smallholder land systems and large-scale,

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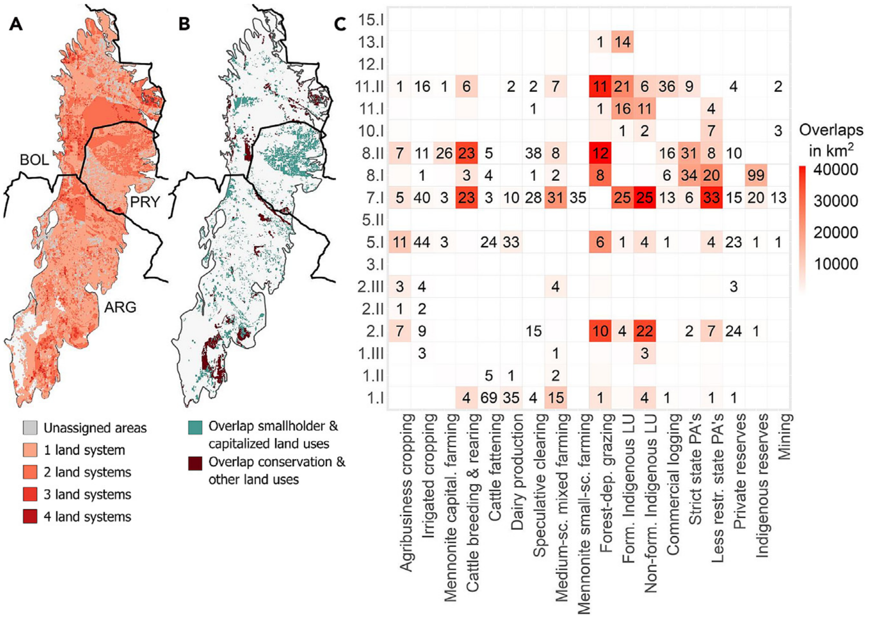

Figure 3. Overlapping land systems

(A) Spatial patterns of land system overlaps across the study region. White areas indicate landscapes not included in our typology (i.e., urban areas, water, rocks, and salt plains).

(B) Spatial patterns of key types of land system overlaps: (1) smallholder land systems overlapping with capitalized land systems and (2) conservation land systems overlapping with other land systems.

(C) Overlap matrix indicating the percentage area of every land system overlapping with every other. Values indicate the overlap as a fraction of systems in the columns. The color indicates the absolute size of the overlap in km.[23]

capitalized ones. We suggest this to be a signal of competition and conflict over land,[55,56] and our system maps therefore provide a means for visualizing where competition materializes. In many agricultural frontier regions worldwide, commodity agriculture expands into areas used by smallholders and Indigenous communities. As a result, these actors are often excluded from accessing resources essential for their livelihoods and cultural identity,[47,56] such as the surrounding forest that is critical for their subsistence as well as traditional communal resource management.[40,57] While some studies have documented the direct displacement of smallholders because of land competition,[47,58,59] there is less insight into the ecological marginalization resulting from loss of access to land. These changes are easier to overlook but significantly impact smallholders' livelihood strategies.[60–62] While the presence of large-scale, commercial agriculture can have positive spillover effects for nearby smallholders, such as through the adoption of improved technologies or employment in times of need, there's little evidence for long-term livelihood benefits without targeted policies that foster this coexistence.[63–65] Spatial data showing not only where smallholder communities live but also where their resource base is are therefore crucial to avoid perpetuating power imbalances in sustainability planning.[27,66,67] This is especially true for the tropics, where many areas still are portrayed as "empty lands" yet are inhabited, and new claims on land, from capitalized agriculture or conservation agendas, are therefore likely to instigate conflict.[20,68] Knowledge about the overlapping nature of who uses forest land, and for what, is therefore important for preventing conflict.[69]

Third, our land system maps revealed many areas where conservation-focused land systems overlap with other land uses. Often, this traces back to protected areas that were created on areas already occupied by land use actors, which have continued their activities after protected area establishment.[70] In the Dry Chaco and Chiquitano forests, many protected areas were created in areas used historically and today by Indigenous communities (e.g., Reserva Nacional Pizarro in Argentina), and some were even explicitly designated to protect Indigenous peoples and their livelihood foundations (e.g., Kaa-Iya del Gran Chaco National Park in Bolivia), explaining the large overlap we found between these land systems. Similarly, smallholders, and particularly those living inside the forest, overlapped substantially with conservation land systems owing to the long history of forest-dependent smallholders in the region.[71,72] Together, this corroborates other work highlighting that conservation rarely takes place on residual lands that are "unused" or "empty" but always interacts or competes with other land uses.[73,74] Importantly, a land cover-focused description of land use patterns would have entirely missed these overlaps, as none of these systems has clearly identifiable land-cover signatures. Moreover, our analyses also uncover potential areas of tension, particularly where conservation is strict and restricts traditional land use, a situation that often leads to unjust conservation outcomes.[68,75]

We also found more industrialized land uses overlapping with public protected areas, although to a much lesser extent. Such overlaps can signal protected area downgrading, downsizing, or degazettement, which are widespread but often unaccounted for.[76] Likewise, such overlaps could signal illegal encroachment of protected areas by other land uses. Illegal activities in protected areas documented for our study region include illegal logging of high-value hardwood,[77] illegal expansion of large-scale cattle ranching or commodity cultivation,[78] or clearing for real estate development and speculation, where deforestation is used to prepare land for sale without official approval.[79] Industrialized land uses also overlapped with private reserves, likely because capitalized actors set aside parts of their territories as nature reserves, voluntarily or because they are required to do, such as in Paraguay (25% of forests on farms have to be retained in the Chaco) or Argentina (substantial areas zoned for sustainable forest use or forest protection). Such private reserves can be of critical importance for conservation,[80] but corporate actors providing conservation territories have also been criticized for engaging in so-called "greenwashing" or using these strategies for tax avoidance.[81]

Overall, our system maps provide a transferable and scalable pathway to capturing land use complexity in sustainability

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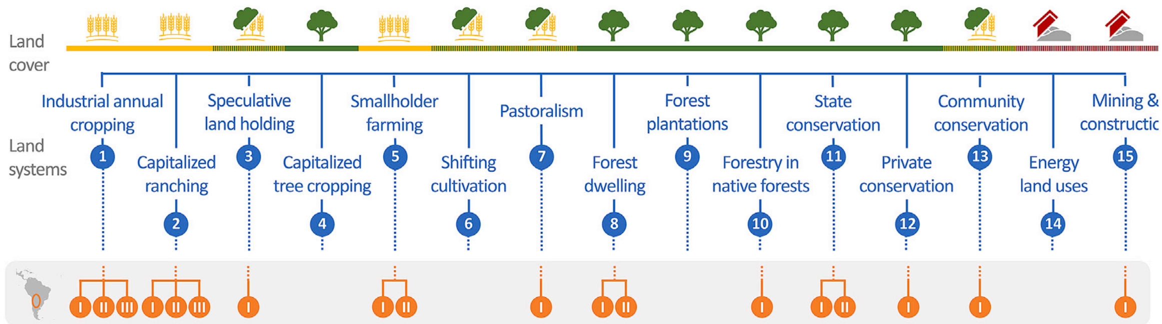

1.I	Agribusiness cropping	Capitalized, large-scale enterprises cultivating commodity crops with high capital-related inputs (mainly soybean, maize, cotton, wheat, sunflower, and sorghum), primarily focused on economic profitability and oriented towards distant markets
1.II	Irrigated cropping	A subtype of agribusiness cropping with irrigation leading to higher cultivation frequency, mainly growing GMO crops and highly productive maize, using center pivot irrigation techniques
1.III	Mennonite capitalized farming	Highly capitalized, industrialized farming by Mennonite communities (closed socio-religious communities with European origin), involving industrial grain cropping (mainly in Bolivia) and semi-intensive cattle-ranching (mainly in Paraguay), producing beef, soybean, sunflower, and maize for local to national markets
2.I	Cattle breeding and rearing	Extensive grazing systems for beef production, involving calves reared to a certain weight on planted pastures with low stocking rates, often combined with cropping, and run as family businesses by capitalized medium to large-scale actors
2.II	Cattle fattening	Intensive ranching practice where calves are raised to slaughter weight in feedlots, heavily reliant on feed supplements and often combined with cropping, usually carried out by more capitalized actors in good agro-ecological conditions
2.III	Dairy production	Cattle ranching systems with intensive management for milk production, involving medium-scale production units with irrigated pasture and silage-based fodder
3.I	Speculative clearing	Practice of increasing land market value by removing natural vegetation and selling the land at higher prices, carried out by private companies with high investment in machinery and strong integration in real estate markets
5.I	Medium-scale mixed farming	Mixed farming systems involving both agriculture and ranching, with medium levels of capital-related inputs, oriented at self-consumption and local to distant markets, often organized in cooperatives or associations
5.II	Mennonite small-scale farming	Less capitalized Mennonite agriculture rejecting technology, based on small but intensive fields, producing industrial and grain crops, dairy, and beef for local to national markets
7.I	Forest-dependent grazing	Livestock grazing inside the forest (mainly cattle, goats, sheep, but also swine, and poultry), often accompanied by small subsistence crop fields or vegetable gardens, subsistence hunting, and the collection of non-timber forest products (NTFP), often under irregular tenure
8.I	Indigenous forest use with secure land tenure	Diverse Indigenous communities with recognized communal land titles, practicing subsistence economies based on hunting, craft-making, forest product harvesting, and small-scale gardening
8.II	Indigenous forest use on non-formalized lands	Indigenous communities lacking land titles, facing violations of tenure rights and competing with outside investors, leading to impoverishment and reliance on seasonal wage labor or social subsidies
10.I	Commercial logging	Large-scale hardwood exploitation by capitalized enterprises for local and international markets, requiring formal permissions but often involving informal and illicit operations
11.I	Strict state area protection	National strictly protected areas (e.g. national parks) established to protect landscapes and biodiversity, preventing extractive economic activities and restricting access, with management focused on control, visitor attention, and national security
11.II	Less restrictive state area protection	Multi-use areas allowing some productive land use while protecting landscapes and biodiversity, often facing challenges in governance and management at the subnational level
12.I	Private reserves	Privately owned lands managed for biodiversity protection and often involving tourism
13.I	Indigenous reserves	Protected areas on Indigenous land managed by Indigenous communities with government support, aiming to protect landscapes and biodiversity while empowering Indigenous rights and cultures
15.I	Mining	Large-scale operations by state or private companies, and frequently illegal small-scale mining, extracting gold, silver, copper, zinc, iron, manganese, granite, and rare earths in the Chiquitano Forest, often on Indigenous or peasant territories

Figure 4. Land system typology with 15 general land systems at the highest level shown in blue (Methods S1A) and 18 regionalized systems for the Dry Chaco and the Chiquitano forests shown in orange (Methods S1B)

The top shows the limited number of classes that a land cover perspective would typically identify (cropland, tree cover, built up, and bare soil). The figure was adapted from Pratzer et al.[31]

planning. Since many prior assessments, both regional and global, have relied on land cover proxies or top-down clustering methods to represent land use,[29,82,83] they tend to emphasize only the most dominant landscape features, thus overlooking the multifaceted nature of land systems.[84] The Chaco and Chiquitano forests are, like many areas, in need of sustainability planning and scarce in spatially detailed data on land use actors and practices. To remedy this, we combined the best available geospatial data on land use patterns and actors with expert knowledge to map our systems in an iterative process. As our validation shows, this resulted in highly reliable land system maps. However, our maps are sensitive to expert decisions and data constraints and are not free from uncertainty. Our map has a relatively high resolution (300 m), but we note that we conducted some methodological steps at coarser resolutions, such as the land cover segmentation for defining selected system boundaries (900 m) and overlaying the final maps with interview data for the validation. This is needed to capture the large-scale and complex nature of land systems (e.g., agribusiness cropping, where large-scale homogeneous agricultural fields are interspersed with strips of forest remnants). However, this unavoidably leads to uncertainty at finer resolutions, particularly at land system boundaries. Therefore, while the maps well depict general land system patterns and overlap, they should be used with caution at finer spatial scales. Furthermore, unassigned areas might not be *de facto* unused but, rather, result from data limitations, as described above. Finally, we highlight that mapped land system overlaps do not necessarily indicate competition or conflict. Yet, our approach challenges existing mapping paradigms and explores the implications of representing land-use complexity, providing further opportunities for research. This means that our land system maps can be improved as more or better data become available.

Land use is often portrayed in overly simplistic ways in sustainability assessments. Gathering fine-scale data on land use is hard and often infeasible for regions in the most dire need of sustainability planning, such as deforestation frontiers in the tropics. We suggest that our approach has the potential to remedy this situation and to enable more context-specific sustainability planning. First, our approach can provide proxies for aspects of land use that are hard to map, such as land use intensity or activities not directly related to agriculture or forestry. Reducing the multidimensional nature of land use intensity to a single measure (e.g., yield) or neglecting activities such as hunting or fuelwood harvesting might underestimate or miss threats to biodiversity. Second, our approach helps to put on the map the diversity of people who engage in land use and live in landscapes. Weak consideration of actor diversity is a major reason for failing sustainability policies and contributes to creating the conditions for ecological marginalization. Third, our maps can help to capture interacting or conflicting land uses, which can point to unclear or contested claims on land that are often the result of imbalances in agency and power. Ignoring such imbalances can hinder targeted sustainability efforts and perpetuate or introduce injustices. Our approach, and particularly the overlapping nature of our land system maps, can thus make visible places where hidden or open conflicts could occur, thereby helping to better consider justice in mapping efforts and sustainability planning.

METHODS

Study region

Our study region comprises two adjacent ecoregions, the Dry Chaco and the Chiquitano forests. The Dry Chaco covers about 800,000 km^2, extending into Argentina, Bolivia, and Paraguay, and is inhabited by approximately 9 million people.[85] The region is characterized by a semi-arid climate and a mosaic of xerophytic forests, open woodlands, scrubs, and grasslands.[86] The Chiquitano forest in Bolivia, characterized by semi-deciduous forests, intersected by rock outcrops, shrublands, wetlands, and savannas, serves as a crucial corridor connecting the Gran Chaco in the south to the Amazonian rainforests in the north.[87] The climate of this ecoregion is warm sub-humid tropical with a rainy period in summer and dry weather in winter. Spanning about 160,000 km^2 in Bolivia, it is home to an estimated 3 million people.[88,89]

The Dry Chaco and Chiquitano forests harbor high biodiversity (e.g., at least 150 and 105 species of mammals and 500 and 384 species of birds in the Dry Chaco and Chiquitano forests, respectively), including many endemic species.[90–92] Both regions are important for carbon storage, both in woodlands and in the many wetlands they contain.[88,93] Moreover, the woodlands have been home to a wide diversity of Indigenous peoples for millennia, including some peoples that remain in voluntary isolation and are rich in cultural heritage.[20,94]

However, in recent decades, growing global demand for agricultural commodities and the incorporation of geographically distant regions into transnational networks of trade has fueled the expansion of agriculture into these ecosystems.[95,96] Technological advancements that overcome the agricultural constraints of arid environments,[97] such as the introduction of genetically modified soybean varieties and productive pasture grasses, have made farming in drylands both economically profitable and feasible and steadily increased the conversion of forest to cropland and pasture.[98–100]

National policies fostering an agro-industrial model of national development have further accelerated this process.[41] Government actions such as offering public land at low prices, promoting export-oriented agriculture, and weak enforcement of environmental regulations have facilitated large-scale land appropriation by new and emerging actors, such as settlers from other regions, agribusinesses, or foreign investors.[101–103] These policies, coupled with shocks like government changes, global economic crises, and currency devaluations, have positioned the region as one of the world's deforestation hotspots.[104,105]

Agricultural expansion not only puts natural assets under immense pressure but has also generated fierce competition for land.[39,40,106] A large proportion of the region is legally unclaimed territory yet inhabited by populations without the means to contest the appropriation of land, which has led to ecological marginalization and displacement of local forest-dwelling communities.[47,56,99] In addition, conservation efforts are increasingly competing with agriculture, with only a small proportion of land under formal protection (18% in the Dry Chaco and 6% in the Chiquitano forest). Even where protections exist, enforcement is often weak and ineffective.[78]

Clearly, the region is in dire need of sustainability planning to help strike a better balance between agricultural production on

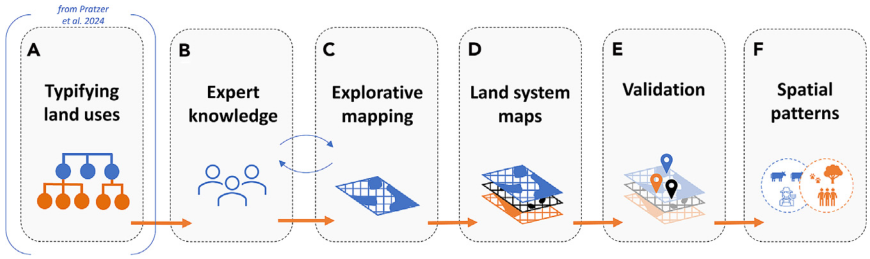

Figure 5. Methodological approach to represent and map the complexity of land use in land systems and then map these land systems for sustainability planning

the one hand and the protection of rural livelihoods, socio-cultural heritage, and natural assets on the other.[107] The lack of reliable information on land use or land tenure has so far impeded such planning.

Land system typology

We built on an actor-based, scalable land system typology developed in our previous work[31] (Figure 5A). This typology seeks to provide a middle ground between overgeneralizing the diversity of land uses on the one hand and idiosyncrasy on the other by structuring this diversity and complexity into a limited number of regionalized land systems for our study region. Land systems were defined as distinct combinations of major types of land use actors as the agents utilizing a specific area of land for a specific purpose and their activities as the diverse agricultural, institutional, and cultural practices leading to an interaction with natural assets. These actors (e.g., capitalized farmers and smallholders) and their activities (e.g., soybean cropping and subsistence farming) then produce typical land use patterns (e.g., a landscape dominated by homogeneous, large soybean fields or a landscape dominated by subsistence agriculture inside a woodland matrix).[108] Our typology was derived in expert workshops to represent land use complexity for sustainability planning at two hierarchical levels: a global/generic level containing systems that could occur in all tropical dry woodland regions, thus allowing for broad-scale conservation planning and comparative work, and, nested within, a regionalized/contextualized level with systems that are specific to individual tropical dry woodland regions, thus providing regional specificity and contextual nuance. Unlike previous approaches to define and classify land systems,[109,110] we explicitly chose not to start from available spatial datasets to construct our typology to avoid pitfalls associated with data-driven approaches (e.g., missing data, data uncertainties, and thematic classes that mask important features or carry important legacies for downstream analyses) and define systems that can, in principle, overlap in space.

Our resulting global typology level (Figure 4) includes 15 land systems (see Methods S1A for a qualitative description of these systems). Our regionalized typology level (Figure 4) refined the global systems into 18 regional systems to fit the context of the Dry Chaco and Chiquitano forests, leaving out land systems that do not occur in a region. Where necessary, global systems were split into several regional sub-systems to better characterize the diversity of land use actors and activities for these regions.[31] This resulted in three systems associated with industrialized cropping; three systems for capitalized ranching; two systems each associated with smallholder farming, forest-dwelling, and state conservation; as well as one system for speculative land holding, pastoralism, forestry, private conservation, community conservation, and mining (see Methods S1B for a more detailed description of these systems).

Land system mapping

We mapped each system independently and derived mapping indicators and conditions for all 18 regionalized land systems in a deductive approach. We did not define system indicators *a priori* but explored them in iterative rounds of mapping and subsequent checking based on expert knowledge. Our mapping approach does not directly translate land cover into land use, meaning that land systems can entail several land covers, such as protected areas including a range of land covers, forest patches, or corridors embedded in large-scale industrialized agriculture or forest-dependent smallholder systems that can contain forests, natural grasslands, and small-scale cropland.

We first organized discussions involving scientific experts on land use in the Dry Chaco and Chiquitano forests (Figure 5B) to identify spatial indicators signaling the presence of a specific land system. We used the outcome of these discussions as a starting point for our explorative and iterative mapping effort. Specifically, we drew upon a large pool of input data representing land cover, institutional, or production-related features (Methods S2) to proxy the expert-derived system indicators. Based on iterative evaluations of mapping outcomes, information from literature, and very high-resolution satellite imagery, we derived a final set of indicators and their conditions and thresholds that most meaningfully represent the individual systems (Figure 5C). Our mapping approach was thus different for every system, with specific, system-dependent rules (see Table 1 and Methods S2 for a detailed description).

Considering the cattle breeding and rearing system as an example (Figure 6), cattle ranching is usually simply proxied by the land cover-class grasslands, but this can contain implanted pastures and natural grasslands. Instead, we first separated the land cover-class pastures, natural vegetation, and other grasslands based on satellite image time-series analysis.[105] We used land cover segmentation at 900-m resolution to identify homogeneous units based on three inputs: (1) land cover fraction pasture; (2) accumulated land cover fractions grassland, pasture, and cropland; and (3) land cover fraction natural vegetation. We experimented with different settings of the segmentation algorithm to yield reasonably sized and homogeneous segments that meaningfully delineate ranching landscapes, implying that segments can include small forest patches or strips (used as windbreaks in the region) as well as small cropland patches but neither larger forest landscapes nor large cropland areas. Next, we combined these units with other geospatial information characterizing specific features of ranching systems (Figure 6A), such as the

Table 1. Iteratively derived land-system mapping conditions and input data used

Land system		Mapping conditions	Datasets
1.I	agribusiness cropping	• Size >1500 ha and • other non-woody natural vegetation cover <5% and • cropland cover >60% and natural vegetation cover <20% or • cropland cover >15% + pasture cover and natural vegetation cover <30% past natural vegetation loss >36 ha or natural vegetation cover in 1985 < 50% • can contain patches of woodland or natural vegetation cover <2,700 ha	Baumann et al.[105]
1.II	irrigated cropping	• size >1,500 ha and • other non-woody natural vegetation cover <5% and • cropland cover >60% and natural vegetation cover <20% or • cropland cover >15% + pasture cover and natural vegetation cover <30% past natural vegetation loss >36 ha or natural vegetation cover in 1985 < 50% and • entails center pivot irrigation imprint • can contain patches of woodland or natural vegetation cover <2,700 ha	Baumann et al.[105] and unpublished data
1.III	Mennonite capitalized farming	• country ≠ Argentina and • Mennonite colonies or • tenure polygon intersecting with Mennonite colony	[111,112]and unpublished data
2.I	cattle breeding and rearing	• pasture or grassland cover >25% and • size >2,000 ha or pasture or grassland cover patch >450 ha and • natural vegetation <80% and • past natural vegetation cover loss >0.1% or natural vegetation cover in 1985 < 70% and • no dairy location and • no feedlots and • number of buildings >0 and • number of strategic supplementation areas >0 or • vaccination data points indicating production type breeding (“cría”) or rearing (“recría”) • can contain patches of woodland or natural vegetation cover <2,700 ha	Baumann et al.[105,112–114] and unpublished data
2.II	cattle fattening	• cropland cover >40% and • entails feedlot	Baumann et al.[105,112,113] and unpublished data
2.III	dairy production	• pasture or grassland cover >25% and • size >2,000 ha **or** pasture or grassland cover patch >450 ha and • natural vegetation <80% and • past natural vegetation cover loss >0.1% or natural vegetation cover in 1985 < 70% and • entails dairy location • can contain patches of woodland or natural vegetation cover <2,700 ha	Baumann et al.[105,112,113] and unpublished data
3.I	speculative clearing	• woodland cover loss without subsequent conversion o agriculture and • size <10,000 ha and • distance to rivers >10 km	Baumann et al.[105]

(*Continued on next page*)

Table 1. *Continued*

Land system		Mapping conditions	Datasets
5.I	medium-scale mixed farming	• smallholder homestead and within surrounding of 1 km: cropland cover >10% and within surrounding of 1 km: woodland + other natural non-woody vegetation cover <30% or • cropland cover <60% and cropland cover >10% and • natural vegetation cover + pasture cover >20% or • other non-woody natural vegetation cover >10% and • cannot contain cropland cover patches >900 ha and • size of resulting patch >1 ha	Levers et al.,[47] Baumann et al.,[105] and GeoBoliva[112]
5.II	Mennonite small-scale farming	• country = Argentina and • Mennonite colonies	le Polain de Waroux et al.[111]
7.I	forest-dependent grazing	• within 5 km surrounding of smallholder homestead and • woodland + other natural non-woody vegetation cover >30% and • cropland cover <10% and • cannot contain cropland or pasture cover patches >900 ha and • cannot contain pasture cover patches >2,700 ha	Levers et al.,[47] Baumann et al.,[105] and GeoBoliva[112]
8.I	Indigenous forest use with secure land tenure	• recognized Indigenous territories or • protected areas managed by Indigenous communities	Camino et al.,[94] GeoBoliva[112], MADES[115],FAPI,[116]and Guyra Paraguay[117]
8.II	Indigenous forest use on non-formalized lands	• demanded Indigenous territories or • forestry by indigenous communities outside their formalized lands or • tenure polygons unsuccessfully claimed as Indigenous territories	Camino et al.[94] GeoBoliva,[112] MADES,[115] FAPI,[116] and Guyra Paraguay[117]
10.I	commercial logging	• lands under forestry concessions or • forest plantations	GeoBoliva[112]
11.I	strict state area protection	• state protected areas in IUCN categories I and II	GeoBoliva[112] MADES,[115] Guyra Paraguay[117] Fundación ProYungas,[118] WWF Paraguay,[119] and UNEP-WCMC[120]
11.II	less restrictive state area protection	• public protected areas in IUCN categories III-V or • protected areas on the sub-national level	GeoBoliva,[112] MADES,[115] Guyra Paraguay,[117] Fundación ProYungas,[118] WWF Paraguay,[119] and UNEP-WCMC[120]
12.I	private reserves	• protected areas designated as private	GeoBoliva,[112] MADES,[115] Guyra Paraguay,[117] Fundación ProYungas,[118] WWF Paraguay,[119] and UNEP-WCMC[120]
13.I	Indigenous reserves	• protected areas under Indigenous administration	GeoBoliva,[112] MADES,[115] Guyra Paraguay,[117] Fundación ProYungas,[118] WWF Paraguay,[119] and UNEP-WCMC[120]
15.I	mining	• bare soil cover around mining facility or • land cover class mining	Baker[121]and Proyecto MapBiomas[122]

presence of feedlots and supplementary feeding areas mapped from high-resolution satellite images,[123] cattle herd composition based on geolocated vaccination records,[113] or past deforestation patterns.[105] The mapping outcome (Figure 6C) thus more appropriately represents the diverse landscapes in which cattle ranching takes place (Figure 6B) than simple proxies based only on grassland cover.

We carried out all processing and mapping steps using Python and QGIS.[124,125] The geospatial mapping techniques we implemented were different for every system. For some, we combined segmentation based on relevant land cover classes with characteristic land use features, as described for cattle breeding and rearing, adjusted to the individual contexts (e.g., agribusiness cropping and cattle fattening). For others, we intersected geospatial data on homesteads with land cover and applied buffering informed by literature (e.g., forest-dependent grazing and medium-scale mixed farming). Some land system maps were informed by spatially explicit cadastral or jurisdictional delineations (e.g., strict state area protection and commercial logging). The final land system maps are presented at a resolution of

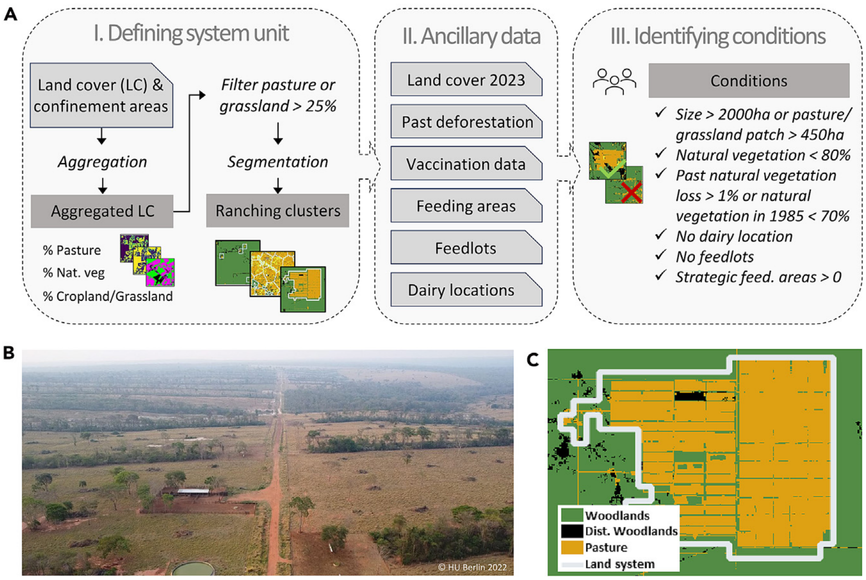

Figure 6. Methodological approach to map the cattle breeding and rearing system
(A) Methodology for deriving system boundaries and indicators.
(B) Photo of a cattle breeding and rearing system in the Chiquitano forest.
(C) An example of the mapping outcome, which contains pasture, woodland, and disturbed woodland.

300 m. For detailed descriptions of individual mapping approaches for each of the 18 land systems, refer to Methods S2.

To validate our resulting land system maps, we compiled a geodatabase of interviews conducted in the region, comprising 845 survey locations from 12 different research projects in Bolivia and Argentina (Methods S3).[126–128] We asked the responsible researchers to assign the best-fitting land system from our typology to the actors they had interviewed, overlaid the geolocated interview data with our system maps, and calculated the level of agreement (Figure 5E). Specifically, we determined the percentage of interviews per land system for which the researchers' land system assignments matched those derived from the overlay with our land system maps. We note that this is the first validation of a land system map we are aware of.

Once all land systems were mapped individually, we combined them into our final multilayered land system maps. We inspected the geographical patterns of the individual land system maps; that is, the extent, location, and distribution of land cover classes within these mapped land systems. Moreover, we compared the spatial patterns of our system maps based on the global versus the refined regional typology. Finally, we analyzed patterns of land system overlaps (Figure 5F) as well as areas remaining "unassigned" (i.e., not covered by any of our land systems).

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Marie Pratzer (marie.pratzer@hu-berlin.de).

Materials availability

This study did not generate new unique materials.

Data and code availability

The source code for processing input data and mapping the land systems is available at https://scm.cms.hu-berlin.de/pratzema/land-system-mapping.git. The maps can be explored at https://hu.berlin/landsystems and are available upon reasonable request from the authors. The interview data used for the validation cannot be shared publicly as it would violate the informed consent that both parties—interviewee and interviewers—agreed upon prior to the interviews.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.P., M.B., P.M., M.V., and T.K.; methodology, M.P., M.B., J.B., P.F., and C.L.; investigation, M.P., O.M., G.B., M.B., J.B., and M.V.; writing – original draft, M.P., P.M., and T.K.; writing - review & editing, O.M., G.B., M.B., J.B., P.F., C.L., M.T., and M.V.; funding acquisition, T.K.; resources, O.M., M.B., P.F., M.T., and T.K.; supervision, P.M. and T.K.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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