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Minimising the loss of biodiversity and ecosystem services in an intact landscape under risk of rapid agricultural development

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Abstract

As humanity's demand for resources continues to rise and productive arable lands become increasingly scarce, many of Earth's remaining intact regions are at heightened risk of destruction from agricultural development. In situations where agricultural expansion is inevitable, it is important to manage intact landscape transformation so that impacts on environmental values are minimised. Here, we present a novel, spatially explicit, land use planning framework that addresses the decision making needed to account for different, competing economic-environment objectives (agricultural production value, biodiversity conservation, ecosystem service retention) when land use change is inevitable within an intact landscape. We apply our framework to the globally significant savannahs of the Orinoquia (Colombia), which in a post-conflict era is under increased agricultural development pressure. We show that while negative environmental impacts can be reduced through planning, the total area of land converted to agriculture is the unavoidable principal driver of biodiversity and ecosystem service loss. We therefore identify planning solutions that perform well across all objectives simultaneously, despite trade-offs among them. When 15%, 20%, 30% and 40% of the study area is allowed to be converted to agriculture, on average planning can improve species persistence and ecosystem service retention by up to 16%, 15%, 12%, and 9%, respectively, when compared to agricultural-focused solutions. Development in the region so far has had an unnecessarily large impact on environmental objectives due to a lack of effective land use planning, creating an 'opportunity debt'. Our study provides an evidence base to inform proactive planning and the development of environmentally sensible agricultural development policy and practice in the region. This framework can be used by stakeholders to achieve agriculture expansion goals and maximise economic profit while minimising impacts on the environment in the Orinoquia, or any relatively intact region that is being developed.

Introduction

With almost 40% of Earth's land surface transformed by farming activity (Clark and Tilman 2017), agriculture is the single largest contributor to biodiversity loss to date (Dudley and Alexander 2017) and considered as one of the main drivers of potential biodiversity loss in the near future (IPBES 2019). Global agricultural activity has also resulted in at least 133bn tonnes of sequestered soil carbon loss to the atmosphere

(Sanderman *et al* 2017), and accounted for approximately 70% of the world's freshwater withdrawals for anthropogenic use (Rosegrant *et al* 2009). The continued expansion of agricultural activity is driving the pace of Earth's continually changing terrestrial human footprint (Venter *et al* 2016), and is a fundamental reason for growing calls to conserve those last remaining ecologically intact landscapes, given their increasing importance for biodiversity and ecosystem service provision, and their disproportionately high ecological value in a time of climate change (Martin and Watson 2016, Scheffers *et al* 2016, Pimm *et al* 2018, Dinerstein *et al* 2019). Yet global demands for food, and the economic opportunities that agriculture presents to developing nations mean that many of Earth's remaining intact ecosystems are under significant threat from agricultural expansion (Vargas *et al* 2015, Morán-Ordóñez *et al* 2017, Potapov *et al* 2017, Roucoux *et al* 2017). This is further exacerbated by the fact that productive arable lands are becoming increasingly scarce, so farmers must continually encroach into intact places (Lambin and Meyfroidt 2011, Bijl *et al* 2017).

When a landscape that is largely ecologically intact is being 'opened up' for development, strategic, proactive planning is needed to identify opportunities for enhanced outcomes for both environmental and agricultural goals (Forman and Collinge 1997). Systematic planning can help guide complex land-use decisions by fostering stakeholder engagement, improving the efficiency of land use allocation, describing the trade-offs between biodiversity and economic objectives thereby identifying compromise solutions and, identifying management opportunities and strategies that can improve biodiversity outcomes in production landscapes (Polasky *et al* 2008, Runting *et al* 2015, Adams *et al* 2016, Estes *et al* 2016, Runting *et al* 2019, Strassburg *et al* 2019). However, to date, these efforts typically have been conducted in transformed (i.e. fragmented) landscapes, in contexts where the environmental goal is to maximise biodiversity and environmental service gain (via restoration or strategic protection). Here, building on this work, we develop a quantitative, multi-objective land use planning framework that allows for a spatially explicit assessment of likely impacts of land use change on environmental values including biodiversity conservation, carbon storage and water retention and one that, by adjusting the relative weights among objectives, is able to minimise the loss of these values while ensuring production value from development can be maintained.

We apply our framework to the relatively intact Llanos (plains) of the Orinoco region of Colombia. The country has recently emerged from 50 years of civil conflict, largely with the militia group FARC (the Revolutionary Armed Forces of Colombia) who, in 2016, signed a peace treaty with the government of Colombia (Gobierno Nacional de Colombia 2016, Salazar *et al* 2018). This treaty has opened economic opportunities, with undeveloped or intact lands that were previously off-limits such as the Orinoquia now being targeted for agricultural expansion (DNP 2018). The tropical climate and grass-covered expanses of mostly flat land, make it an ideal location for agricultural expansion, and it is increasingly the focus of livestock, forestry, soy, rice and palm oil industries (López-Ricaurte *et al* 2017).

We assess the impacts of the conversion of native vegetation to agriculture on biodiversity (species persistence and ecosystem representation) and ecosystem services (water provision and carbon sequestration), describe the trade-offs between environmental and agricultural objectives, the trade-offs among environmental objectives, and assess the effectiveness of the current distribution of land uses. In doing so, we provide an evidence base to inform proactive planning for environmentally sensible agricultural development policy and practice in the region. Our planning framework is flexible and can be translated to any intact region that is undergoing development, and where the goal is to maximise economic gains while simultaneously minimising loss of environmental values.

Methods

Study region

The Orinoquia is located in the eastern part of Colombia, covering 255 123 km^2 or approximately 26% of the country (figure 1) and contains 36 ecosystem types that span dense forests, gallery forests, wetlands and the dominant tropical grassland savannahs (Llanos) (Lasso *et al* 2010, Etter *et al* 2017). The Llanos of the Orinoquia is one of the most important reservoirs of biodiversity in the Neotropics (Gassón 2002), but agricultural development is a key objective of the National Planning Department of the Colombian government (Gassón 2002, DNP 2018). Currently, 12% of the Orinoquia's natural landscape has been converted to agriculture and associated urbanisation. The most extensive land use is cattle grazing on natural savannah grasslands. However, agricultural activities such as oil palm cultivation have become lucrative industries in the region in part due to government incentives (Vargas *et al* 2015), and are foreseen to continue expanding (Castiblanco *et al* 2013). Five major forms of agriculture likely to influence the future of the region include livestock, palm oil, forestry, rice, and soy (DNP 2014).

Framing the decision support problem

The objective of our formulation is to optimise the allocation (areal expansion) of livestock, oil palm, forestry, rice, and soy 'zones' within the region in order to maximise agricultural production value (USD yr^{-1}) while minimising impacts on biodiversity, quantified in terms of species persistence and ecosystem

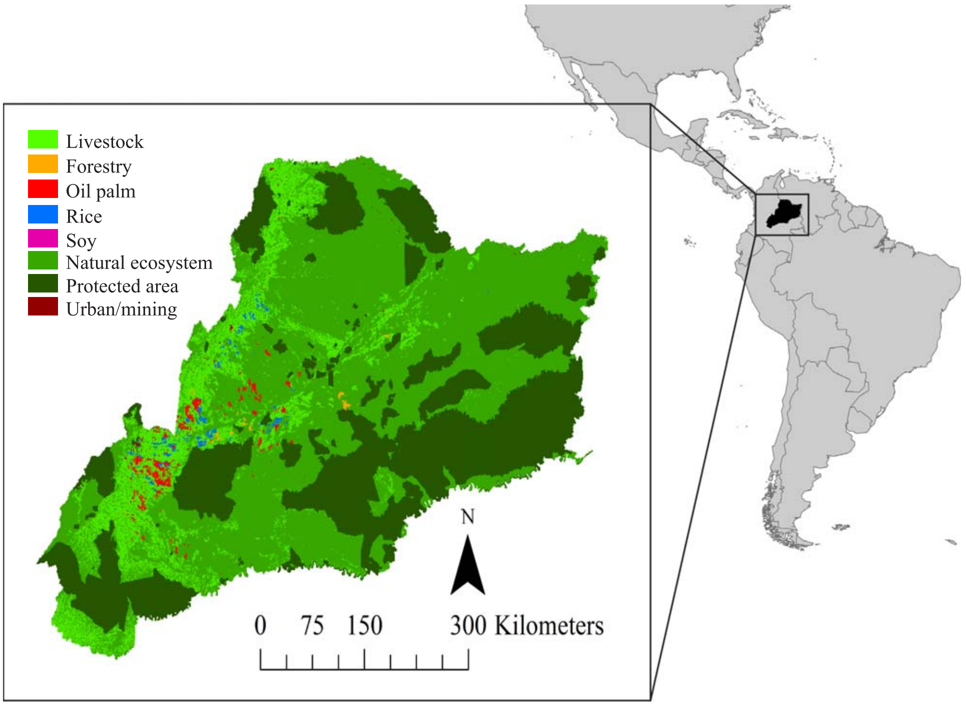

Figure 1. The boundary and current simplified land use of our study region in the Orinoquia, Colombia. It is defined by the four departments that make up the region, Meta, Casanare, Arauca, and Vichada. We divide this area into $n = 2477\ 901$ km^2 planning units.

representation (Watson and Venter 2017, Dinerstein *et al* 2019), and ecosystem services, quantified in terms of water loss (l yr^{-1}) and carbon loss (t). As the study area is currently largely undeveloped, there is an implicit sixth zone, natural vegetation. Existing urban and mining land (234 km^2) and formally protected areas (83 586 km^2) within the study area are not permitted to be converted to agricultural land use. Agricultural gains are estimated as the potential production value for each commodity, adjusted in accordance with the estimated yield for each commodity and by transportation cost (Estes *et al* 2016, SM 1.2 is available online at stacks.iop.org/ERL/15/014001/mmedia).

We use a land cover map based on the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) land cover map (IDEAM 2010), updated with relevant agricultural land use classes from an ecosystem map containing finer detailed agricultural data (IDEAM, Instituto Humboldt, IGAC, INVEMAR, MADS 2015). These maps are the most up to date and comprehensive land use/land cover maps that currently exist for the region. We assign these to a set of 1 km^2 planning units ($n = 247\ 790$) which we identify as natural ecosystems ($n = 129\ 765$), pasture for livestock ($n = 30\ 935$), oil palm ($n = 1913$), forestry ($n = 269$), rice ($n = 1087$), soy ($n = 1$), protected areas ($n = 83\ 586$) or urban/mining areas ($n = 234$) (SM 1.8).

Species persistence benefit is based on mammal, bird and reptile species that were either (i) savannah habitat specialists, (ii) endemic to the Orinoquia, or (iii) had an International Union for Conservation of Nature categorisation of near threatened, vulnerable, endangered or critically endangered. We select these species groups to represent the faunal assemblages within savannah ecosystem types, that are unique to the Orinoquia and are already threatened (SM 2 table S2.1). We use range maps for these 145 species to determine which species benefited from conservation within each planning unit. Species benefit, summed across all species following Strassburg *et al* (2019), is quantified as local extinction risk, which is based on the ratio of the remaining and original habitat area for each species within the study area (sensu Thomas *et al* 2004, Strassburg *et al* 2019; SM 1.3).

Beyond reducing local species extinction risk, we adopt a retention target of 50% of historic extent (defined as the potential extent of a given ecosystem if it was left uninfluenced by anthropogenic activity; SM table S3.2) for each natural ecosystem type of the region (Etter *et al* 2017) to ensure the persistence of a diverse range of natural habitats for species assemblages, ecological process and provisioning services (Pressey *et al* 2003, Loreau *et al* 2006). We choose 50% because this threshold of habitat loss has been broadly identified as the point at which species extinction risk dramatically increases in intact systems (Noss *et al* 2012, Pimm *et al* 2014, Baillie and Zhang 2018). Ecosystems that already had <50% of their historic extent lost were given a retention target of 100% of the remaining habitat.

Our optimisation model includes objectives representing the averted loss of carbon and hydrological ecosystem service value of each planning unit. Carbon value is quantified as soil organic carbon stocks (SOC) up to 30 cm in depth (t km^{-2}; SM 1.4) as conversion to agricultural land uses would result in losses of carbon within this stratum (Assad *et al* 2013, Yigini *et al* 2018) that are difficult to restore (Zinn *et al* 2005, Sommer *et al* 2018). Following Egoh *et al* (2008), hydrological value is quantified as water runoff (l yr^{-1} per hydrological unit), which reflects geomorphic and hydrological processes including land cover, precipitation, evapotranspiration, soil moisture, and recharge (percolation). Our estimations are based on the hydrological models of Thomas (1981) and Angarita *et al* (2018) (SM 1.5). Conversion to agricultural land use diminishes water provision due to water demands of livestock and crops (Power 2010). Therefore, we assume if a natural area is converted to agriculture, that planning unit's carbon and hydrological value does not contribute to environmental objectives.

We formulate this as a mathematical optimisation problem (specifically an integer linear programming problem) and solve it using Gurobi version 8.1.0 (Gurobi Optimisation 2019). See SM 1.1 for mathematical formulation and more details.

Scenario analysis

We explore scenarios that allow thresholds of natural ecosystem conversion of 15% (38 269 km^2), 20% (51 025 km^2), 30% (76 538 km^2) and 40% (102 050 km^2) of the landscape, inclusive of areas already cleared (12% of region) using our optimisation framework (figure 2). These thresholds of conversion are politically relevant as analogous ecosystems have lost similar, and higher, amounts of native vegetation cover (for example, the Brazilian Cerrado has lost 46%) (Strassburg *et al* 2017). For each threshold of total natural ecosystem loss, we evaluate three scenarios to assess the impacts of land conversion. Trade-offs among objectives are quantified for each scenario by evaluating a range of relative weights between agricultural and environmental objectives, solving the optimisation problem each time to obtain a spatially explicit 'solution'. Trade-off curves are, therefore, described by a set of solutions, each of which represents a different weighted sum of objectives. These trade-off curves are the lines presented in figure 3.

In the first scenario, we assume agricultural lands are fixed and cannot change to a different land use. The trade-off between agricultural and combined environmental objectives (a composite metric that weights species persistence, carbon sequestration and water retention equally) is quantified among solutions. In the second scenario, agricultural lands are again fixed, and the trade-off between agricultural objectives and single environmental objectives is quantified among solutions separately (rather than with a composite metric) for species persistence, carbon sequestration, and water retention. Ecosystem retention targets are not considered here but were considered in all other scenarios. The third scenario is an extension of the first, where lands already converted to agriculture are allowed to be allocated to other use types and the trade-off between agricultural and environmental objectives are again quantified using the composite environmental metric (table 1).

Results

Impacts of different thresholds of natural ecosystem loss across scenarios

We found that all future loss of natural ecosystems to agriculture will be positively associated with agricultural production value, and negatively associated with biodiversity persistence, and ecosystem service retention (table 2, figures 3, 6).

Within a given land conversion threshold, we quantify the trade-off between agricultural production value, species persistence and ecosystem service loss (figure 3). Compromise solutions (solutions that balance agricultural and environmental objectives through equal (0.5:0.5) weighting) achieve on average 95.9%, 96.6%, 96.3% and 96.7% of maximum production value in the 15%, 20%, 30% and 40% land conversion thresholds while reducing negative impacts on species and ecosystem service retention by on average 9.84%, 9.22%, 6.85% and 5.85%, respectively. Hence, the magnitude of possible reductions in environmental impacts for a given threshold of land conversion is relatively small compared to the differences among thresholds of areal land conversion (figure 3). In other words, while negative environmental impacts can be reduced through planning, the reduction is small relative to the impacts of the loss of natural ecosystems.

Relationship between combined environmental and agricultural objectives

The trade-offs between combined environmental and agricultural objectives indicate that it is possible to achieve gains for species, carbon, and water, with minimal reduction in agricultural benefit through spatial planning, but more so at lower land conversion thresholds (figure 3—solid lines). We found that at higher thresholds of loss, there is less opportunity to reduce negative impacts on the environment (table 3—Scenario i). Additionally, there is more opportunity to reduce negative impacts on water retention and carbon sequestration than to species persistence (table 3—Scenario i, figure 3—solid lines).

Relationship between single environmental and agriculture objectives

Trade-offs between single environmental objectives (species persistence, carbon sequestration and water retention) and agricultural objectives are exacerbated

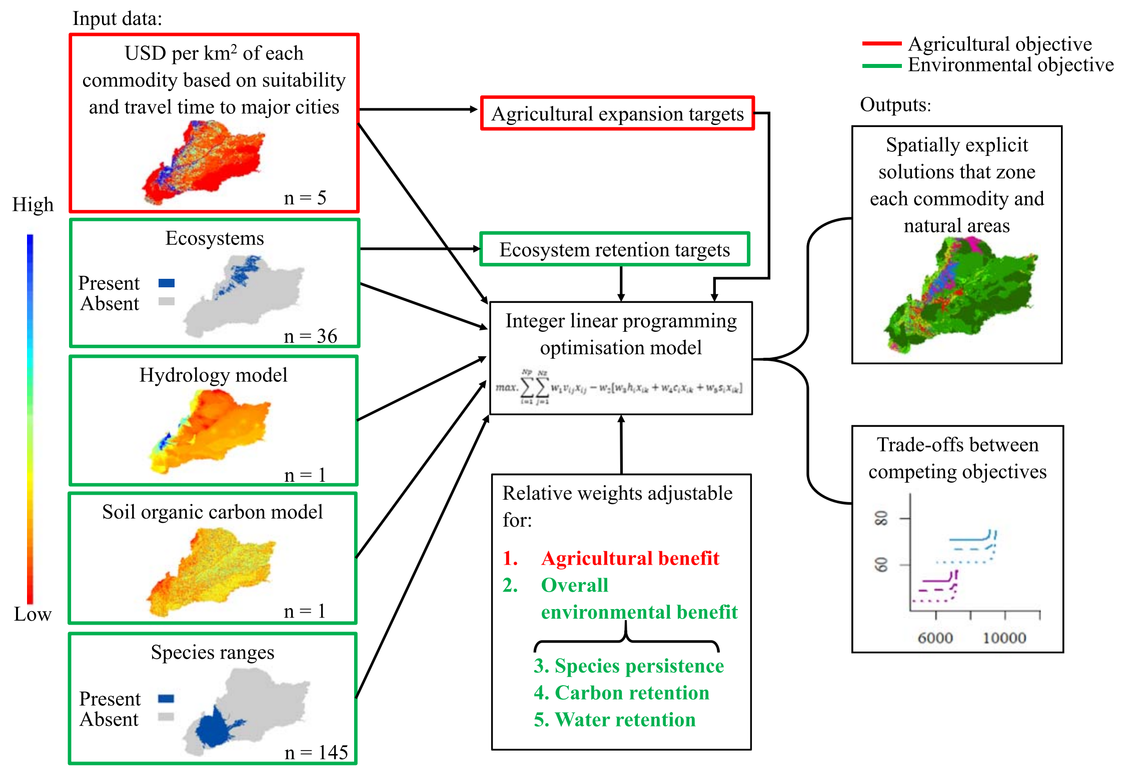

Figure 2. Methodological flow diagram of the input data, targets, and weighting requirements used to develop exact spatially explicit land use solutions solved using Gurobi Optimizer version 8.1.0 (Gurobi Optimization 2019). Datasets were continuous rasters for agricultural production value ($n = 5$), water run-off ($n = 1$), soil organic carbon stocks ($n = 1$) and binary present/absent range maps for species ($n = 145$), and ecosystems ($n = 36$). Agricultural objectives are represented in red and environmental objectives in green.

when planning for each one independently rather than simultaneously (table 3—Scenario ii, figure 3—dotted lines; figure 4). Therefore, potential realised gains for each environmental objective are higher than those that consider species persistence, carbon sequestration and water retention simultaneously (table 3, figure 3—solid lines and dashed lines which represent a composite environmental metric where all objectives are weighted equally versus dotted lines which optimise for single environmental objectives). Intuitively, the environmental objectives not accounted for in these scenarios performed worse (SM 4). This is reflective of the trade-offs that exist among environmental objectives at all conversion thresholds (SM 1.6, SM figure S1.2).

Spatial allocations of land use differ greatly between solutions. When optimising for water retention future agricultural land is concentrated to the north (figure 5(a)), more scattered when optimising for carbon (figure 5(b)), and spread more south for species persistence (figure 5(c)). When optimising for only agricultural production value, converted lands are largely restricted to the north–west of the region (figure 5(d)).

Effectiveness of current land use configuration

The 'can transition' scenarios lead to, on average across solutions, 18 350 km^2 or 54% of land that is currently agriculture to change to a different land use (either a different agricultural type, or to be allocated to the 'natural' zone). Future agricultural and environmental objectives can be better achieved when lands that are currently agriculture are allowed to transition to another land use type (figure 3—dashed lines representing 'can transition scenarios'), compared to when they cannot (figure 3—solid lines representing 'fixed scenarios'). The difference between the two scenarios were on average \$316, \$402, \$868, and \$1999 million USD yr^{-1}, 0.13, 0,14, 0.12 and 0.22 expected local extinctions, 0.03, 0.03, 0.04 and 0.01 million t of SOC loss, and 2.72, 2.80, 2.57 and 1.39 trillion l of water loss yr^{-1} at the 15%, 20%, 30% and 40% land conversion thresholds. This indicates that the current distribution of land uses does not represent optimal solutions for maximising benefits towards agricultural production value, species persistence, carbon sequestration or water retention.

Ecosystem retention across scenarios

All ecosystem retention targets, which are applied as a constraint within the objective function, can never be met in situations where current agricultural lands are fixed. In the 15%, 20%, 30%, and 40% land conversion thresholds targets cannot be met for 2, 3, 3, and 5 ecosystems respectively (SM 3 table S3.3). These are associated with two endangered savannah ecosystem

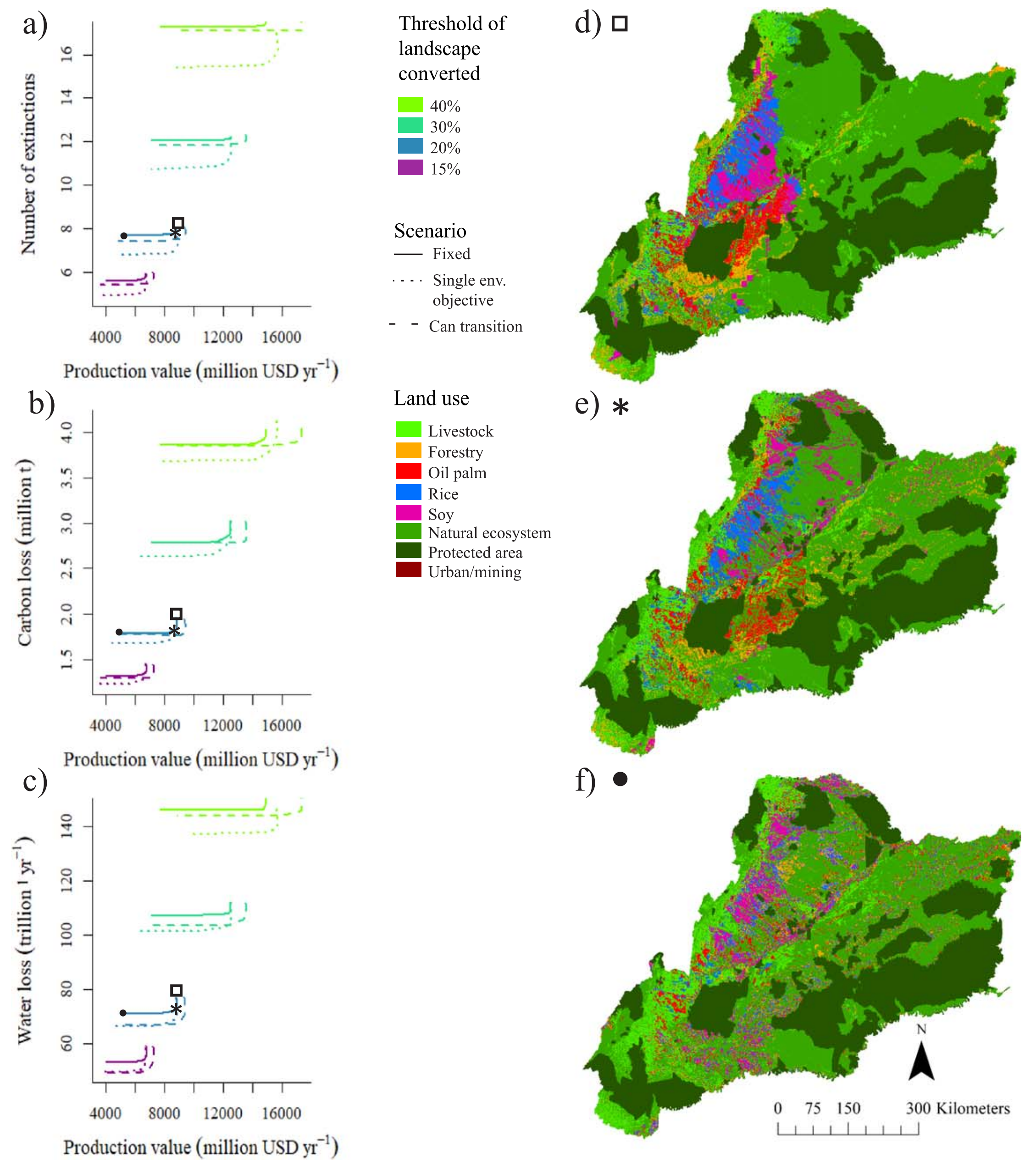

Figure 3. Trade-off curves between total agricultural production value (x axis) and (a) expected increase in mean number of local extinctions (number of extinctions), (b) carbon loss (million t) and (c) water loss (trillion l yr^{-1}) when allowing varying thresholds of the study region's natural ecosystems to be converted to agriculture. Points on the trade-off curves represent planning solutions that reflect different weights among objectives. The lower-right portion of each curve represents solutions where improvements to environmental objectives can be made with minimal impact on production value. Flat trade-off curves indicate scenarios in which large reductions in production value only result in small improvements to ecosystem service benefits. Solid lines represent the scenario where current agricultural lands must remain agriculture, dotted lines represent the single environmental objective scenario, and dashed lines indicate the scenario where agriculture is allowed to transition to a different state. Spatially explicit solutions (d)–(f) at different weightings between agricultural benefit and combined environmental value within a scenario that allows approximately 20% of the study region to be converted to agriculture. Those weightings are (d) 1:0 weighted towards agricultural objectives □, (e) 0.5:0.5 equal weighting between objectives * and (f) 0:1 weighted towards environmental objectives●.

types, and two endangered and one vulnerable dense forest ecosystem. This is because, due to the current distribution of land use types new expansion is forced into certain ecosystems that it otherwise would not be, were agricultural lands allowed to be re-allocated. In the scenario where existing agricultural land is free to transition to another type, all targets are met.

For confidence intervals for all solutions see SM 4.

Discussion

This analysis represents a rare and important opportunity to apply an evidence-based approach for simultaneously informing development and conservation planning in an intact and biodiverse area that is in the process of becoming developed. We found that development so far has had an unnecessarily large impact

Table 1. Description of the three scenarios evaluated. Where a dash (–) is present, a range of values were assessed to describe the trade-off curves (presented in figure 3). In every scenario presented here, agricultural expansion targets are equally divided between the respective threshold of loss.

Scenario	Scenario i	Scenario ii	Scenario iii
Description	Solutions that describe the trade-off between agricultural and combined environmental objectives	Solutions that describe the trade-off between agricultural objectives and single environmental objectives	Evaluate the effect of allowing land already converted to agriculture to be allocated to other use types or back to a natural state in scenario i
Purpose	To identify a suite of compromise solutions that consider both agricultural and environmental objectives across a range of weightings. To assess the impact of different thresholds of conversion on all objectives	To identify the best and worst-case solution for each individual environmental objective, and the suite of compromise solutions in between. To assess the impact of different thresholds of conversion on all objectives	To assess the effectiveness of the current distribution of land uses in terms of both agricultural and environmental objectives. To assess the impact of different thresholds of conversion on all objectives
Thresholds of conversion	15%, 20%, 30%, 40%	15%, 20%, 30%, 40%	15%, 20%, 30%, 40%
Agricultural weight range	0–1	0–1	0–1
Overall environmental weight range	1–0	1–0	1–0
Weights among environmental objectives	• Minimise local species extinctions (0.33) • Minimise carbon loss (0.33) • Minimise water loss (0.33)	• Minimise local species extinctions (0 or 1) • Minimise carbon loss (0 or 1) • Minimise water loss (0 or 1)	• Minimise local species extinction risk (0.33) • Minimise carbon loss (0.33) • Minimise water loss (0.33)
Can existing agricultural lands change?	No	No	Yes
Are ecosystems considered (at 50% retention target)	Yes	No	Yes
Shown in	Figure 3, solid lines	Figure 3, dotted lines	Figure 3, dashed lines

Table 2. Average values of solutions across all scenarios at each threshold of natural ecosystem conversion.

Threshold of natural ecosystem conversion	Total production value (million USD\$ yr^{-1})	Carbon loss (Mt)	Water loss (Tl yr^{-1})	Local extinction risk (no. species)	Average loss of each ecosystem
15%	\$6,223	1.32	52.8	7.05	10.7%
20%	\$8,137	1.79	70.5	9.55	12.1%
30%	\$11,626	2.80	106	14.8	15.8%
40%	\$14,731	3.87	144	20.9	22.8%

Table 3. Percentage increase between the agricultural-focused (which refers to a weighting in the objective function of 1:0 towards agriculture) and the environmental-focused solutions (which refers to a weighting in the objective function of 0:1 towards overall environmental objectives). Values are for the scenario that considers combined environmental objectives (scenario i; differences between either end of the trade-off curves presented in figure 3—solid lines) and for the scenario that considers single environmental objectives (scenario ii; differences between either end of the trade-off curves presented in figure 3—dotted lines).

	Scenario i			Scenario ii		
Threshold of natural ecosystem conversion	Increase in carbon loss (Mt)	Increase in water loss (Tl yr^{-1})	Increase in local extinction risk (no. species)	Increase in carbon loss (Mt)	Increase in water loss (Tl yr^{-1})	Increase in local extinction risk (no. species)
15%	9.05%	10.3%	6.52%	15.8%	15.4%	17.2%
20%	8.93%	7.93%	3.30%	14.6%	13.9%	15.2%
30%	8.15%	4.32%	1.16%	12.9%	9.45%	12.3%
40%	4.29%	4.98%	4.13%	10.8%	6.24%	9.34%

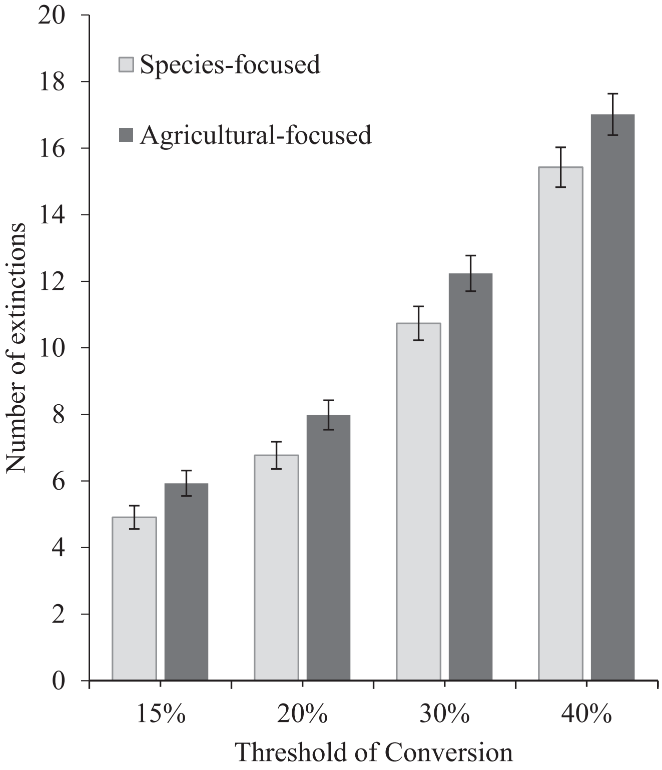

Figure 4. The expected mean number of local extinctions in solutions based solely on species persistence objectives (light) or agricultural objectives (dark). Error bars represent the 95% confidence intervals of the mean number of extinctions.

on biodiversity and ecosystem services outcomes (figure 3—solid 'fixed scenarios' versus dashed lines 'can transition scenarios') and as such, an 'opportunity debt' has been created, where important opportunities to take advantage of land use allocation to the benefit of economic profit and environmental objectives were missed. We show that through the use of our multi-objective optimisation framework to inform planning, we can address this debt and ensure better future outcomes can be achieved with respect to both agricultural production value and environmental values (figure 3).

The fundamental land management decision to be made is what proportion (or conversion threshold) of the landscape should be permitted to be converted to agriculture. This threshold had the strongest influence on both agricultural production benefit and loss of biodiversity and ecosystem services (table 2, figure 3). For a given threshold of total land conversion, our spatially explicit planning framework provides important opportunities to minimise impacts on biodiversity and ecosystem services while maintaining high production values. Within the Orinoquia, planning can reduce some of the negative impacts that development has on species and ecosystem persistence, carbon sequestration and water provision, at all thresholds of conversion. As the proportion of the landscape that is converted increases, there appear to be diminished opportunities to mitigate these impacts (figure 3, table 3).

Our analysis indicates that it is not possible to maximise the performance of planning solutions against all three environmental objectives simultaneously, and trade-offs exist among them (figure 3—dotted lines 'single environmental objective scenario' versus solid lines 'fixed/combined environmental scenarios', SM 1.6), indicating that land use planners must carefully consider the relative importance of each objective. However, we have identified planning solutions that represent a compromise between these environmental objectives. The relative importance of the objectives can be readily adjusted to reflect the values of different decision-makers and stakeholders.

Greater protection of ecosystem service provision can be made if some areas that are currently agriculture are restored to a natural state (figure 3—solid 'fixed scenarios' versus dashed lines 'can transition scenarios'). Grazing lands within the region are stocked at low density and many have not been severely degraded (Smith *et al* 1997), therefore some areas are likely amenable to restoration with good potential for recovery of ecosystem function and relatively minor impact on agricultural production (Usma and Trujillo 2011). In addition to protected area planning, activities that restore or prevent deterioration of lightly degraded lands, such as low density grazing lands, should be considered. Obstacles to ecosystem restoration associated with de facto land ownership may require government intervention in the form of incentive programs, such as payment schemes for ecosystem services, and enforcement in legally protected

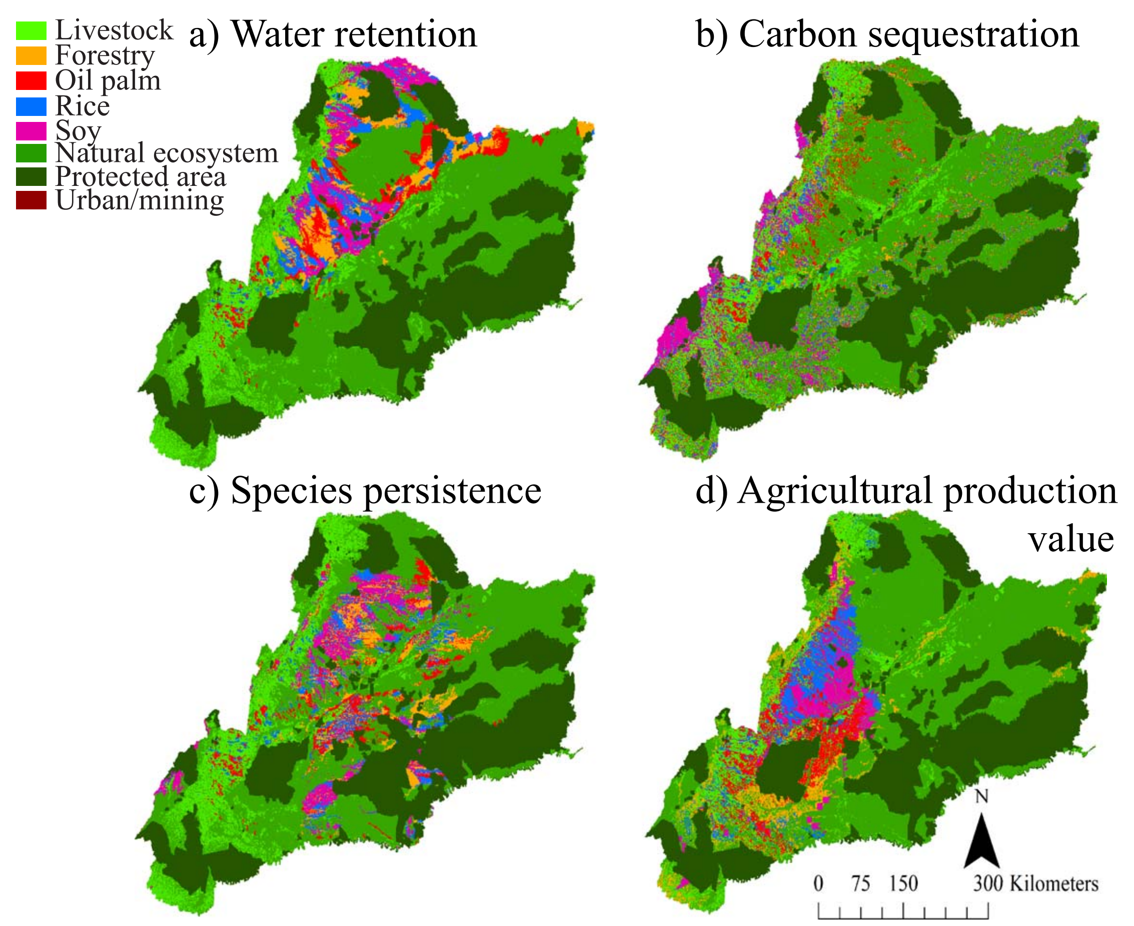

Figure 5. Spatial allocation of livestock (fluro green), oil palm (red), forestry (orange), rice (blue), soy (pink) and natural or unconverted lands (light green) when allowing 20% of the landscape to be lost to agriculture when planning for (i.e. the best-case solution for) (a) water retention, (b) carbon sequestration, (c) species persistence, and (d) agricultural production value. Protected (dark green) and urban/mining areas remain stagnant as we assume no development can occur within them.

areas. The current distribution of agricultural lands prevents meeting ecosystem representation targets for 2, 3, 3, and 5 ecosystems in the 15%, 20%, 30%, and 40% land conversion thresholds respectively (see SM 3 table S3.3). Conservation planning for these ecosystems should prevent further loss of native vegetation and consider restoration of low productivity agricultural lands. It is important to consider both species and ecosystem representation as planning for one does not necessarily account for the other (Polak *et al* 2015).

This analysis can inform two major current policy initiatives in Colombia. The National Agricultural Frontier (Frontera Agricola Nacional) is a national government-defined agricultural zone, which aims to guide the formulation of public policy, focus and enhance investments and management of the agricultural and rural development sector, promote efficient use of land, streamline social ordering of the rural property, and contribute to stabilizing and reducing the loss of ecosystems of environmental importance by dictating where agriculture should and should not expand (MADR 2016). While excluding protected areas and some forested ecosystems, the full development of this zone would be associated with a conversion threshold of approximately 75% in the Orinoquia, which our analysis indicates would be associated with large losses of biodiversity and ecosystem service values. While the results of our study cannot determine the maximum threshold of land conversion that should be permitted, as this depends on the values of national and regional stakeholders, our framework and results can inform this decision by providing an objective, transparent, evidence-based approach to assessing the consequences of different thresholds of conversion, and inform decisions about compromises between agricultural development and environmental protection. The second policy initiative is ZIDRES (Areas of Interest for Rural, Economic and Social Development), which supports agricultural development projects within government-defined rural zones across Colombia (El congreso de Colombia 2016). Although the ZIDRES initiative still lacks explicit expansion targets and environmental objectives (beyond the criteria that environmental sustainability must be considered), the zones cover 37% of the Orinoquia and our framework could be used

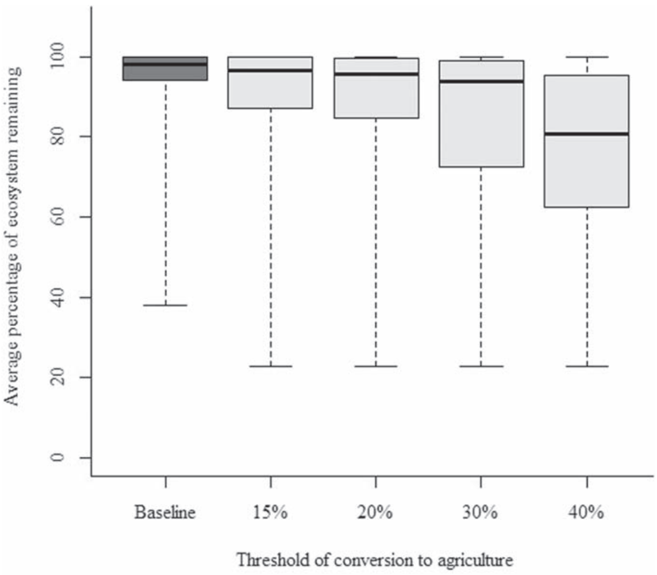

Figure 6. The proportions of each of the region's 36 ecosystems remaining among different land conversion thresholds (*x* axis) among the scenarios where ecosystem retention targets were used. The baseline represents the average amount of each ecosystem that currently remains. Horizontal lines represent the average proportion remaining at each threshold among all ecosystems.

within these to achieve development objectives (once explicitly defined) while minimising the loss of environmental values.

The assumption that planning units converted to agriculture provide no effective value to biodiversity is warranted because, while there are exceptions, most of the species considered are strongly dependent on native savannah habitat, and agricultural lands when intensely farmed may be unlikely to support sustainable populations of species (Fleischner 1994, Alkemade *et al* 2013, Newbold *et al* 2015, Pardo *et al* 2018, 2019). Furthermore, we assume that once a planning unit is converted to agriculture it contributes no water to downstream regions, which we believe is reasonable as most water resources would be allocated to sustaining agriculture (Hanasaki *et al* 2010, Power 2010). The assumption that there would be significant SOC loss once an area is converted to agriculture is justified because this is a well-observed outcome following land conversion and disturbance (Zinn *et al* 2005, Klumpp *et al* 2009, Sommer *et al* 2018). Therefore, for the purpose of this analysis, we assume that agricultural land uses contribute no value to environmental objectives; however, future studies might quantify and account for each land uses respective biodiversity, water, and carbon loss as compared to the natural state. We also assume that protected areas are effective at preventing ecosystem conversion. However, illegal clearing of land is a substantial concern in this region (Armenteras *et al* 2019), implying that enforcement of protected areas will be essential when implementing land use planning.

This work could be further advanced by considering the reduction in negative environmental impacts or differences in yields that might occur through different intensities of farming or sustainable agricultural practices such as promotion of traditional cattle-ranching or Roundtable on Sustainable Palm Oil certified palm oil. We have shown that loss can be reduced through careful spatial allocation of land uses, and further reductions not quantified here may come from best practices. Additionally, we considered the entire Orinoquia region as a whole, and defined agricultural expansion targets for the entire region. However, different departments in the region sometimes behave independently from one another. Implementation of an Orinoquia-wide plan would require coordinating revenue sharing among departments, perhaps through a payment for ecosystem services framework, so that regions in which protected areas are concentrated are not penalised economically. We also do not account for the additional cost of changing one land use to another in the 'can transition' scenario, only the potential production value of a parcel of land for a given commodity. We included only five agricultural commodities and have not considered the variations in production value among producers that occur due to the scale of farming practices. Our framework could be further developed to include more commodities, and economic data relating to scale of production and the costs of transformation of crops to secondary products.

Conclusion

For regions such as the Orinoquia where the loss of intact ecosystems to agricultural expansion is inevitable, development must be strategically planned in order to avoid unnecessary impacts on biodiversity and ecosystem services. Given that the magnitude of the impacts on biodiversity and ecosystem services are driven primarily by targets for land conversion, the key policy decision is what those targets should be. Spatial planning can improve outcomes for species persistence, ecosystem retention, carbon sequestration, water provision and agricultural production value to avoid accrual of further opportunity debt that exists due to previous unplanned expansion. The novel spatially explicit, quantitative, multi-objective framework presented here is designed to help decision-makers solve the difficult challenge of meeting development goals while minimising negative impacts to the environment through strategic land use planning. It differs from approaches which are typically designed for transformed or fragmented landscapes, and can be applied to any relatively intact environment that is being opened up for development, where minimising loss of core environmental values is a key objective.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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