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What is still at stake in the Gran Chaco? Social-ecological impacts of alternative land-system futures in a global deforestation hotspot

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Abstract

Commodity agriculture continues to spread into tropical dry forests globally, eroding their social-ecological integrity. Understanding where deforestation frontiers expand, and which impacts this process triggers, is thus important for sustainability planning. We reconstructed past land-system change (1985–2015) and simulated alternative land-system futures (2015–2045) for the Gran Chaco, a 1.1 million km^2 global deforestation hotspot with high biological and cultural diversity. We co-developed nine plausible future land-system scenarios, consisting of three contrasting policy narratives (Agribusiness, Ecomodernism, and Integration) and three agricultural expansion rates (high, medium, and low). We assessed the social-ecological impacts of our scenarios by comparing them with current biodiversity, carbon density, and areas used by forest-dependent people. Our analyses revealed four major insights. First, intensified agriculture and mosaics of agriculture and remaining natural vegetation have replaced large swaths of woodland since 1985. Second, simulated land-system futures until 2045 revealed potential hotspots of natural vegetation loss (e.g. western and southern Argentinian Chaco, western Paraguayan Chaco), both due to the continued expansion of existing agricultural frontiers and the emergence of new ones. Third, the strongest social-ecological impacts were consistently connected to the Agribusiness scenarios, while impacts were lower for the Ecomodernism and Integration scenarios. Scenarios based on our Integration narrative led to lower social impacts, while Ecomodernism had lower ecological impacts. Fourth, comparing recent land change with our simulations showed that 10% of the Chaco is on a pathway consistent with our Agribusiness narrative, associated with adverse social-ecological impacts. Our results highlight that much is still at stake in the Chaco. Stricter land-use and conservation planning are urgently needed to avoid adverse social-ecological outcomes, and our results charting the option space of plausible land-system futures can support such planning.

1. Introduction

Although globally peak agricultural land might have been passed (Taylor and Rising 2021), agriculture continues to expand in the tropics (le Polain de Waroux *et al* 2016), creating major social-ecological costs (Laurance *et al* 2014). Within the tropics, many deforestation frontiers occur in dry forests, woodlands, and savannas (hereafter: tropical dry forests) (Pacheco *et al* 2021, Buchadas *et al* 2022). Tropical dry forests account for about 40% of all subtropical and tropical forests (van Bloem *et al* 2004), and harbour unique biodiversity and major carbon stocks (Miles *et al* 2006). These ecosystems provide key services (Pennington *et al* 2018) and their conversion thus threatens the livelihoods of forest-dependent people, including many Indigenous communities (Oldekop *et al* 2020, Levers *et al* 2021). Despite their high social-ecological value, tropical dry forests have received less attention than rainforests, and many dry forests are weakly protected (Prieto-Torres *et al* 2021, Schröder *et al* 2021). As demand for agricultural commodities continues to grow, understanding where and how deforestation will increase is key for supporting sustainability planning (Strassburg *et al* 2017, Prieto-Torres *et al* 2021). Yet, this is largely unknown for most tropical dry forest regions.

Three main challenges need to be overcome in this regard. First, there is great diversity in land-use actors (here: agents who can decide on the use of land, such as farmers, agribusinesses companies, Indigenous communities) and practices in tropical dry forests, with diverse social-ecological impacts (Buchadas *et al* 2022). Capturing and structuring this diversity across extents relevant for sustainability planning is challenging though. Archetype analysis has recently emerged in sustainability science for such purposes (Oberlack *et al* 2019, Sietz *et al* 2019). Identifying and mapping typical land systems, defined here as recurring combinations of land-use practices, actors, and configurations, holds considerable promise (Václavík *et al* 2013, Levers *et al* 2018). Land-systems approaches have, for example, helped to identify archetypes of land change in Europe (Levers *et al* 2018), link land use and social-ecological conditions globally (Václavík *et al* 2013) or in South America (Zarbá *et al* 2022), or explore biodiversity impacts of global agricultural change (Kehoe *et al* 2017). Yet, we know of no study that has identified and mapped land systems for any dry forest region of the world across large geographic extents at spatial resolutions relevant for broad-scale land-use planning and environmental assessments (i.e. $\leqslant 1\ km^2$).

A second challenge is the urgent need to better understand plausible future land-system change. Deterministic forecasts of land use are not feasible given the many land-use actors and practices, the many factors that influence their decisions, and the complexity of cross-scale interactions, including feedbacks and telecouplings (Verburg *et al* 2016, Meyfroidt *et al* 2022). Scenario analysis is a powerful tool for dealing with such uncertainty and thus for supporting sustainability planning (Polasky *et al* 2011, Alexander *et al* 2017). Specifically, charting the range of plausible land-system futures (i.e. the 'option space') can reveal how stable or volatile land systems are, where hotspots of change are likely to emerge, and how policy measures might impact land-system changes (Popp *et al* 2017, Kalt *et al* 2021). Typically, such efforts involve the development of storylines or narratives that describe social-economic and policy conditions, and the spatial simulation of these scenarios. Such approaches have provided deep insights into land-system futures in the Global North (Radeloff *et al* 2012, Stürck *et al* 2018) but remain scarce in the Global South, and especially so for tropical dry forest regions. Moreover, where simulations exist, they are rarely compared to actual, observed pathways of change that could provide opportunities for targeted policies before lock-in situations and path dependency manifest (Meyfroidt *et al* 2022).

A third challenge for sustainability planning in dry forest regions is the need for spatially-detailed social-ecological indicators that capture the heterogeneity of these systems to assess potential future impacts (Miles *et al* 2006, Siyum 2020). For example, expanding deforestation frontiers might threaten places with high social-ecological value (e.g. if environmental assets, such as biodiversity and carbon stocks, correlate with agro-ecological suitability) or low value (e.g. if only the most remote areas remain undegraded). Overlaying future land-system patterns with social-ecological indicators can uncover potential social-ecological trade-offs and how to address them.

Our overarching goal here was to assess future land-system patterns and their social-ecological impacts for the entire 1.1 million km^2 Gran Chaco ecoregion (hereafter: Chaco; see appendix 1 for a detailed study area description). This region extends across Argentina, Bolivia, and Paraguay, harbours unique biodiversity (Nori *et al* 2016), major carbon stocks (Baumann *et al* 2017), and large areas used by forest-dependent people, including many Indigenous communities (Levers *et al* 2021, Camino *et al* 2023). The Chaco is one of the most threatened tropical dry forest regions globally (Buchadas *et al* 2022), with a diverse portfolio of agricultural frontier dynamics (Baumann *et al* 2022). Advancing deforestation frontiers have triggered major social-ecological costs (Periago *et al* 2015, Barral *et al* 2020), pushing the Chaco towards critical thresholds of social-ecological integrity (Macchi *et al* 2020, Law *et al* 2021). Incomplete knowledge on plausible land-system futures and their impacts are barriers to sustainability planning in this region. In this context, we addressed the following research questions:

(1) What are the patterns of recent land-system change in the Chaco (1985–2015)?
(2) What are plausible land-system futures and associated social-ecological impacts in the Chaco?
(3) How do recent land-system changes compare to our alternative land-system futures?

2. Methods

Our approach involved four main steps: mapping recent (1985, 2000, 2015) land-system patterns (figure 1(A)), developing scenarios used for simulating future land systems until 2045 (figure 1(B)), assessing social-ecological impacts of our scenarios (figure 1(C)), and comparing simulated and observed pathways of change from 2015 to 2020 (figure 1(D)).

2.1. Land-system mapping

We understand land systems as typical combinations of (1) land-use actors (e.g. small-scale farmers or agribusinesses), (2) major land uses (e.g. cropping or ranching), and (3) land-use configurations (e.g. uniform or mixed landscapes). The majority of land-use conversions in the Chaco result in changes in land cover. We mapped contemporary land-system patterns at 1 × 1 km^2 spatial resolution across the entire Chaco for 1985, 2000, and 2015. Based on our own previous work, we used maps of land cover/use (Baumann *et al* 2017, 2018, 2022) as input data, which we combined with maps of underrepresented land-use actors, particularly forest-dependent people (Levers *et al* 2021) and Indigenous communities (Camino *et al* 2023). Importantly, both actor groups are not mutually exclusive. We integrated these data using a set of decision rules (see appendix 2 for details), which resulted in 15 distinct land systems.

2.2. Developing future land-system scenarios

We developed nine future land-system scenarios, systematically comparing three contrasting policy narratives and three agricultural expansion rates until 2045 (table 1 and appendix 3). We selected this time frame to simulate only as far into the future as we had data for the past (i.e. 30 years, 1985–2015). Our scenarios are based on assumptions and hence cannot forecast the future, yet they demonstrate the option space of potential directions and associated spatial patterns into which land systems in the Chaco might develop given starkly contrasting expectations on agricultural expansion rates and policy choices. Both, expansion rates and policy choices, are crucial in shaping land-system futures in the Chaco, as they represent the amount and pattern of forest conversion to agriculture, as well as different land-management options to meet agricultural demand.

Our scenarios are meant to span a plausible option space of land-system futures rather than to accurately predict land-system change or to identify the most likely scenario. The latter would not be credible and resulting predictions connected to high uncertainty given the social-ecological complexity surrounding land use in the Chaco and frequent social-ecological shocks happening there (e.g. economic crises, currency devaluations, major government and policy changes). This reasoning was strongly supported by the extensive expert and stakeholder process to develop our policy narratives (appendix 3).

Our policy narratives were co-developed with regional and local stakeholders, government officials, and land-use experts (table 1; see appendix 3 for details). This co-creation process ensured that our policy narratives were plausible and grounded in the reality of Chaco conditions. We conducted two workshops in which participants developed visions of land-system change. All narratives assume further increases in the global demand for livestock feed and beef, as well as technological development (e.g. drought-resistant, high-yielding crop varieties; crossbred livestock). To translate increased future demand into land area required for agriculture, we used historical expansion rates of agriculture over natural vegetation. For the Chaco, this was about 20% in 1985–2015 (Baumann *et al* 2017; table S4.3). Both an

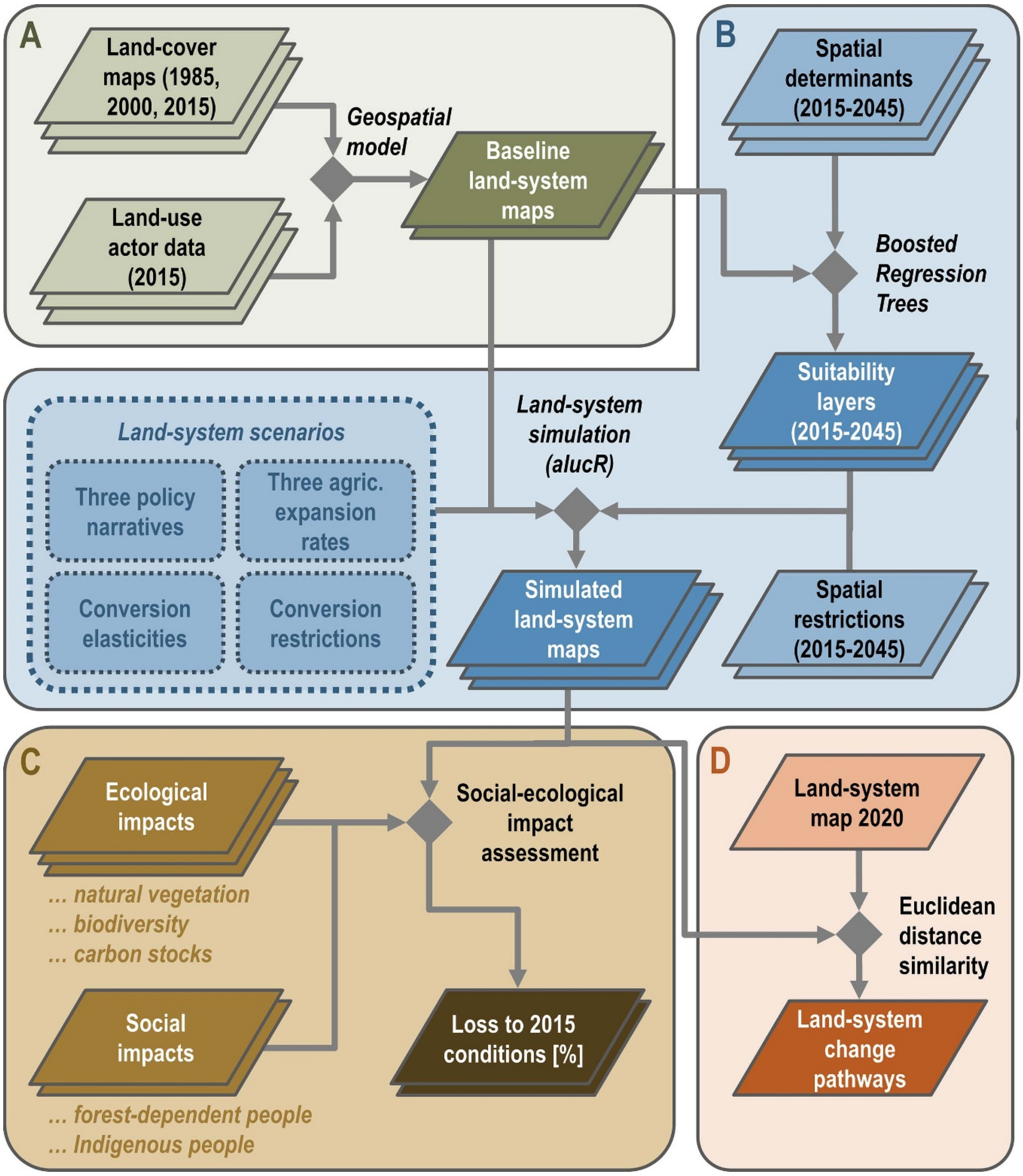

Figure 1. Overview of key processing steps to analyse land-system futures in the Chaco. (A) Land-system mapping, (B) scenario development and land-system simulation, (C) social-ecological impact analyses, and (D) comparison of actual vs. simulated land-system changes. Light colours indicate input data sets, dark colours results, and diamonds analysis steps.

increase in this rate (e.g. due to increasing demand for meat and soy (Alexander *et al* 2015)) as well as declining rates (e.g. due to expanding protection of remaining natural areas (CBD 2022)) are plausible. We explored three expansion rates of agricultural area compared to 2015: *low* (10%, 0.5 times the baseline rate), *medium* (20%, baseline rate), and *high* (30%, 1.5 times the baseline rate). Importantly, our scenarios are designed that expansion rates scale the overall impacts of future land-system change, yet the resulting spatial pattern of land-system changes will vary between scenarios due to different, land-system specific demands for agricultural expansion.

The three policy narratives regionalize Chaco-wide demand trends by allocating demand across different land systems and modifying transition elasticities (see tables S3.1 and S3.3–S3.5 for details). If certain land conversions were identified in the workshops as being instrumental for a narrative, we enforced this transition in our simulation by allowing an easier conversion through lower transition elasticities (figure S4.2). For example, agricultural expansion under *Agribusiness* is expected to occur in natural areas, first through conversions to pasture and later to cropland. Contrastingly, increasing agricultural production in *Ecomodernism* is assumed

Table 1. Summary of the three policy narratives (PN) used to build our nine land-system futures. For a detailed description of these narratives and their development, please see appendix 3.

Narrative	Key assumptions and characteristics
PN-1: Agribusiness	• High investment into capital-intensive agriculture due to increased global demand, supported by low (export) taxes and soft loans. • Fast and widespread infrastructure development for storage and transportation. • Weak environmental protection (no formal recognition of land rights for forest-dependent people, no expansion of protected areas). • Strong expansion of agricultural areas into natural vegetation.
PN-2: Ecomodernism	• Policy measures and technological developments favouring agricultural intensification. • Slower but widespread investments into road and railway infrastructure. • Policies and incentives for environmental protection (e.g. stricter enforcement and delayed implementation of protected area expansion, carbon credits), although formal land tenure is not granted to forest-dependent people. • Intensification and concentration of existing agricultural areas with moderate expansion in mosaic landscapes.
PN-3: Integration	• Targeted measures to redistribute capital (e.g. land titling, credits for small-scale producers, taxes on inputs for large-scale producers) to promote the de-intensification of agriculture through more environmentally-friendly farming. • Existing infrastructure is modernised and maintained. • Implementation and enforcement of environmental protection laws and land-use zoning, accompanied by efforts to quickly expand protected area networks. • Conversion of intensified production systems (cropping and ranching) into mosaic systems and expansion of integrated silvopastoral systems.

to happen mainly via intensifying and concentrating existing agricultural areas, while *Integration* puts an emphasis on de-intensifying agriculture, and on multifunctionality by establishing silvopastoral systems.

2.3. Simulating future land-system patterns

We simulated our nine scenarios (three policy narratives * three expansion rates) separately for Argentina, Bolivia, and Paraguay in annual time steps between 2015 and 2045. As land-system futures in the Chaco are strongly determined by the national policy framework and socio-economic setting, developing and modelling scenarios per country is important. Recent land-change trajectories in the Chaco underline this: while agricultural expansion in the Argentinian Chaco dates back to the 1970s, it surged in the Paraguayan Chaco only after 2010, yet has been slower in Bolivia until very recently. Importantly, countries might follow different policy narratives and expansion rates. Our simulated land-system futures can thus be combined to reflect country-specific pathways and their overall impact on the ecoregion as a whole (a total of 729 combinations), yet for simplicity we here report results assuming all countries following the same policy narrative and expansion rate.

We excluded areas used by forest-dependent people and Indigenous communities from our simulations (i.e. their spatial dynamics were not modelled), yet their area of use can be affected by the expansion of other land systems. This had three reasons. First, as we were interested in assessing the impacts from future land-system change on forest-dependent people and Indigenous communities (see section 2.4), simulating these land systems would have created circularity. Second, land systems connected to forest-dependent people and Indigenous communities have a long history of stability in the Chaco (Levers *et al* 2021), and are not expected to substantially expand further (e.g. due to high competition for land, unclear/insecure land tenure, outmigration). Third, the location of these systems cannot well be described by suitabilities, but is largely driven by historical processes, land tenure, and land availability. We built upon the land-change model *alucR* (Gollnow 2016, Gollnow *et al* 2017) for our simulations, which requires five inputs: (1) a baseline land-system map, (2) suitability layers per land system, (3) future area demands per land system undergoing change, (4) conversion elasticities and trajectories for each allowed land-system transition, and (5) information on spatial restrictions on transitions between systems (see appendix 4 for details).

We used our 2015 land-system map as a baseline. To derive suitability layers per land system, we parameterized Boosted Regression Tree models for the year 2015 that explain the current distribution of land systems based on a set of spatial determinants (climatic conditions, soil quality, topography, accessibility, and population density; see table S4.1) identified during the two expert workshops as factors important for land-use decision-making in the study region. We used these models to predict suitability layers per land system until 2045 (see table S4.2). While most spatial determinants were held static, we temporally varied the two main ecological and socio-economic drivers of agricultural development pathways in the region: climate and transportation costs (Piquer-Rodríguez *et al* 2018a, 2018b).

Conversion elasticities (see appendix 4 for details) define how easily a land system can transition to another one, and thereby capture the reversibility of land change, ranging from 0 to 1. The higher the elasticity value, the more persistent and difficult to convert a land system is. We based conversion elasticities on past land-system change in 1985–2015 (table S4.3–S4.6) and our policy narratives (i.e. distinct conversion characteristics not represented by past elasticities; figure S4.2). Conversion trajectories are stricter realisations of elasticities and constrain which types of conversions can take place. Spatial restrictions (figure S4.3) prohibit where land conversion can take place, for which we used strictly protected areas (UNEP-WCMC and IUCN, 2017) and priority areas for conservation (Nori *et al* 2016). We refrained from implementing the current Argentinean land-use zoning (the 'Forest Law': Presupuestos mínimos de protección ambiental de los bosques nativos—Ley 26.331, figure S4.3), given the large spatial overlap of protection zones with priority areas for conservation (Nori *et al* 2016) and documented violations and enforcement problems of this law (Volante and Seghezzo 2018, Vallejos *et al* 2021).

To ensure that our simulations are plausible, we performed a pixel-wise assessment of the agreement between observed and simulated land-system patterns for 2015, for which we simulated the period 1985–2015 in annual time steps. Our simulation was able to reproduce past land-system changes very well, most notably for systems characterised by natural vegetation, such as woodlands and natural grasslands. Some disagreement occurred for intensified and mosaic agricultural systems (figure S4.4, table S4.7), most likely because the suitability for these systems (intensified vs. mosaic) is similar. We compared simulated land-system maps for 2045 to the initial land-system map of 2015 to identify change hotspots. Therefore, we calculated conversion frequencies from natural vegetation (woodlands, natural grasslands) to agriculture (intensified cropping/ranching, mosaics of cropping/ranching and natural vegetation, silvopastoral ranching) per cell across all nine scenarios. We defined agricultural expansion hotspots as areas with change in five or more scenarios.

2.4. Social-ecological impacts of land-system futures

We used our simulated land-system futures to assess five social-ecological impacts (see appendix 5 for details): on (1) natural vegetation, (2) carbon stocks, (3) biodiversity, (4) areas used by forest-dependent people, and (5) areas used by Indigenous communities. To assess natural vegetation loss, we calculated area differences of land systems with natural vegetation (grassland and woodland) between 2015 and 2045 for all scenarios. To assess biodiversity impacts, we used indicators of species richness for 48 larger mammals in the Chaco (Romero-Muñoz *et al* 2020) and estimated mean species richness loss per system transition based on historical impacts (i.e. difference in richness between 1985 and 2015) (figure S5.1). To assess carbon stocks, we used a recent map of aboveground biomass (Pötzschner *et al* 2022), from which we derived carbon loss (table S5.1) following Gasparri *et al* (2008). To assess social impacts, we used data on areas used by Indigenous communities (Camino *et al* 2023) and forest-dependent people (Levers *et al* 2021), and calculated woody vegetation loss, the main driver of the loss of key livelihood resources, within these areas.

2.5. Assessing agreement between observed and simulated land-system patterns

To assess which of our scenarios best resembled recent land-system changes in the Chaco, we compared our simulations to land-change data for 2015–2020 that has been mapped annually based on spectral-temporal metrics derived from the Landsat satellite archive (Baumann *et al* 2022) (see appendix 5 for details). This comparison of simulated and actual land-system change allows for a reality check of our scenarios and provides an indication of change pathways followed. We first calculated land-system compositions (per cent cover of individual land systems per hexagon) of observed and simulated land systems in 2020 within hexagons of 10 km diameter for each of our nine scenarios. Second, we calculated Euclidean distances between observed and simulated changes for each hexagon and scenario. Third, we identified the scenario with the highest similarity (i.e. the smallest distance) to the observed land-system composition and interpreted this scenario as the most probable land-system change pathway for that hexagon. If two or more scenarios had equal shortest distances, we labelled that hexagon as indifferent as we could not identify a dominant change pathway.

3. Results

3.1. Recent land-system change

Land system dynamics were considerable across the Chaco between 1985 and 2015 (figures 2 and S6.1), most notably for woodlands (47.5%–32.6% = 512 000 km^2–352 000 km^2), intensified cropping and ranching (0.8%–2.7% = 8500 km^2–29 000 km^2, and 0.2%–2.7% = 2300 km^2–29 000 km^2, respectively), and mosaic cropping and ranching systems (3.1%–5.1% = 33 200 km^2–54 800 km^2, and

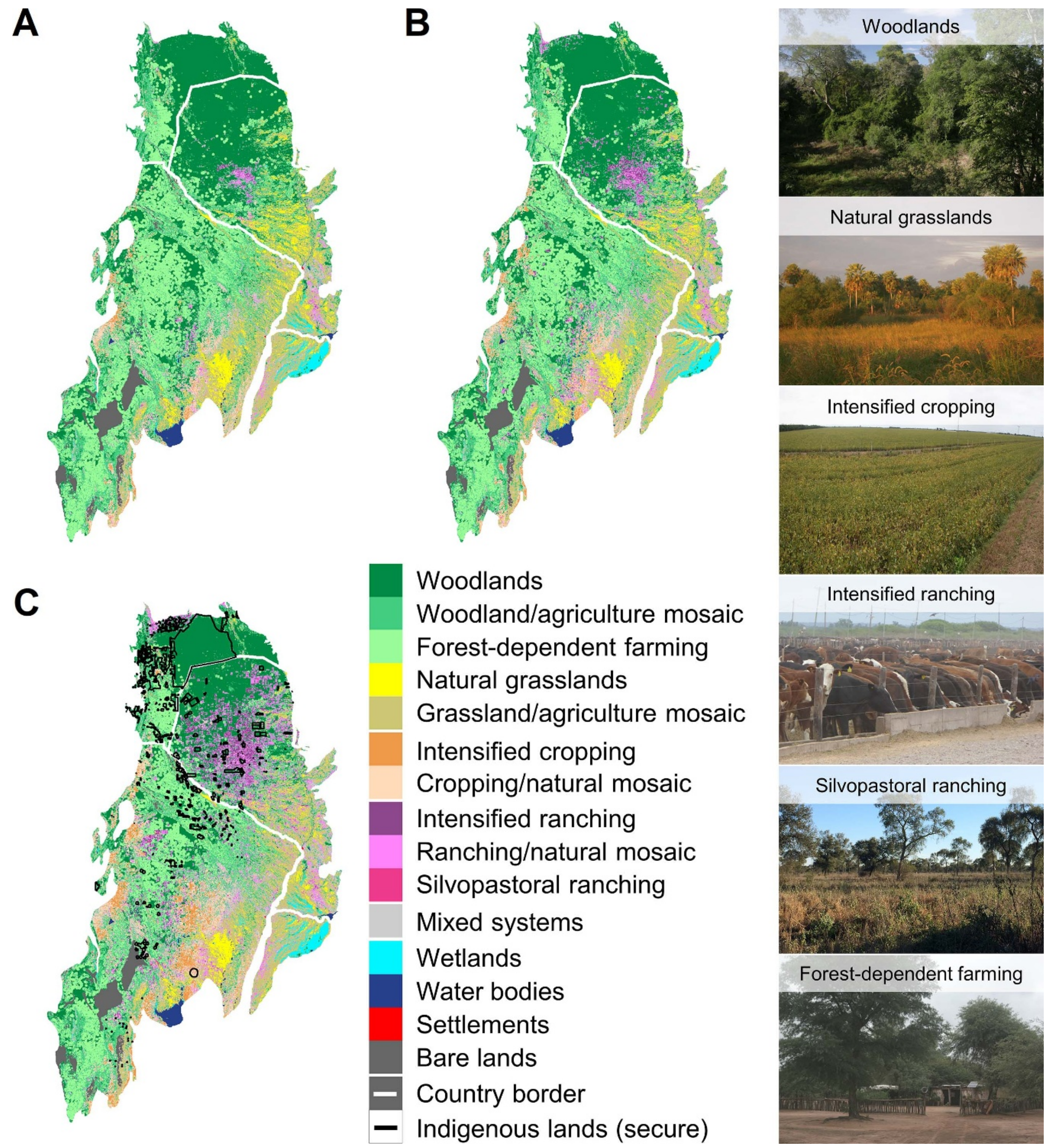

Figure 2. Land-system patterns for 1985 (A), 2000 (B), and 2015 (C). We assume an impact radius of 5 km for forest-dependent farming on woodlands. Black polygons indicate the location of Indigenous lands (secure land titles). See figure S1.1 for a more detailed overview (photos: authors).

1.5% to 8.0% = 16 600 km^2–86 200 km^2, respectively). Most changes occurred in Argentina and Paraguay, whereas land systems remained fairly stable in Bolivia. In Argentina, we observed strong increases in intensified cropping and cropping/natural mosaics (1.3%–4.4% = 8400 km^2–28 500 km^2, and 4.8%–8.0% = 31 300 km^2–51 800 km^2, respectively), while increases in intensified ranching and ranching/natural mosaics dominated in Paraguay (0.6%–7.6% = 1700 km^2–23 000 km^2, and 2.9%–15.9% = 8800 km^2–48 300 km^2, respectively). Mixed systems expanded across the entire Chaco (4.6%–7.6% = 49 600 km^2–82 000 km^2), and within Argentina (5.4%–8.5% = 35 400 km^2–55 100 km^2) and Paraguay (3.8%–7.7% = 11 600 km^2–23 300 km^2). The area of subsistence-oriented forest-dependent farming decreased by about 21% (from 330 000 km^2 to 260 000 km^2).

3.2. Future land-system patterns

Simulated land-system patterns varied strongly across scenarios (figure S6.2), with multiple hotspots of agricultural expansion (figure 3). Such hotspot regions represent existing or new expansion frontiers and our analyses distinguished three main types: first, continued expansion of existing cropping and ranching frontiers in Argentina, as in the provinces of Santiago del Estero, Tucumán, and Jujuy; second, expanding

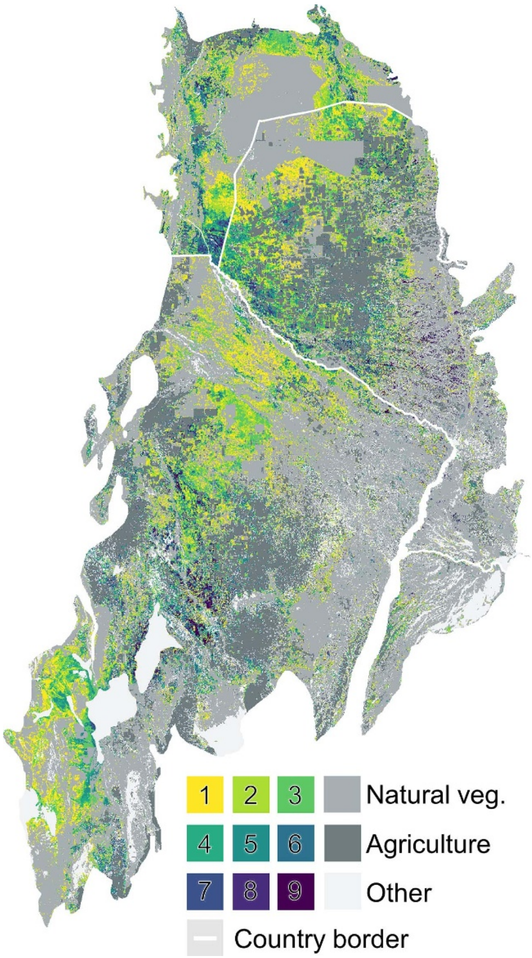

Figure 3. Summary of simulated land-system patterns for the Chaco in 2045 for our nine future scenarios. The colour gradient from yellow to purple indicates how many scenarios simulated a change from natural vegetation to agriculture (i.e. cropping or ranching, max: 9). Results for individual scenarios are shown in figure S6.2.

ranching frontiers in the western part of Boquerón (Paraguay) and Santa Cruz (Bolivia); and third, new and emerging frontiers for cropping and ranching in Tarija (Bolivia).

Scenarios following the Agribusiness narrative showed widespread expansion of intensified ranching in the central Argentinian Chaco and intensified cropping in the southern Argentinian Chaco and along the Paraguay/Bolivia border (figure S6.2). Scenarios following the Ecomodernism narrative showed a strong expansion of silvopastoral ranching and a concentration of intensified cropping in the central Argentinian Chaco, intensified cropping on the Paraguayan side of the border triangle, and intensified cropping and ranching in western Bolivia. Scenarios following the Integration narrative showed a strong expansion of silvopastoral ranching in all three countries (central Argentinian, north-eastern Paraguayan, northern Bolivian Chaco), and widespread concentration of agriculture (mostly in cropping/natural mosaics).

3.3. Social-ecological impacts of future land-system change

We found that the choice of agricultural expansion rates had a stronger impact than that of policy narratives on the loss of natural areas in the Chaco (figure 4), but that policy narratives modulated these overall effects considerably (figures S6.3–S6.5). Our Agribusiness narrative was characterised by agriculture expanding primarily into woodlands, and consequently showed the highest proportional woodland loss rates across our policy narratives. Natural vegetation losses in Ecomodernism and Integration were both lower than those of Agribusiness, and overall similar in magnitude. Yet, woodland loss was higher for Integration than for Ecomodernism, especially at low expansion rates, mostly due to expansion of silvopastoral ranching over woodlands. Grassland/agriculture mosaics were most strongly affected by expanding agriculture in Ecomodernism. Natural grasslands remained virtually constant across all scenarios.

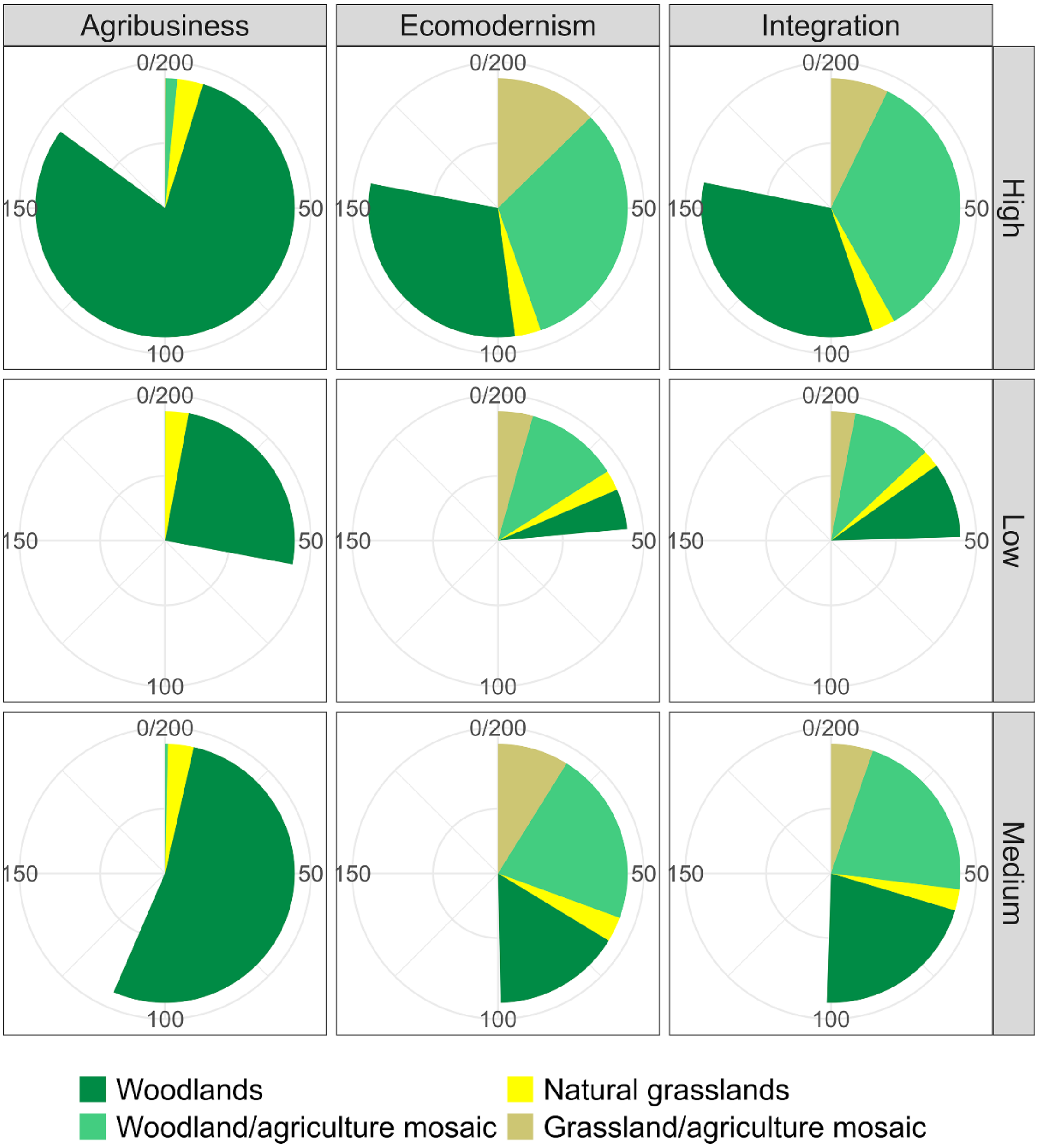

Figure 4. Simulated loss of natural vegetation until 2045 across our nine scenarios (policy narratives: columns, expansion rates: rows). Segment sizes represent area losses (1000 km^2).

Social-ecological impacts associated with simulated land-system changes, expressed as relative change compared to 2015 conditions, also varied considerably across scenarios (figure 5). Expansion rates were again determining the magnitude of impact, modulated by policy narratives. Agribusiness had by far the most substantial impacts, being 25%–50% higher compared to those of Ecomodernism and Integration. Overall, impacts of Ecomodernism and Integration were similar, yet with distinct differences. Ecomodernism had lower ecological impacts (i.e. biodiversity and carbon stocks), while Integration had lower social impacts (i.e. areas used by forest-dependent and Indigenous communities).

3.4. Land-system change between 2015 and 2020 compared with simulated land-system futures

Comparing simulated and observed land-system compositions in 2020 within 10 km hexagons showed that about 60% of all hexagons followed change pathways in land-system composition. About half of these had a distinct change pathway (the remainder had indifferent pathways, figure 6), with the majority following high expansion rates of agricultural areas (high, 14.8%), followed by low (8.2%) and medium (4.3%) expansion rates, across all policy narratives. The policy narrative, across all expansion rates, that most hexagons followed between 2015 and 2020 was Agribusiness (10.7%), followed by

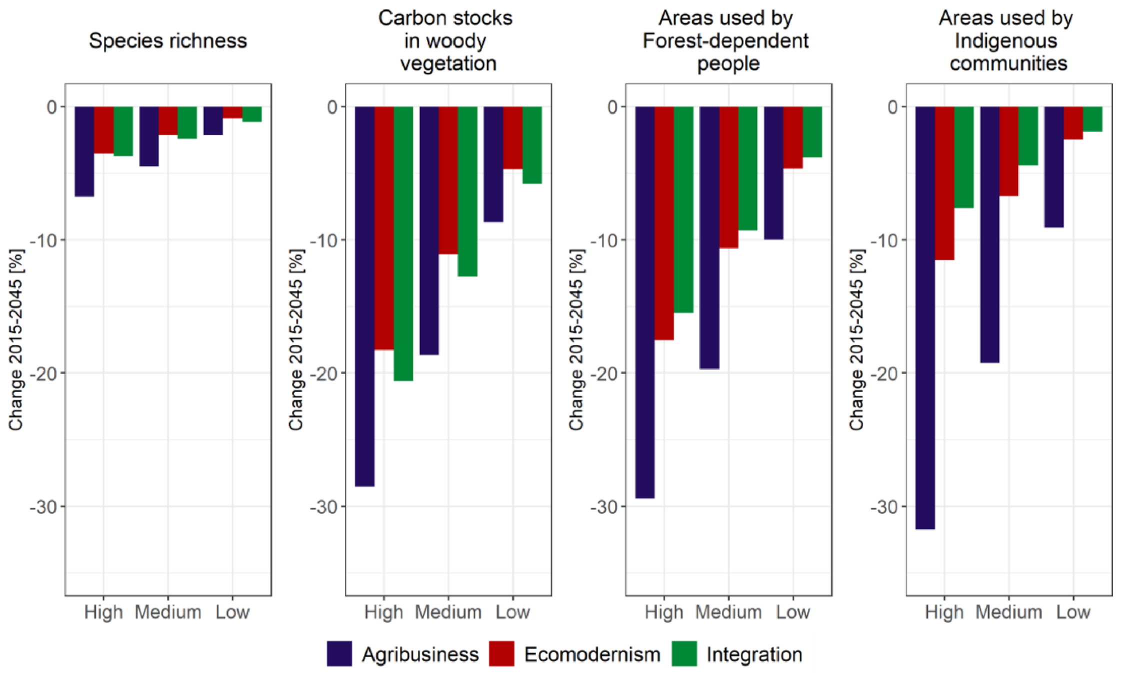

Figure 5. Social-ecological impacts of simulated land-system pattern for the Chaco in 2045 under three different area demands (high, medium, low) and three policy narratives (Agribusiness, Ecomodernism, Integration). Impacts are shown as percentage loss compared to 2015 conditions for species richness, carbon stocks in woody vegetation, and areas used by forest-dependent people and Indigenous communities. Note that areas used by forest-dependent people and Indigenous communities can overlap.

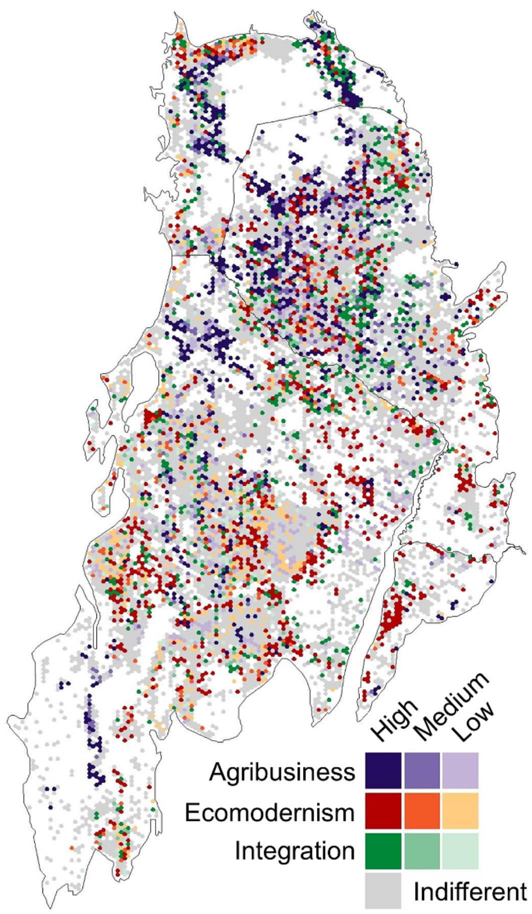

Figure 6. Comparison of simulated vs. actual land-system changes in the Chaco between 2015 and 2020. We evaluated similarity by comparing land-system compositions within hexagons of 10 km diameter. Indifference indicates that at least two scenarios had the same (highest) similarity to observed land-system change.

Ecomodernism (9.9%) and Integration (6.7%). Areas following the scenario high/Agribusiness were mostly located in western Paraguay, but also east and west of the Kaa-Iya National Park in Bolivia and in the Salta region in northern Argentina (figure 6). The scenario high/Ecomodernism was most prevalent in Argentina, while high/Integration mostly occurred in central Paraguay, the eastern Bolivian Chaco, and the central Argentinian Chaco.

4. Discussion

Tropical dry forests globally are under high and rising pressure from agricultural expansion, yet how and where this will potentially lead to social-ecological impacts remains weakly understood. We simulated nine plausible land-system futures for the Chaco, a global deforestation hotspot, until 2045. Comparing our scenarios to a range of social-ecological indicators revealed four key insights. First, our reconstruction of past land-system changes showed that agricultural expansion had mainly occurred at the expense of former woodlands, but that post-deforestation changes varied considerably. Second, we point to several future hotspots of agricultural expansion over natural vegetation, both in existing and in new expanding frontier regions. Third, policy choices strongly modulated the social-ecological impacts of land-system change, with the highest impacts in the least regulated narrative (Agribusiness), and generally lower social-ecological impacts in both Ecomodernism and Integration narratives compared to Agribusiness. Fourth, large parts of the Chaco undergoing changes in land-system composition between 2015 and 2020 followed pathways most similar to our social-ecologically most detrimental narrative (Agribusiness), mostly with high agricultural expansion rates. Overall, our analyses suggest that current land-use policies and zoning should be revised fast to reduce the strong ongoing social-ecological impacts.

Our analyses confirm that the rapid expansion of agriculture in the Chaco between 1985 and 2015 occurred mainly at the cost of woodlands, not other natural areas. We furthermore show that industrialized agricultural systems replaced large areas of natural vegetation used by forest-dependent people, suggesting major, but so far largely unquantified social impacts of past land-system change, in addition to the stark environmental impacts that agricultural expansion has caused (Romero-Muñoz *et al* 2021, Pötzschner *et al* 2022). Past and recent land-system changes in the Chaco created large areas of mosaic landscapes of agriculture and remaining natural vegetation. Given that retaining natural vegetation can lower social-ecological trade-offs in major ways (Garibaldi *et al* 2021), retaining this natural vegetation is important. This could be achieved through multiscale spatial planning to maintain connectivity of remaining natural vegetation (Torrella *et al* 2018), or by securing land rights for forest-dependent people, especially indigenous communities (Camino *et al* 2023).

Our simulated land-system futures revealed hotspots of potential agricultural expansion, which are plausible given that our model reproduced past changes with high agreement. Despite the structural differences of our scenarios (different agricultural expansion rates and policy narratives), we consistently highlight regions likely to undergo change from natural vegetation to agriculture. These areas should be primary targets for land-use planning to ensure that land-system change benefits a wide array of actors, especially local communities, and avoids unwanted environment trade-offs (Tamburini *et al* 2023). Several expansion hotspots occurred in agro-climatically marginal regions, such as in the southern and central Argentinian Chaco, the western Paraguayan Chaco, and the southern Bolivian Chaco (San Martín *et al* 2023). We consider such expansion as realistic, given the very substantial investments into developing drought-resistant crop varieties that would allow the utilization of currently marginal regions (Nature Biotechnology 2021), the presence of the Yrenda aquifer, which is increasingly used by people for irrigation and livestock (TWAP 2015), and the recent development of transportation infrastructure, especially the Bioceanic Corridor that will connect Chile to Brazil via Argentina and Paraguay, associated with potentially strong economic, socio-political, and environmental risks such as land speculation (Alamgir *et al* 2017). Further, the recent trend of transitioning from ranching to (soybean) cropping systems in the Paraguayan Chaco (Henderson *et al* 2021) is highlighted by our scenarios (figure S6.2), especially in scenarios assuming high expansion rates and narratives with a low degree of regulation. Our simulated expansion hotspots are in visual agreement with ongoing, active deforestation frontiers in the region (Baumann *et al* 2022), especially those in Bolivia (emerging) and western Paraguay (expanding), and with scenario-based results of market opening and state regulation (Mosciaro *et al* 2022), especially for Bolivia (high transformation scenarios). This underscores the plausibility of our scenarios, although the assumptions necessary for parameterising our land-change model can influence our results. Different choices, for example for future land-system demands, policy narratives that regionalise these demands, but also model parameters such as conversion elasticities and restrictions, would have resulted in different simulations outcomes. Despite this, our conclusions remain valid given the scope of our scenario-building and -simulation process to provide an option space of potential land-system futures.

Our third main finding was that policies can substantially lessen the social-ecological impacts of land-system change, adding to a growing body of literature that makes this point (OECD 2020). While expansion rates defined the amount of agricultural expansion into natural vegetation, policy choices expressed in our narratives modulated these impacts by altering the spatial patterns where expansion would occur. For example, social-ecological impacts were much higher (25%–50%) in the agribusiness-friendly and least regulated narrative. Interestingly, the impacts of the Ecomodernism and Integration narratives were overall similar. Ecomodernism emphasized agricultural intensification (i.e. conversion of mosaic landscapes to intensified systems) with agricultural expansion restricted to semi-natural systems, while Integration allowed conversions of natural vegetation to less ecologically detrimental land systems (silvopastoral ranching, agriculture/natural mosaics). Evidence points to agricultural intensification occurring alongside, rather than lowering, agricultural expansion in the Chaco (Mastrangelo and Aguiar 2019). Assumed land-sparing effects of our Ecomodernism narrative might therefore be overly optimistic and not materialize without strong regulatory mechanisms, considering the relatively weak institutions (le Polain de Waroux *et al* 2016) and unbalanced power relations toward large corporations (Baumann *et al* 2016). Importantly, assessing economic impacts of land change was not possible in our analyses due to a lack of consistent data on production costs and profits for all land systems in the three countries. Strong trade-offs between agricultural profits as well as biodiversity and carbon stocks are evident in the northern Argentinean Dry Chaco (Law *et al* 2021), which might be indicative for similar trade-offs in other Chaco regions. More generally, our results demonstrate that trade-offs in land management can occur between biodiversity conservation, productive land uses, ecosystem services, and livelihood of rural communities (Fastré *et al* 2020, Grass *et al* 2020). Thus, embracing the multiplicity of stakeholder voices and visions in the development of scenarios is critically important (Vigliano Relva and Jung 2021).

In our simulations, aboveground carbon was more strongly affected by land-system change than biodiversity. One explanation for this is the dissipating carbon-biodiversity relationship found for tropical forests (Ferreira *et al* 2018, Schuldt *et al* 2023). Land-use planning aiming at addressing biodiversity and carbon objectives should consider this in addition to the slower recovery times of biodiversity compared to carbon (Parrotta *et al* 2012). Moreover, we caution that we focused on one taxon only (mammals), for which detailed spatio-temporal data were available. Using a wider set of biodiversity taxa (e.g. plants, insects, birds) and more facets of biodiversity (e.g. functional and phylogenetic diversity) would undoubtedly reveal that our estimation of biodiversity impact is conservative. Indeed, more localized work suggests that biodiversity and carbon stocks in woody vegetation change largely in parallel (Macchi *et al* 2019, Law *et al* 2021), suggesting an underestimation of biodiversity impact in our work. Observed differences in carbon stocks and biodiversity responses could also be explained by the indictor-specific calculation of land-change impacts (see appendix 5), or the linear loss of carbon stocks due to deforestation in contrast to the often non-linear biodiversity loss in response to land-use intensification (Beckmann *et al* 2019).

Areas used by forest-dependent people outside indigenous communities were more strongly affected by land-system change compared to those used by Indigenous communities. Forest-dependent people living in remote homesteads are more widespread across the Chaco, especially Argentina, and inhabit almost half of all Chaco forests (Levers *et al* 2021), while Indigenous communities are more concentrated in certain parts of the Chaco (Camino *et al* 2023). Furthermore, some areas used by Indigenous Peoples overlap with strict protected areas, especially in Paraguay and Bolivia (Camino *et al* 2023), potentially curbing future deforestation. Since Indigenous lands hold the most biodiversity among land systems in the Chaco (Marinaro *et al* 2017), and function as deforestation barriers (Camino *et al* 2023), understanding where future deforestation could impact these lands is crucial.

Comparing our future scenarios to actual change for the period 2015–2020 revealed that a considerable share of the Chaco followed land-system pathways most similar to our social-ecologically most detrimental narrative (Agribusiness with high expansion rates). A major advantage of scenario-based analyses is the timely development and implementation of interventions necessary to steer sustainability transitions onto desired pathways (Haasnoot *et al* 2013, Sietz *et al* 2022). Given that stark social-ecological trade-offs are widely acknowledged to be undesirable (Scherer *et al* 2018, Law *et al* 2021), swift interventions and adjusted spatial planning could avoid some of these trade-offs, as well as potential lock-in situations they could bring about (Searchinger *et al* 2018, Meyfroidt *et al* 2022). Such lock-in situations are evident if past land-use decisions constrain future options (Seto *et al* 2016, Meyfroidt *et al* 2022). Regaining social-ecological values in locked-in agricultural systems will likely require transformative adaptation (Fedele *et al* 2019) an threaten to lead to sustained high trade-offs through rebound-effects where industrialized agriculture spreads (García *et al* 2020). Our work shows how purposefully starting the simulation of future land systems in the past can uncover how regions start embarking on a certain land-system pathway, thus helping to target interventions.

As agricultural commodity frontiers continue to expand into tropical dry forest around the world, sustainability planning and policies for reducing social-ecological impacts are urgently needed. Our study shows the option space of potential land-system futures for the Gran Chaco, a global deforestation hotspot with high biological and cultural diversity. We highlight how social-ecological impacts of alternative land system futures vary across space, expansion rates, and policy narratives, highlighting where interventions can be beneficial. The Chaco has seen rampant deforestation in the past, just as many others dry forests globally, such as in India, Madagascar, Southeast Asia, or South and Central America. Despite this, and likely similar to other dry forests, the Chaco still contains considerable social-ecological value that is at stake from future agricultural expansion. The time for sustainability planning in the Chaco and other dry forests is now if the goal is to ensure the well-being of people and nature in these regions.

Data availability statement

The source code for our land-system model is available on: https://github.com/floriangollnow/alucR_v01.

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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