Fading opportunities for mitigating agriculture-environment trade-offs in a South American deforestation hotspot

Elizabeth A. Law [1,2] *, Leandro Macchi [1,3], Matthias Baumann [1], Julieta Decarre[4], Gregorio Gavier-Pizarro[4], Christian Levers [1,5], Matías E. Mastrangelo[6], Francisco Murray[7,8], Daniel Müller[1,9], María Piquer-Rodríguez[1,10], Ricardo Torres[11] , Kerrie A. Wilson[12] & Tobias Kuemmerle [1,13]

[1] Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany.

[2] Norwegian Institute for Nature Research (NINA), PO Box 5685 Torgarden, NO-7485 Trondheim, Norway

[3] Instituto de Ecología Regional (IER – CONICET), Universidad Nacional de Tucumán, 4107 Tucumán, Argentina

[4] Instituto de Recursos Biológicos (IRB-CIRN), Instituto Nacional de Tecnología Agropecuaria (INTA), De los Reseros y Las Cabañas S/N, HB1712WAA Buenos Aires, Argentina

[5] Department of Environmental Geography, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, De Boelelaan 1111, 1081 HV, Amsterdam, The Netherlands

[6] Grupo de Estudios de Agroecosistemas y Paisajes Rurales (GEAP), CONICET - Universidad Nacional de Mar del Plata, 3350 Buenos Aires, Argentina

[7] Agencia de Extensión Rural San Luis, Instituto Nacional de Tecnología Agropecuaria (INTA), Ruta 20 km 4.5, D5700HHW, 5700 San Luis, Argentina

[8] Grupo de Estudios Ambientales – IMASL, Universidad Nacional de San Luis & CONICET, Ejército de los Andes 950, D5700HHW San Luis, Argentina

[9] Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Theodor-Lieser-Str. 2, 06120 Halle (Saale), Germany

[10] Lateinamerika-Institut, Freie Universität Berlin, Rüdesheimer Str. 54-56, 14197 Berlin, Germany.

[11] Museo de Zoología, Facultad de Ciencias Exactas, Físicas y Naturales, and Laboratorio de Biogeografía Aplicada, Instituto de Diversidad y Ecología Animal (CONICET), Universidad Nacional de Córdoba, Vélez Sarsfield 299, X5000JJC Córdoba, Argentina

[12] Queensland University of Technology (QUT), Gardens Point campus, 2 George St Brisbane QLD 4000, Australia

[13] Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany.

* Corresponding author: workingconservation@gmail.com

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Supplementary information, code, and data

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Abstract

Strong trade-offs between agriculture and the environment occur in deforestation frontiers, particularly in the world's rapidly disappearing tropical and subtropical dry forests. Pathways to mitigate these trade-offs are often unclear, as well as how deforestation or different policies alter the option space of available pathways. Using a spatial optimization framework based on linear programming, we developed a landscape-scale possibility frontier describing trade-offs between agricultural profit, biodiversity, and carbon stock for the Argentinean Dry Chaco, a global deforestation hotspot. We use this framework to assess how current land-use zoning, as well as past and future land-use-trajectories, alter the option space to minimize trade-offs between biodiversity, carbon, and agriculture. Our analyses yield four major insights. First, we found substantial co-benefits between biodiversity and carbon, yet strong trade-offs of both with agriculture. Second, development according to the current zoning could lead to highly suboptimal socio-ecological outcomes, and our analysis pinpoints how this zoning could be improved. Third, high landscape-scale multifunctionality can be achieved using different land-use strategies, but maintaining >40% of forest is essential in all of them, and silvopastoral systems appear to be central for achieving high overall multifunctionality. Finally, our results suggest the window of opportunity is closing rapidly: recent land-use changes since 2000 have rapidly moved the Chaco within the options space, with forest extent declining towards critical thresholds for maintaining balanced, multifunctional landscapes. Our results emphasize that the time for sustainability planning in the Chaco is now. More broadly, we show how multi-criteria optimization can describe dynamic trade-offs between agriculture and the environment at landscape and regional scales. This can help to identify land-system tipping points that, once crossed, would inhibit more sustainable futures, and policies to avoid such potential traps.

Keywords: Agricultural expansion; Agricultural intensification; Conservation planning; Gran Chaco; Pareto frontier; Spatial prioritization; Tropical dry forests and savannas.

INTRODUCTION

Where agriculture expands and intensifies, environmental trade-offs are typically stark (Foley *et al.*, 2011, Laurance *et al.*, 2014). Moving to sustainable agriculture that achieves more positive environmental outcomes is therefore a central goal for stakeholders from local to global scales (IPBES, 2019, Leclère *et al.*, 2020). This is particularly pressing in tropical and subtropical deforestation frontiers, where agricultural expansion leads to rapid and drastic environmental trade-offs, including widespread biodiversity loss (Laurance *et al.*, 2014, Kehoe *et al.*, 2017) and massive carbon emissions (Baccini *et al.*, 2017, Pendrill *et al.*, 2019). Given diminishing forests and surging demands for agricultural products, the urgency for policies to effectively mitigate agriculture-environment trade-offs has never been greater (Lawrence & Vandecar, 2015, Carrasco *et al.*, 2017, Law *et al.*, 2017).

To deliver evidence-based policy and mitigation measures, knowledge of agriculture-environment trade-offs is needed, and such knowledge is particularly sparse in the world's tropical and subtropical dry forests and savannas (hereafter: dry forests). These ecosystems cover about 20% of the global terrestrial surface, provide 30% of global primary productivity, sustain about 20% of the world's human population, and harbor high biodiversity (Miles *et al.*, 2006, Murphy *et al.*, 2016). Yet dry forests remain weakly protected (Miles *et al.*, 2006, Parr *et al.*, 2014, Banda-R *et al.*, 2016) and are experiencing high and escalating rates of human pressure, especially from land-use change (Blackie *et al.*, 2014). Many dry forests regions are deforestation frontiers, particularly the South American Cerrado, Chaco, and Chiquitania regions (Baumann *et al.*, 2017, Strassburg *et al.*, 2017, Romero-Muñoz *et al.*, 2019). Given the escalating threats to the values of dry forest across the globe, these regions are in dire need of improved land-use and conservation planning (Miles *et al.*, 2006, Parr *et al.*, 2014).

The dynamic nature of landscapes undergoing rapid land-use change, such as in deforestation frontiers, is an additional challenge to understanding trade-offs between agriculture and the environment (Carrasco *et al.*, 2017, Barral *et al.*, 2020, Macchi *et al.*, 2020). Many types of land-use change are quasi-irreversible at time-scales relevant for sustainability planning, including the conversion of old-growth forests to agriculture (Watson *et al.*, 2018). Major irreversible land-use changes can therefore drastically limit future options to achieve sustainability. However, despite increasing evidence for strong agriculture-environment trade-offs (Seppelt *et al.*, 2013), our understanding of how land-use policies alter the option space for mitigating trade-offs is weak. This is particularly so for those regions that are changing most rapidly, such as many tropical and subtropical dry forests.

Attempts to analyze agriculture-environment trade-offs have often been local assessments or limited to patterns across a specific land-use intensity gradient. While this provides important insights into the relationship of agricultural production and environmental outcomes (Newbold *et al.*, 2015, Williams *et al.*, 2017, Macchi *et al.*, 2020), upscaling from local assessments to landscape and regional scales – scales that are most relevant for land-use and conservation planning – requires more than a simple extrapolation. Accepting strong local trade-offs (e.g. from intensified agriculture) in some locations might lessen overall pressure on land at broader scales (Macchi *et al.*, 2013, Butsic *et al.*, 2020), and understanding the environmental impacts of specific systems (e.g. intensified agriculture, agroforestry) does not elucidate on which combination of land uses are best to minimize agriculture-environment trade-offs (Butsic & Kuemmerle, 2015). This is highly relevant because there is increasing evidence that landscapes that harbor a mix of land uses might mitigate trade-offs more than homogeneous landscapes (Law *et al.*, 2015, Butsic *et al.*, 2020). As most production landscapes fall somewhere on a multidimensional gradient between wild areas and fully intensified agriculture (Kremen & Merenlender, 2018, Kennedy *et al.*, 2019), understanding the trade-offs between land-use outcomes in regions where a diversity of land uses co-occur is important.

Multi-objective optimization at regional scales can reveal trade-offs between agricultural production and the environment (Polasky *et al.*, 2008, Bryan *et al.*, 2011, Moilanen *et al.*, 2011), with examples from Oregon (Nelson *et al.*, 2009), California (Chan *et al.*, 2006), the Brazilian Cerrado (Kennedy *et al.*, 2016) and Indonesia (Law *et al.*, 2015). Possibility frontiers (also known as Pareto frontiers) are a powerful tool for such analyses, as they assess the dynamic trade-offs between two or more competing objectives (e.g. agricultural production and biodiversity) for entire regions (Polasky *et* *al.*, 2008). Possibility frontiers construct option-spaces of land-use outcomes that can be achieved given a set of constraints and allow exploration of the effects of alternative policies on this option space. Thus, the possibility frontier describes the fundamental trade-offs between the objectives and identifies feasible and optimal land-allocation solutions to mitigate these trade-offs (Law *et al.*, 2017). This, in turn, helps to identify combinations of goals that can be aligned through planning, versus goal combinations that are simply impossible to achieve (Watts *et al.*, 2009, Bryan *et al.*, 2015). Likewise, past, current, and future landscapes can be traced inside the possibility frontier, and the potential effectiveness of policies (e.g. zoning plans) to achieve higher multifunctionality can be evaluated. In short, possibility frontiers are strong tools for aligning agricultural and environmental goals in regions undergoing deforestation, but have so far been rarely applied for that purpose.

The Argentinean Dry Chaco is a particularly interesting region to explore agriculture-environment tradeoffs. The expansion of cattle ranching and soybean production destined for international markets have turned this region into a global deforestation hotspot (Baumann *et al.*, 2017, Kuemmerle *et al.*, 2017), with major impacts on biodiversity (Periago *et al.*, 2015, Romero-Muñoz *et al.*, 2020), and globally-relevant carbon emissions (Baumann *et al.*, 2017). Previous work on agriculture-environment trade-offs has focused on local scales, yielding diverging results about what land-use strategy might mitigate these trade-offs best (Mastrangelo & Gavin, 2012, Macchi *et al.*, 2013). Likewise, it remains unclear whether the regional land-use zoning (National Law 26331, known as the 'Forest Law 2007') has been effective in alleviating agriculture-environment trade-offs (Volante & Seghezzo, 2018) and how the current zoning policy constrains the possible option space for achieving multifunctionality (i.e. lower agriculture/environment trade-offs). Finally, there is an ongoing debate about the role of specific land uses in facilitating or inhibiting more sustainable and multifunctional landscapes, particularly related to the potential role of silvopastoral systems and subsistence forest smallholders.

Here, we use possibility frontiers to assess the fundamental trade-offs between agricultural profits, biodiversity (relative abundance of birds and mammals), and aboveground carbon stocks across the northern Argentinean Dry Chaco. Specifically, we ask:

1. What is the fundamental nature of the trade-offs between agricultural profit, biodiversity, and carbon stocks in the Argentinean Dry Chaco?
2. How does the current land-use zoning plan affect the option space to mitigate these trade-offs?
3. How are current, past, and possible future land-use allocations placed against the possibility frontier, and what adjustments to the current land-use zoning would foster higher landscape-scale multifunctionality?

METHODS

Study region

Our study region in the northern Argentinean Dry Chaco stretches across four provinces (174,197 km², Figure 1). Maximum temperature can reach 48°C in the summer and annual precipitation ranges from 400 mm to 900 mm, 80% of which falls between November and March (Morello *et al.*, 2012). Natural vegetation is composed of forests and grasslands. The Chaco region is rich in biodiversity, with >3,400 plant species, >150 mammals, >500 birds, and many endemic animal and plant species (Bucher & Huszar, 1999, Banda-R *et al.*, 2016, Nori *et al.*, 2016).

Major land-use changes began in the early 20th century, with smallholders settling in the Chaco forests (hereafter: forest smallholders), practicing subsistence ranching with livestock grazing freely in the forests around homesteads. Together with firewood extraction, selective logging, and charcoal production, this has degraded forests substantially in many areas (Grau *et al.*, 2008). Beginning in the 1980s, industrialized cattle ranching and cropping, mainly for soybean production, has resulted in degradation of over 80% of the Argentinean Chaco, driven by technological innovation, rising commodity prices, and the opening of regional land markets to international trade (Zak *et al.*, 2008). This rendered the greater region a global deforestation hotspot in the early 21st century (Hansen *et al.*, 2013), and the study region a frontier landscape likely to experience severe deforestation in the near future.

In response, Argentina implemented a regional zoning plan (the 'Forest Law', *Ley 26.331 de Presupuestos Mínimos de Protección Ambiental de los Bosques Nativos*) in 2007 to reduce deforestation rates and to mitigate its environmental trade-offs. The Forest Law subdivides the remaining forest in the region into a *'red'* conservation, a *'yellow'* sustainable use, and a *'green'* development zone (Fig. 1). The exact definition and implementation of these zones vary by province, but can be simplified as follows: conservation zones are primarily for environmental protection (8.2% of the study region); sustainable development zones allow low-impact uses such as sustainable forestry, tourism, and partial clearing of forest for silvopasture (47.5% of the study region); and development zones allow clearance of forest, pending conditions (e.g. provincial limits to deforestation, retaining forest strips, and acquiring permits; 26.0% of the study region, here combined with the 26.4% of the region not zoned under the Forest Law).

Forest smallholders and silvopastures have both recently received attention in the context of sustainable development in the Argentinean Chaco. Forest smallholder systems are currently widespread (more than 2,100 homesteads in our study region) and use surrounding forest areas for various purposes, including livestock grazing and timber extraction. In addition, forest smallholders exert considerable pressure on wildlife through hunting (Romero-Muñoz *et al.*, 2020). Silvopastures, in contrast, are highlighted as a potentially low-impact, multifunctional land use and a potential future sustainable development pathway. Silvopastures ideally are managed both for meat and timber production, and are being promoted both in Argentina and internationally to manage environment-development trade-offs (Kremen & Merenlender, 2018, Nunez-Regueiro *et al.*, 2018, Mauricio *et al.*, 2019). However, as of 2015 silvopastures remain scarce at 2.0% across the study region, typically do not appear to be managed for timber or tree regeneration, and retain only a minor portion of carbon and biodiversity of undisturbed forests (Fernández *et al.*, 2020, Macchi *et al.*, 2020). The potential for these land uses to contribute to landscape-level efficiency and multifunctionality is unknown.

Overall, the effects of the Forest Law zoning, in terms of mitigating agriculture/environment trade-offs, and thus to achieve higher multifunctionality at landscape and regional scales, are unknown. A provision to update the regional zoning plan provides an important window of opportunity for policy review and reform.

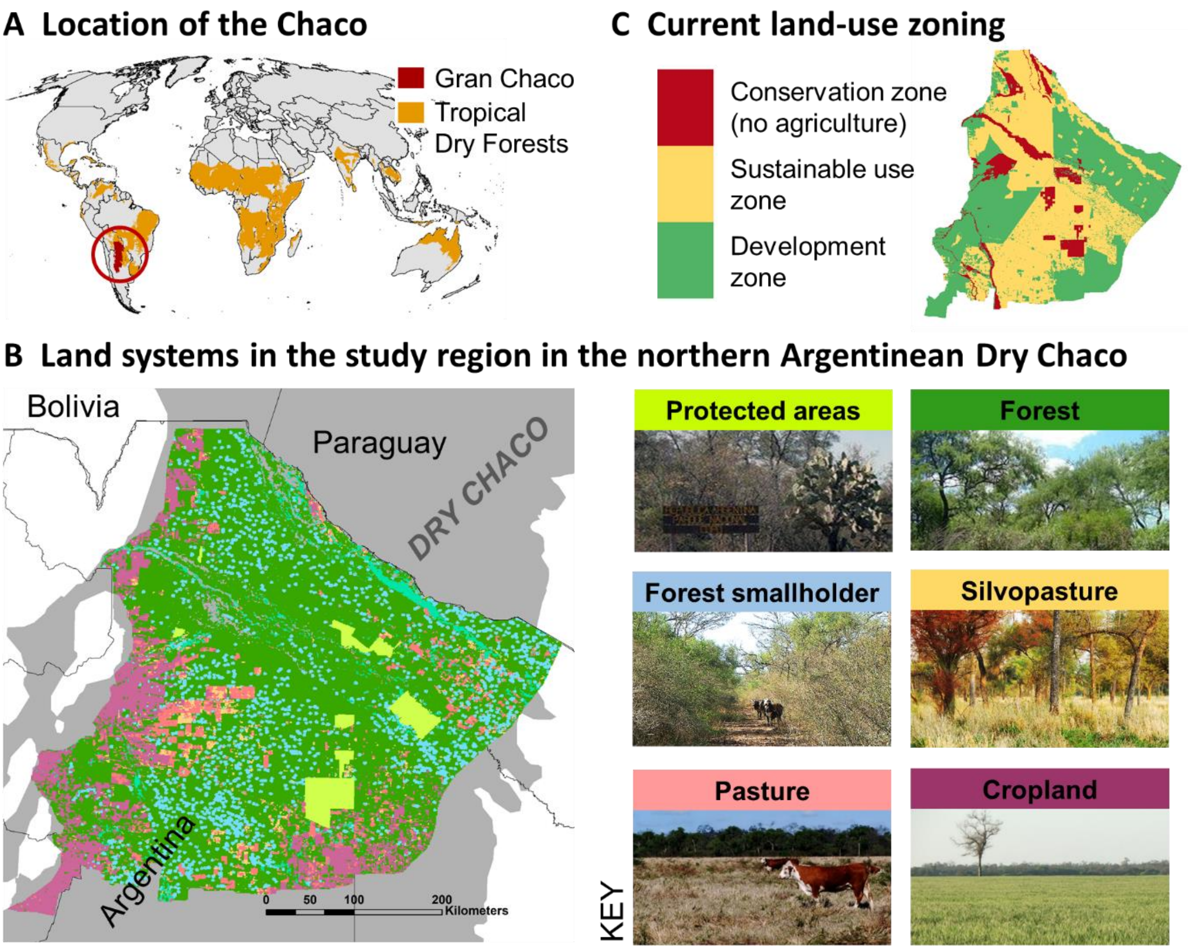

Figure 1: Major land systems (i.e. social-ecological system dominated by a specific land use) in the northern Argentinean Dry Chaco. (A) Location of the Gran Chaco (Data: Olson et al. (2001)). (B) Study region in the northern Argentinean Dry Chaco, with the distribution of major land systems as of 2015, color key with illustrations on the right. (C) Current land-use zoning in the study region (forest smallholders shown here by a 2km radius within forest area).

Analysis framework

Given the ramifications of rapid agricultural expansion on biodiversity and carbon, we focused our analysis on these three dimensions (agricultural profit from soy and beef, a biodiversity metric representing aggregate relative abundance of 26 bird and 17 mammal species, and aboveground carbon stock) and analyzed the trade-offs between them under different potential future policies using a possibility frontier analysis (Fig. 2). We defined the frontier as a spatial multi-objective optimization problem (Bryan *et al.*, 2015, Law *et al.*, 2017) across a landscape (i.e. our study region, defined as a heterogeneous region with multiple interacting socio-ecological systems). In short, our approach optimized a set of *decision variables* (i.e. variables determining which land system is allocated to each cell across the landscape), given a *maximization objective*, subject to *constraints* (described in brief below, and in full in Appendix A).

Decision variables allocated cells into one of five alternative land systems (defined as a social-ecological system dominated by a specific land use). Specifically, for our study region, these are: cropland, pasture, silvopasture, forest smallholders, and forest (Figure 1). Each of these land systems provide spatially-variable benefits for biodiversity, agricultural profit, and carbon stock, with values of each cell determined by their underlying biophysical capacity and past land use. A sixth land system collectively included areas that both contributed to biodiversity and carbon benefits (e.g. natural grasslands, protected areas), as well as areas that did not contribute to any benefits (i.e. waterbodies, built-up, bare ground), all of which were assumed to stay constant during the optimization (henceforth: 'static').

The *maximization objective* and *target constraints* jointly describe the three dimensions of the frontier: We traced this 3D-frontier with the objective of maximizing our biodiversity metric for iteratively increasing targets for agriculture and carbon. Target constraints traced the possibility frontier across a gradient of agricultural profit and carbon stocks that must be achieved (from 0% to 100% of their respective maxima, in 2% intervals). Transition constraints determined which land systems were allowed to be allocated to a cell, based on different land-use policy scenarios and historical land-use trajectories. For example, we assumed that areas previously subject to extensive clearing (i.e. cropland, pasture, and silvopasture) would not be able to be restored back to forest over the time horizon relevant for planning (e.g. years to decades). We prepared all data in R (v3.1.2; R Core Team 2014), using *prioritizr* (Hanson *et al.*, 2020) to facilitate development of the optimization problem, which was solved using Gurobi v6.0 (Gurobi Optimization, 2010). Further R-packages used in data development and processing are detailed in Appendix A.

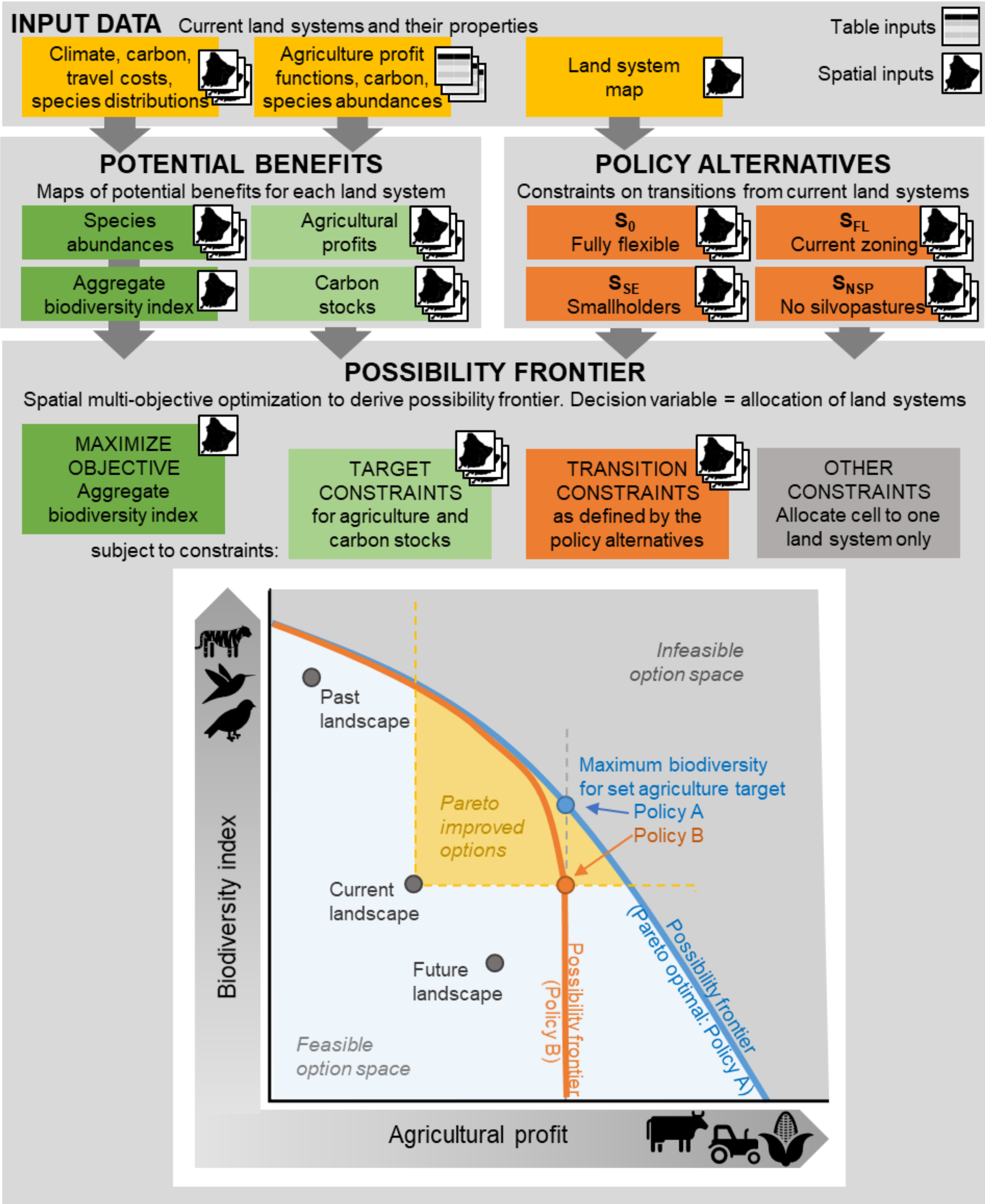

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Figure 2: Analytical framework for analyzing the trade-offs between agriculture, biodiversity, and carbon in the Argentinean Dry Chaco. We first mapped potential benefits per land system across the study region and developed alternative spatial policy scenarios regarding which transitions between land systems were allowed (see Table 1 for transition scenarios). Next, we used spatial optimization of land systems for the whole study region to yield a landscape-scale possibility frontier (here illustrated

showing two dimensions, agricultural profit and biodiversity index, only). Points on the frontier are efficient (i.e. more biodiversity can only be achieved if agricultural profit goes down or vice versa). Points along the middle of the frontier are described here as configurations of land systems that efficiently achieve high landscape-level multifunctionality (i.e. a feasible balance of relatively good outcomes for all objectives).

Land systems and their current and potential benefits

We mapped land systems and the potential benefits per land system for each of the three dimensions: agricultural production, biodiversity, and carbon stocks. To map land systems, we selected the year 2015 as a baseline for our analyses. The land-systems map (Fig. 1) was based on a land-cover map derived from 30 m-resolution Landsat images (Baumann *et al.*, 2017), aggregated to the dominant land system in 1 km cells (i.e. forest, cropland, pasture, natural grasslands, and other). Silvopastoral systems were identified as pastures with 12-30% woody cover (Macchi *et al.*, 2020). Forest smallholder homesteads were digitized from very-high-resolution imagery in Google Earth (Romero-Muñoz *et al.*, 2020). We assumed a smallholder footprint radius of influence on surrounding forests of 1 km (carbon stocks) or 2 km (biodiversity and agricultural profit) around homesteads, representing an average estimate of the strongest effects on most species and forest structure (Baumann *et al.*, 2018, Vallejos *et al.*, 2020a). As the spatial footprint of some activities by forest smallholders (e.g., livestock grazing, hunting) can be larger than 2 km, we also examined results for a smallholder footprint radius of 5 km for biodiversity and agricultural profit. We assigned protected areas according to the World Database of Protected Areas (www.protectedplanet.net), including the recently designated national park *El Impenetrable*. For further details and discussion on land system mapping, including assumptions regarding smallholders and silvopasture, see Appendix A1.

To define agricultural profits per land system, we focused on beef and soy, the two major commodities in the region. Functions deriving agricultural yield and gross profit (USD $km^{-2}yr^{-1}$) for soy (from cropland) and beef (from pasture, silvopasture, and forest smallholders)(Murray *et al.* 2016), were spatially differentiated with reference to precipitation (ClimateSA v1.0; *http://tinyurl.com/ClimateSA*) and distance to trade centers (Piquer-Rodríguez *et al.*, 2018). Our biodiversity indicator represented the weighted sum of the relative abundances of a set of focal species (i.e. 26 birds and 17 mammals) for which data were available. We used potential distributions of these species (Torres *et al.*, 2014) to define potential presence. Within these distributions, we used the land system map and the relative abundance per land system (Macchi *et al.*, 2013 & this study) to create an abundance index per species. We gave each species equal weighting in the optimization by scaling species-wise indices by their respective landscape-scale maxima. For carbon stocks in forest, we used models of above-ground potential biomass in forest as a function of precipitation (Gasparri & Baldi, 2013), and we assumed 50% of the above-ground forest biomass to be carbon (Baumann *et al.,* 2017). For cropland, pastures, and natural grasslands, we used above-ground carbon estimates from Baumann et *al.* (2017). For silvopastures, we used the average above-ground carbon stock mapped in silvopastures (Gasparri & Baldi, 2013). We acknowledge several assumptions and simplifications. For example, we did not consider interactions between land systems (such as dependencies between beef and soy production), carbon emissions from livestock, or the costs or benefits of transitioning between land-uses (e.g. developing crops on previously forested areas). For a detailed description of the mapping of all three benefits, including input data and discussion of caveats, see Appendix A2.

Policy scenarios

We defined four policy scenarios with regards to allowed transitions between land systems (Table 1; Appendix A3) to reflect different land-use planning agendas. S_0 defines the 'fundamental' frontier (i.e. the frontier limited only by biophysical constraints). S_{FL} reflects transition constraints imposed via the current Forest Law zoning. Given discussion surrounding 'sustainable-use' options under the Forest Law, we developed S_{SE}, which tests the impact of supporting forest smallholders as a culturally important land system (i.e. a socio-ecological scenario), and a 'no silvopasture' scenario, S_{NSP}, to ascertain the importance of this land system. Further details are given in Appendix A3.

Table 1: Policy scenarios summarizing the constraints imposed on transitions allowed between land systems in the optimization process. Further details on transitions are given in Appendix A3.

Scenario	*Description*
S_0 *- the 'fundamental' frontier*	Subject to biophysical constraints only, this scenario reflected a hypothetical, most flexible policy that describes an upper baseline of potential possibilities. All land systems could transition to all others except (1) cropland, pasture, and silvopastures, were assumed as unable to transition to forest, (2) forest smallholders could persist but not expand, and (3) the static zone remained constant.
S_{FL} *- Forest Law scenario*	This scenario reflected a pragmatic interpretation of the Forest Law zoning (Figure 1): The development zone allowed transitions among all zones as for S_0. In addition to basic constraints, the sustainable-use zone required (1) any transitions from forest to be for silvopasture, (2) mandated the transition of existing cropland and pasture to silvopasture, and (3) allowed but did not mandate persistence of forest smallholders. The conservation zone maintained forest and mandated transitions of other land systems to the most biodiversity-friendly system possible (i.e. forest smallholders to forest, cropland and pasture to silvopasture).
S_{SE} *- Socioecological scenario*	This scenario reflects a perspective that forest smallholders are a culturally important and desired land system. Forest smallholders were therefore assumed to persist (i.e. held constant) in this scenario. All other transitions constraints were as in the S_0 scenario.
S_{NSP} *– No silvopasture scenario*	This scenario was developed to test the importance of the silvopasture land system. S_{NSP} specified that silvopastures were not allowed to expand from 2015 levels (2%), with all other transition constraints as in S_0.

In addition to these four transition scenarios, we assessed eight *point scenarios* representing past and future land-allocations. We located these point scenarios relative to the possibility frontiers and compared outcomes. Past point scenarios used the actual land-system configurations from 1985, 2000, and 2015. Future point scenarios included both optimized land-system allocations and projected future land allocations. For the former, we selected points from each transition scenario's possibility frontier that gave efficient multifunctional outcomes at the landscape scale, defined here as the maximum biodiversity (and near maximal carbon) outcomes while achieving 50% of the maximum agricultural production possible for the study region. For the latter, we projected future land-system allocations as if the Forest Law zoning would be fully developed (i.e. all of the development zone transitions to cropland, all of the sustainable-use zone transitions to silvopasture, and all of the conservation zone transitions to the land system providing the highest biodiversity score possible at a given location). We stress that this explores the hypothetical endpoint of full development for a pragmatic interpretation of the current zoning: some provinces currently specify maximum conversion proportions, so our scenario explores the situation should these restrictions be relaxed (e.g. in case land for expansion becomes scarcer, or due to weak enforcement). Further details on the point scenarios are given in Appendix A3.

Frontier analyses

To assess the trade-offs between agricultural profit, biodiversity, and carbon stocks, we first assessed the general shape of the fundamental possibility frontier under S_0. Next, to assess the impact of the Forest Law policy, we compared the possibility frontiers developed for the policy scenarios S_0 and S_{FL}. Given that the Forest Law designates special importance on silvopasture and forest smallholders, we also assessed the impacts of these on the possibility frontier by comparing S_{SE} and S_{NSP} with S_0. We then located the past and potential future point scenarios within the fundamental possibility frontier (S_0) to understand trends in landscape change relative to this frontier. We also identified critical area thresholds for land-system allocations required for the future, optimized multifunctional point scenarios. Finally, we compared land-system allocations at these points to propose safeguards or modifications to the Forest Law to improve the likelihood of achieving an efficient (i.e. on the possibility frontier) *and* multifunctional (i.e. balancing agricultural production, carbon storage and biodiversity) landscape in our study region. Results presented in the main text apply to the assumed radius of smallholder forest influence of 2 km; the alternative 5km assumption is presented in Appendix B5.

RESULTS

Fundamental trade-offs between agricultural profits, carbon stocks, and biodiversity

The possibility frontier for S_0 reveals the fundamental trade-offs between agricultural profit, carbon stocks, and biodiversity in the Argentinean Dry Chaco (Fig. 3). We found high compatibility of biodiversity and carbon in the study region, with both dimensions changing largely in parallel. However, both carbon and biodiversity show a consistent trade-off with agriculture (Figure 4). In other words, while there are strong synergies between the two environmental dimensions, both are diminished by increasing agricultural profit in the Argentinean Chaco. We provide a more detailed description of the fundamental possibility frontier in Appendix B (Fig. B1).

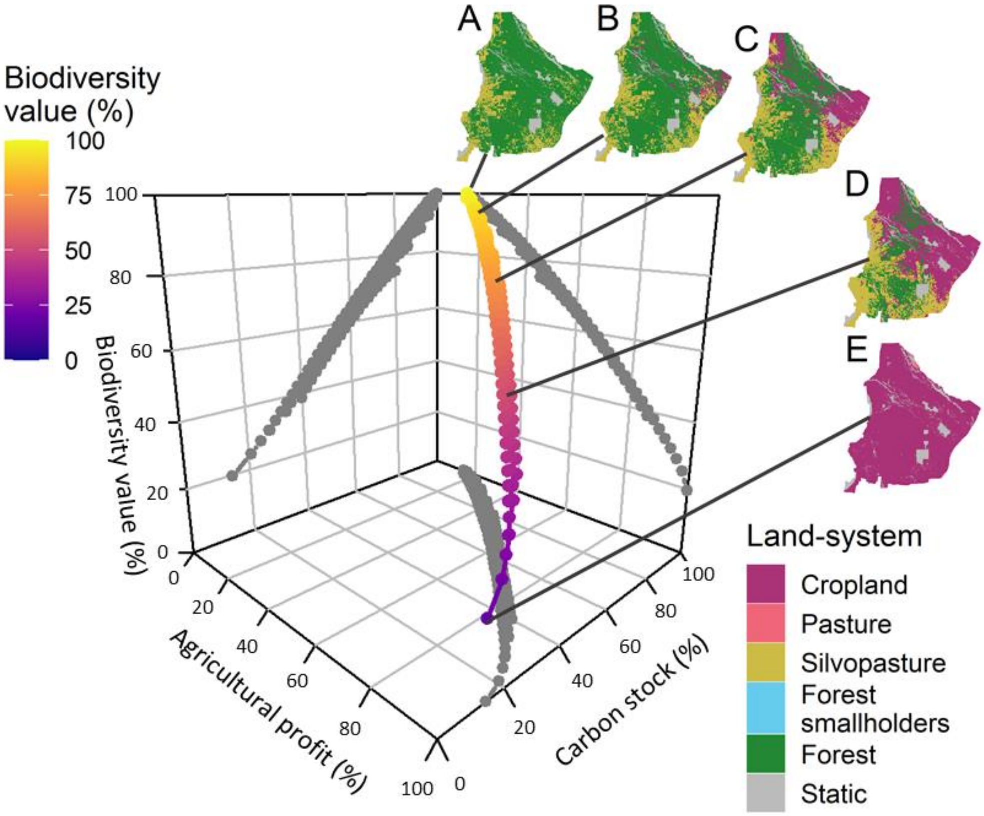

Figure 3: The 3D possibility frontier for the most flexible scenario, S_0. (in color, with the corresponding 2D trade-offs shown in grey), showing the fundamental trade-offs (i.e. given only biophysical constraints, no policy constraints) between agricultural profits (x-axis), carbon stocks (y-axis), and biodiversity (z-axis, and color gradient). A-E show land-system configurations for points across the possibility frontier, with A representing the maximum carbon and biodiversity endpoint, E the maximum agriculture endpoint, and B, C, and D intermediate positions on the frontier.

Our scenario S_0 shows the hypothetical endpoints of maximizing each of the three dimensions (although none of these endpoints are likely socially desirable or practically feasible). The maximum value of agricultural profit for the entire study region (i.e. maximum agricultural development) was about 2.76 billion USD per year. The maximum value for above-ground carbon stock of the region was about 730.1 PgC and the maximum value of biodiversity in S_0 was 92.6% of the theoretical maximum (this is <100% due to trade-offs between species requirements, as some species prefer forest and others open habitats; Fig. B3). Our possibility frontier also highlights the magnitude of the trade-offs. For instance, at the endpoint with maximum agricultural profit (i.e. at 100%), only 14.2% and 19.6% of the possible maximum carbon and biodiversity was retained, respectively. Conversely, 100% of the potential carbon was retained for the maximum biodiversity endpoint, although only 14.4% of the agricultural-profit dimension is achieved at this point.

At the maximum biodiversity endpoint of the S_0 frontier, the landscape was predominantly allocated to forest (72.4% of the study region; Fig. 4), while existing crop and pasture are allocated to silvopastures (19.0%), with the remaining 8.7% held static. When agricultural profit is maximized, virtually all available land is allocated to cropping (91.1%), except for small areas in the north where low rainfall results in a higher predicted profitability of pasture (<0.3%). Approximately a quarter of the region was allocated to silvopasture across all but the highest agricultural or biodiversity target values; and virtually no pasture is allocated (Fig. 4).

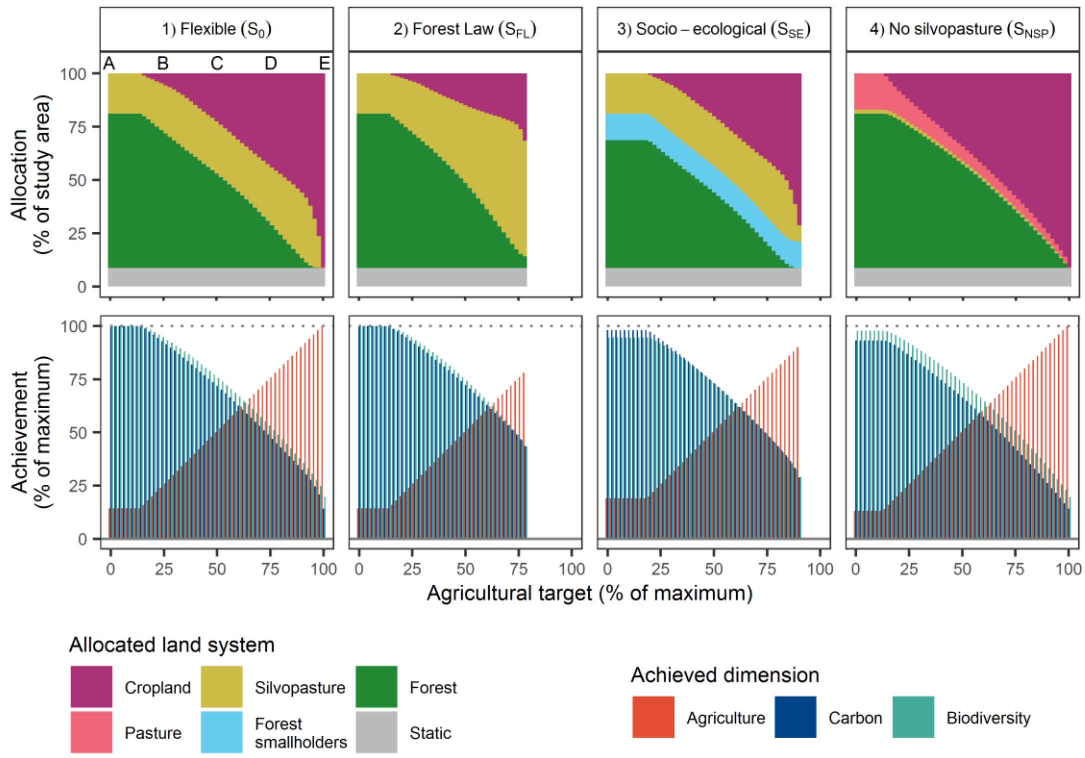

Figure 4: Characteristics of optimized solutions: allocations of land systems (top row) and achievement for all three targets (agricultural profits, carbon stocks, biodiversity) relative to maximum (bottom row), for each transition scenario (columns). Bars represent values for point solutions that achieve maximum biodiversity (and near-maximum carbon) for each agricultural target (x-axis). Missing bars represent infeasible solutions.

Impacts of the current land-use zoning, forest smallholders, and silvopastures

Optimizing land systems under the Forest Law (S_{FL}) had little impact on the overall shape of the frontier below the 75% agriculture target. Agricultural profit targets higher than 78% become infeasible due to Forest Law zoning restrictions (second column Figure 4, Appendix B2 Fig. B2). This implies that environmental trade-offs beyond agricultural profit targets of 78% are likely too stark to be socially acceptable. Given this assumption (i.e. social irrelevance of the outcomes at agricultural targets past that feasible in S_{FL}), a key outcome from comparing S_0 and S_{FL} is that the land-system configuration within the current zoning *can* be optimized to deliver outcomes equivalent to our most flexible baseline scenario. At the biodiversity and carbon endpoints, land-system allocations of S_{FL} and S_0 are similar. Towards the agricultural profit endpoint, silvopastures play a much stronger role in S_{FL} (< 58.8%) compared to S_0, reflecting the constraints imposed by the Forest Law (Figure 4).

Forest smallholders, when a 2 km footprint is assumed, currently occupy 12.4% of our study region and 17.1% of the remaining forest outside protected areas (Figure 5). Comparing the scenario where forest smallholder systems are maintained in the landscape (S_{SE}) with the most flexible scenario (S_0), showed that maintaining forest smallholders reduces the maximum agricultural profit endpoint by 10%, as well as the maximum carbon and biodiversity endpoints by 2.0% and 5.5% respectively (third column in Figure 4, and Fig. B2). When compared to the most flexible scenario, S_0, the S_{SE} scenario reduces biodiversity across the frontier by an average of 5.7 percentage points, and carbon by 1.8 percentage points. Agriculture is reduced overall by an average of 3.0 percentage points, despite increasing up to 4.7 percentage points at high carbon endpoints (Figure 4, Fig. B2). Across the frontier slices of maximum carbon for set agricultural targets, the forest smallholder area increased, up to 8.9% in S_0 (mean = 3.9%), and similar in the S_{FL} and S_{NSP} scenarios, indicating that further use of forest smallholders than that indicated here may be near-optimal.

If silvopastures were not allowed to expand, agricultural development would be restricted to the 'green' development zone (49.0% of the allocable area, of which a third is already revelop), imposing severe constraints on total agricultural profits. Across much of the S_{NSP} frontier, optimal solutions for maximizing biodiversity sometimes includes smaller shares of tree-less pasture, but comparing S_{NSP} to the most flexible scenario S_0 showed that without silvopastures, reduced agriculture, carbon and biodiversity levels are achieved for equivalent target combinations (average decrease by 4.1, 11.3 and 8.3 percentage points, respectively; fourth column in Figure 4, and Fig. B2).

Past, current, and future land-system achievements

The study area remains one of the least developed areas of the Gran Chaco, yet even here forest conversion has tripled from about 7,300 km² between 1985 and 2000, to 23,100 km² between 2000 and 2015, with crops and pasture rapidly expanding during this period (Figure 5, Table B1). Assessing past land-system allocations against our possibility frontier reveals how past changes have increased agricultural profit at a major cost to carbon and biodiversity (Fig. 5, Table B2). With a cursory glance, our analysis seems to show that recent land-use changes are tracking the currently viable frontier, but frontiers constructed with past land system constraints would have been larger, as indicated by the >100% scores for biodiversity and carbon for past land system configurations (Fig. B1). This suggests that land use change, if viewed relative to a past frontier, would likely show increasing inefficiency (distance from the frontier).

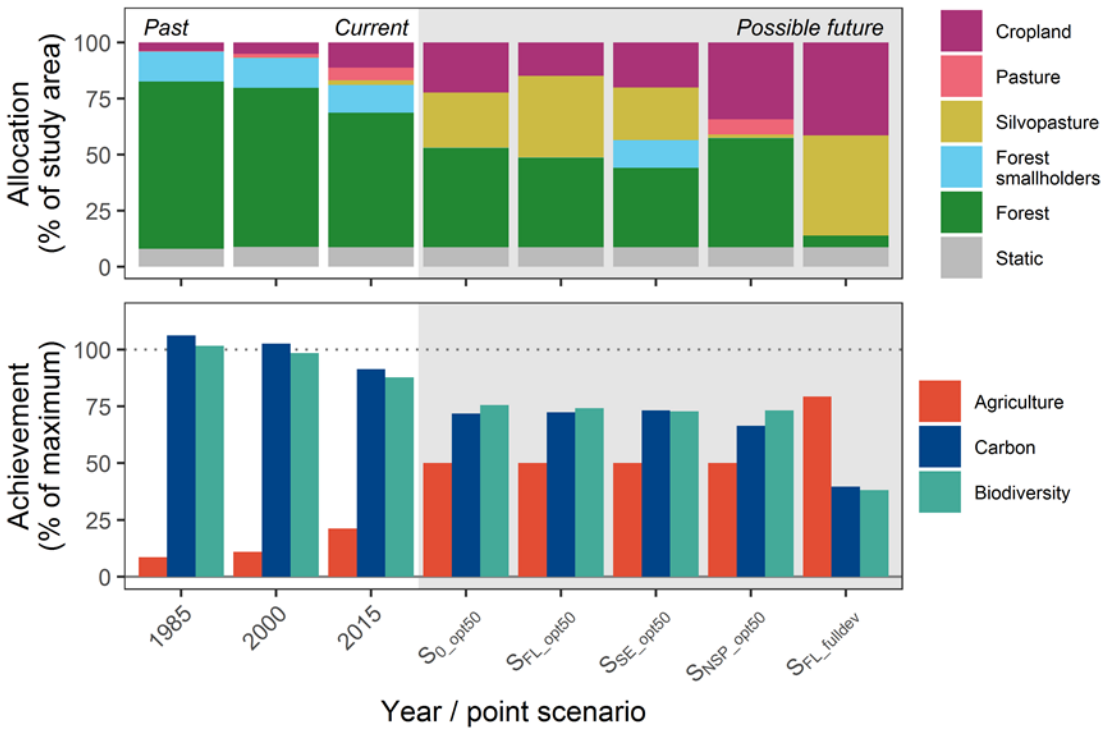

Figure 5: Achievement in terms of agricultural profit, carbon stock, and biodiversity for past, current and possible future point scenarios. Past land-system allocations are based on the mapping of land systems for that year. Point scenarios (representing possible future land-system allocations) include both solutions that exist on the frontier (i.e. maximize biodiversity, then carbon) at a 50% agricultural target (for each of the transition scenarios; suffix "_opt50"), and an allocation representing full development of the S_{FL} scenario (suffix "_fulldev"). Axes are defined by the maximum endpoints for each feature under the S_0 frontier, in which constraints include the infeasibility of full forest restoration from cropland, pasture, and silvopastures extant in the baseline year

(2015). As such, past landscapes with more extant forests can achieve more than 100% carbon or biodiversity.

All of the optimized, multifunctional point scenarios assessed here (i.e. solutions representing possible future land-system allocations that maximize for biodiversity, then carbon, at the 50% agricultural target - which is 2.4 times the agricultural profit in 2015; Table B4) resulted in similar levels of achievement, albeit with different land-system allocations, with the exception of reduced carbon if no silvopastures were allowed (Fig. 5; Table B3). These alternative point solutions showed that both land-sharing or land-sparing tendencies are possible: solutions either rely on silvopastures or on a mix of crop and forest to achieve landscape-scale multifunctionality. Yet, all of these solutions require large areas of forest cover. Across these point scenarios, the minimum forest cover (i.e. forest, smallholder forest livestock, and forest in protected areas) was 42.7% under S_{FL} and the highest was 51.4% under S_{NSP} (with an area with intensive agriculture of 15.0% and 41.1%, respectively (Figure 5: Appendix B). If forest smallholders are maintained under S_{SE} this substitutes for cover in the 'forest' land system, resulting in a 3.6 percentage point increase in total forest area required over S_0.

Full development of the landscape under the Forest Law (S_{FL}) scenario would be highly suboptimal, particularly for biodiversity (Fig. 5, Appendix B). Forest cover, at 7.9%, is far below the 40%-50% critical thresholds identified in the optimal 'multifunctional' solutions. Further, cropland, at 41.4%, and silvopasture, at 44.7%, together cover 1.7 times the respective area in the S_{FL} point solution (15.0%, 36.3% respectively). In other words, while the Forest Law in principle would allow for near-optimal, multifunctional outcomes, it does not seem to encourage this.

Comparing the S_0 and S_{FL} point scenario allocations in different Forest Law zones, and at equivalent agricultural profit targets, indicates opportunities to improve efficiency of the Forest Law and landscape multifunctionality. Over 50% of the 'yellow' sustainable-use zone would be better allocated to remain as forest, along with almost a quarter of the 'green' zone (Fig. 6). The sustainable use zone could also be extended over a further third of the existing 'green' development zone (Fig. 6).

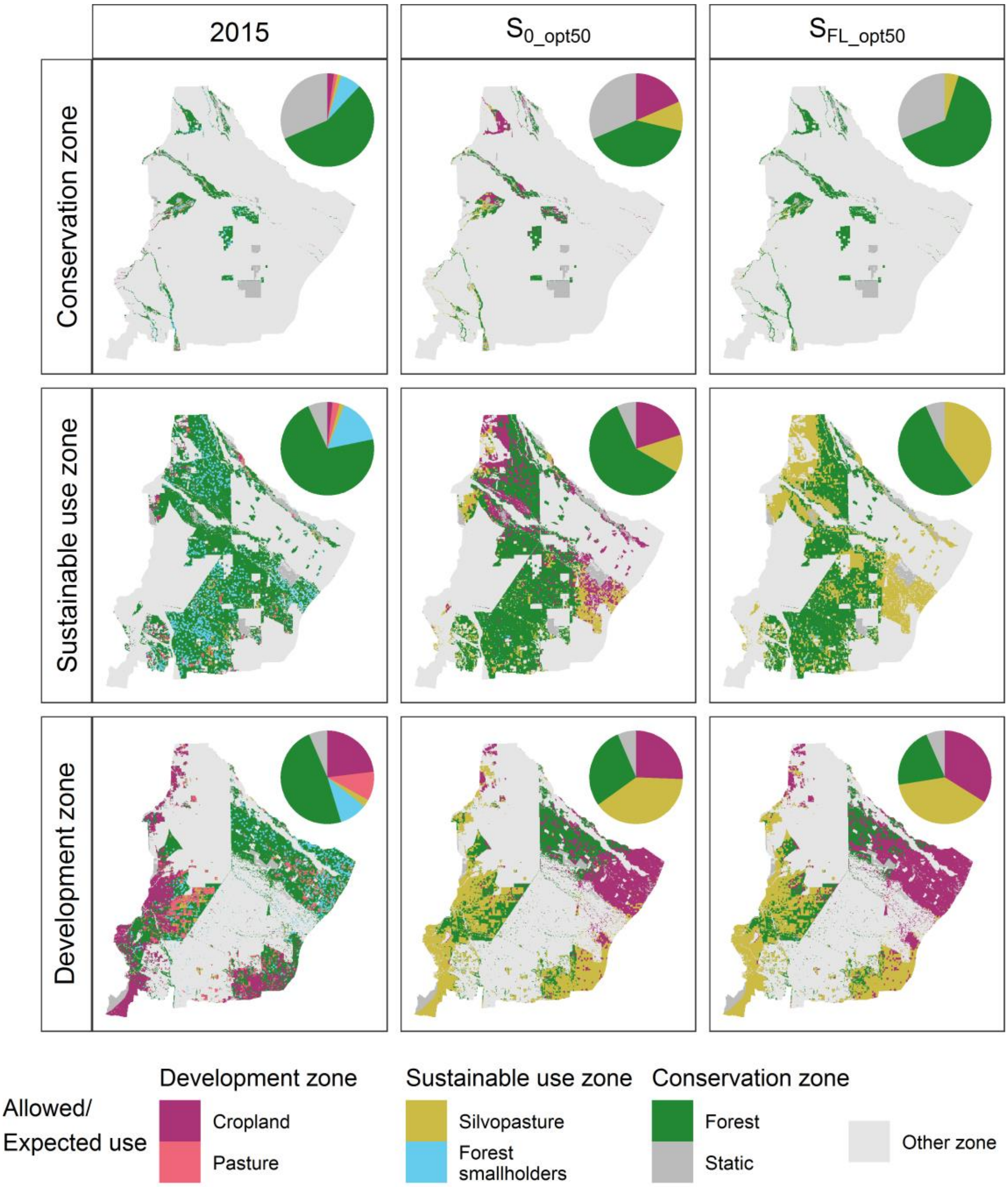

Figure 6: Land-system allocations for the 2015 landscape and optimal point solutions (giving maximum biodiversity for 50% agriculture) for the Flexible (S_{0_opt50}, i.e. unconstrained by zoning regulations) and Forest Law (S_{FL_opt50}) scenarios (columns), with respect to the current Forest Law zones (rows). Land systems allowed under the different Forest Law zones are shown in the key (the exception being 'static' which includes both protected areas likely falling in the conservation zone, and other land systems potentially in any zone). Existing areas of cropland, pasture, and silvopasture

are assumed as unable to transition to forest, and therefore in the S_{FL} scenario conservation and sustainable use zones are forced to silvopasture.

DISCUSSION

Transitioning to landscapes that balance human resource use, ecosystem service provisioning, and biodiversity conservation has become a central goal in the tropics and subtropics (Laurance *et al.*, 2014, Carrasco *et al.*, 2017, Law *et al.*, 2017). Designing such multifunctional landscapes critically rests on understanding what the available option space for planners and policy makers to mitigate trade-offs is, and how policies and progressing deforestation alter that option space. This necessitates moving from local-scale to landscape-scale trade-off assessments (Polasky *et al.*, 2008, Kennedy *et al.*, 2016, Butsic *et al.*, 2020). We here applied landscape-scale possibility frontiers to quantify trade-offs between agricultural production, biodiversity, and carbon stocks for the Argentinean Dry Chaco, one of the world's major deforestation hotspots. This allowed understanding how the current land-use zoning, as well as past and future land-use change, foster or inhibit multifunctionality. Collectively, our results demonstrate that there remain opportunities for transitioning to multifunctional landscapes in the study region, but these are disappearing rapidly. The time for sustainability planning in the Chaco is now.

Quantifying trade-offs at a landscape-scale across the north Argentinean Dry Chaco revealed substantial co-benefits between biodiversity and carbon stocks, yet also strong trade-offs of both with agricultural profits. Substantial synergies between protecting carbon stocks and biodiversity have been suggested for tropical moist forests, in South America and elsewhere (Strassburg *et al.*, 2010, Deere *et al.*, 2018, Soto-Navarro *et al.*, 2020). Here we show that such synergies also exist for tropical and subtropical dry forests. The strong, positive relationship between carbon stocks and biodiversity that we find is encouraging, because it suggests considerable potential for carbon funding to leverage biodiversity co-benefits, as envisioned in REDD+ or similar initiatives. Spatially-detailed biodiversity data is scarce in the Chaco and other tropical dry forests (Blackie *et al.*, 2014, Periago *et al.*, 2015, Romero-Muñoz *et al.*, 2020). Yet possibilities for monitoring carbon stocks and changes therein are increasing thanks to rapid advancement of remote-sensing technologies (Joshi *et al.*, 2016, Qi *et al.*, 2019).

Our results suggest this can deliver useful spatial proxies for sustainability planning in tropical and subtropical dry forests.

Our analyses show that agricultural profit in the Chaco trades off strongly with the environment, as in other deforestation frontiers (Laurance *et al.*, 2014). This underlines that agricultural expansion and no-net-loss in tropical biodiversity might simply not be feasible and some level of trade-off needs to be accepted (Phalan *et al.*, 2013, Kehoe *et al.*, 2017). Importantly, our possibility frontiers (Fig. 3, Fig. B1), show fairly consistent regional-scale agriculture-environment trade-offs across the fundamental possibility frontier, despite highly non-linear relationships at local scales (Mastrangelo & Gavin, 2012, Macchi *et al.*, 2013, Macchi *et al.*, 2020). On one hand, this could be interpreted as a relatively low risk of regional-scale tipping points, however we caution that our analysis did not include spatial and temporal dependencies which may reveal these phenomena. On the other hand, our results also suggest that further large-scale agricultural expansion is likely to (continue to) cause major losses in biodiversity and carbon stocks. With potential environmental assets spread fairly homogeneously throughout the region, the Chaco is clearly at risk of a 'death by 1000 cuts', a situation that is likely emblematic for many regions where modern commodity frontiers expand (Phalan *et al.*, 2013, Laurance *et al.*, 2014, Elsa *et al.*, 2017).

Smart landscape design can help to transition towards more sustainable land systems, and zoning is a key instrument in this context (Turner II *et al.*, 2013, Torrella *et al.*, 2018). Our analyses of the current zoning of the Argentinean Chaco suggest considerable unused potential for managing agriculture-environment trade-offs. While the zoning, as currently implemented, would allow for landscapes that near-optimally manage trade-offs at the regional scale, it does neither mandate nor encourage these. Our analyses also showed that full land-use development according to the current zoning would lead to highly suboptimal outcomes, with substantial (and likely irreversible) losses of remaining biodiversity and carbon stocks (Figure 4). Adjusting the zoning so that it encourages and ensures higher socio-ecological outcomes (i.e. closer to the mid-point of the possibility frontier) is therefore urgently needed. Landscapes that better align agriculture and the environment are possible, and our analyses showed a wide range of land-use strategies that can foster them in the study region (Fig. 5). Yet, a critical component for all these strategies is to maintain at least 40%, and preferably closer to 50%, of remaining forests, in line with recommendations from local-scale studies (Semper-Pascual *et al.*, 2019, Daskalova *et al.*, 2020, Macchi *et al.*, 2020). More generally, our analyses underline the key importance of maintaining substantial areas of natural habitat (Di Marco *et al.*, 2019).

A central finding from our work is that agricultural systems that retain woody cover, such as silvopastures, can mitigate agriculture-biodiversity trade-offs at the regional scale in the Dry Chaco. The potential biodiversity value of wildlife-friendly production systems has been previously identified for the Chaco (Mastrangelo and Gavin, 2012) and elsewhere (Mauricio *et al.*, 2019). Yet, whether silvopastures can mitigate trade-offs at broader scales has been questioned, as more intensified ranching could potentially spare more forest from conversion (Macchi *et al.*, 2013). Silvopastures featured prominently in most of our optimal solutions that most efficiently balance agriculture and biodiversity (Figure 5), reflecting the considerable potential of this land system in the region. However, very different land-system configurations had relatively similar environmental benefits, provided at least 40- 50 % of the forest area was retained (Figure 4). Importantly, our optimal solutions did not fall into the categories of pure land sparing and land sharing, but consisted of a mix of land systems (Figure 5), providing further evidence that mixed and regionally adapted strategies require careful consideration and mainstreaming (Law *et al.*, 2017, Butsic *et al.*, 2020). We caution that these recommendations include the caveat that extinction in fragmented and degraded forests can occur with a time delay (Semper-Pascual *et al.*, 2018); these reflect non-linear dependencies that were not included in our model.

Some uncertainty surrounding the role of silvopastures remains. On one hand, silvopastures are not yet widely adopted in the Chaco, and, as currently implemented are often poor in carbon and biodiversity retained (Fernández *et al.*, 2020, Macchi *et al.*, 2020). For example, bird communities collapse below woody thresholds of around 40% (Macchi *et al.*, 2019), and most silvopastures in the Chaco have much lower levels of woody cover (<15%; Appendix A). Our estimates of the potential value of silvopastures are therefore likely conservative, in this regard, and their importance for multifunctionally would increase if more biodiversity-friendly and carbon-rich silvopastoral practices were adopted. On the other hand, there is considerable doubt if silvopastoral systems, as currently practiced, will maintain environmental values in the long-term; with evidence that they rapidly loose trees and carbon (Fernández *et al.*, 2020). Likewise, biodiversity found in silvopastures might heavily depend on nearby forests (Macchi *et al.*, 2020), and silvopastures might constitute sink habitat as hunting pressure on them can be high (Romero-Muñoz *et al.*, 2020). All this cautions against a widespread expansion of silvopasture into remaining forests (as encouraged by the current zoning), and our results suggest rather that areas currently under intense agricultural land systems are converted to silvopasture. It also highlights the need for more empirical data on how the environmental benefits of silvopastures vary across different levels of woody cover and over time.

Many dry forest regions harbor indigenous people and other traditional communities who critically depend on forests for their livelihoods (Blackie *et al.*, 2014, Newton *et al.*, 2016). Expanding commodity agriculture increasingly leads to hidden or open conflicts with such forest-dependent communities, and the Chaco is no exception to this (Vallejos *et al.*, 2020b). Yet forest smallholders also cause considerable local forest degradation and defaunation (Altrichter, 2006, Grau *et al.*, 2008, Romero-Muñoz *et al.*, 2020), and it has therefore been questioned whether smallholder systems can be aligned with regional-scale conservation goals (Grau *et al.*, 2008). Here, we show that this is indeed possible: maintaining forest smallholders in the landscape (our scenario S_{SE}), while not optimal, was largely able to balance agriculture-environment trade-offs in our case (Figure 4, Figure 5). This demonstrates that promoting or protecting traditional livelihoods does not have to conflict with reasonable conservation or agricultural production goals. This does not mean that local environmental degradation by forest smallholders should be accepted. Rather, decreasing their environmental impacts (e.g. adopting more sustainable silvopastoral systems, or shifting to sustainable forest use and hunting) provides considerable potential for fostering increased sustainability at local and regional scales. Importantly, we note that there are also important pull factors at play leading to the outmigration of forest smallholders from the Chaco (e.g. better income opportunities, civil services, and infrastructure in cities) and that maintaining the status quo of many forest smallholders (e.g. high tenure insecurity, extreme poverty, low access to health care) is likely socially undesirable. Rather, allowing for the development of forest smallholders in a way that maintains and strengthens the ties between people and environment should be a goal (Fischer *et al.*, 2012).

Our perhaps most central finding is that the window of opportunity for achieving more multifunctional landscapes in the Chaco is closing rapidly. Recent land-use changes have moved the north Argentinean Dry Chaco rapidly along the possibility frontier, and potential future land-use change will continue to do so (Figure 5). Two land-use changes chiefly drive this development. First, commercial agriculture (cropland and pastures) currently continues to expand into areas that our optimizations often allocated to silvopastures. Second, forest continues to be lost, and our analyses clearly suggest that reducing forest cover below 40-50% should be avoided (Figure 5). This threshold broadly converges with empirically and theoretically identified critical thresholds in woody cover of about 40%, in the Chaco and elsewhere (Macchi *et al.*, 2019, Arroyo-Rodríguez *et al.*, 2020), and recent high-level calls for providing more space for nature (Ellis, 2019). It is important to highlight that our study region still contains sizeable forest areas (Figure 1), but other areas in the greater Chaco (e.g. the southern Argentinean Chaco, the Paraguayan Chaco) have been deforested much more (Baumann *et al.*, 2017). Unfortunately, the zoning in the current Forest Law leaves a door open to agricultural development, and if current land-use trends continue, our study region would rapidly fall below the 50% forest threshold, sliding into suboptimal biodiversity and carbon outcomes. It cannot be overemphasized that the time for sustainability planning in the Chaco is now. Our analyses show that such planning is urgently needed to avoid stark environmental trade-offs, as in other South American tropical dry forest and savanna regions (Strassburg *et al.*, 2017). The now overdue revision and reform of the Argentine Forest Law, originally scheduled for 2014-16, provides a clear policy mandate and opportunity in this regard.

Several concrete recommendations for land-use planning derive from our work. First, as outlined above, protecting the majority of remaining forests and ensuring forest cover remains above 40-50% is pivotal. Second, the transition from pastures to silvopastures, especially silvopastures with high woody cover, should be a priority. This is important to foster better outcomes of the current land-use zoning but should not come at the expense of regional forest cover. Third, an adjustment of the current zoning can encourage higher landscape-level multifunctionality and lower trade-offs in the long run. This should include (a) protecting remaining larger forest patches (e.g. in the *El Impenetrable*) from conversion, even to silvopastures, (b) ensuring connectivity between areas of natural habitat (Torrella *et al.*, 2018), (c) fostering the establishment of carbon- and biodiversity-rich silvopastures, including in areas where that is currently not required (i.e. in 'green' development zones), and (d) supporting forest smallholders to transition to more sustainable modes of forest and wildlife use, in order to increase the overall environmental benefits of forest smallholder systems. As we show here, forest smallholders should not be seen as a barrier for achieving regional-scale multifunctionality, and lowering their local environmental impact entails major opportunities. Finally, our analyses provide both a pathway and a petition to leave the binary, polarized view of land sparing vs. land sharing behind. Optimal landscapes that mitigate trade-offs at the regional scale typically entail elements of both (e.g. intensified agriculture, protected forests, and wildlife-friendly production systems).

More generally, our approach based on spatial multi-criteria optimization and efficiency frontiers highlights how regional-scale trade-offs can be quantified, and how such knowledge can help to strike a better balance between agriculture and various environmental outcomes. This is a central policy goal for many regions in the Global South, particularly for deforestation frontiers (Turner II *et al.*, 2013, Laurance *et al.*, 2014, Leclère *et al.*, 2020). The approach we showcase here can be powerful for that purpose by quantifying multi-dimensional trade-offs, identifying land-system configurations that would most efficiently manage such trade-offs, detecting critical, regional-scale thresholds, and by identifying policy levers to set landscapes onto pathways towards more sustainable futures. There are few regions in the world where this is more urgently needed than in tropical dry forests and savannas, many of which are under high and rising pressure from agricultural expansion and intensification

(Blackie *et al.*, 2014, Parr *et al.*, 2014, Strassburg *et al.*, 2017). Our approach provides a powerful framework for adaptive sustainability planning that can monitor trade-offs as land-use change progresses and new data becomes available, and a testbed for assessing the potential efficacy of land-use plans, polices, and land systems that seek both social and ecological outcomes.

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