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Balancing tradeoffs: Reconciling multiple environmental goals when ecosystem services vary regionally

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Abstract

As the planet’s dominant land use, agriculture often competes with the preservation of natural systems that provide globally and regionally important ecosystem services. How agriculture impacts ecosystem service delivery varies regionally, among services being considered, and across spatial scales. Here, we assess the tradeoffs between four ecosystem services—agricultural production, carbon storage, biophysical climate regulation, and biodiversity—using as a case study the Amazon, an active frontier of agricultural expansion. We find that the highest values for each of the ecosystem services are concentrated in different regions. Agricultural production potential and carbon storage are highest in the north and west, biodiversity greatest in the west, and climate regulation services most vulnerable to disruption in the south and east. Using a simple optimization model, we find that under scenarios of agricultural expansion that optimize total production across ecosystem services, small increases in priority for one ecosystem service can lead to reductions in other services by as much as 140%. Our results highlight the difficulty of managing landscapes for multiple environmental goals; the approach presented here can be adapted to guide value-laden conservation decisions and identify potential solutions that balance priorities.

1. Introduction

Increasing demand for agricultural products from a global population that is becoming larger and wealthier has led to widespread conversion of natural habitats: agriculture’s footprint now covers nearly 40% of the planet’s ice-free land (Foley et al 2012). Agricultural demand is projected to increase in the coming decades (Tilman et al 2011). Alongside intensification on current agricultural lands, expanding croplands and pasturelands can also support growing demand for food, fuel, fiber, and other agricultural products. However, large-scale land conversion from natural vegetation to agriculture affects several key aspects of the earth’s environmental systems, including standing stocks of biomass and soil carbon (Harris et al 2012), biodiversity (Pimm et al 2014), and biophysical climate regulation (Bonan 2008).

While land use conversion for agriculture can lead to loss of ecosystem service delivery (Daily et al 2009, Tallis and Polasky 2009, Kanter et al 2016), individual ecosystems services are not necessarily spatially aligned (Nelson et al 2009, Cavender-Bares et al 2015a, Landuyt et al 2016). This difference in distribution,
which is strongly influenced by the landscape’s ecological context (Goldstein et al 2012, Stickler et al 2009), creates a challenge in managing for multiple ecological goals (Cavender-Bares et al 2015b), Lazos-Chavero et al (2016). For instance, Lima et al (2014) found that deforestation led to opposing impacts on hydrology in three adjacent Amazonian watershed systems, requiring different management approaches to address water balance concerns (Lima et al 2014). While some socio-ecological contexts have shown synergies between food production and biodiversity preservation (Hanspach et al 2017), it remains unclear how often this is the case.

These points lead to a fundamental challenge: how can conservation strategies intended to increase agricultural production with one environmental goal at the fore (e.g. carbon storage) adequately address a second, third, or fourth environmental goal (e.g. biodiversity protection)?

Here, we use a general approach to illustrate the environmental challenges associated with the provision of multiple ecosystem services in the Amazon. Amazonia provides ecosystem services of regional and global importance and is a dynamic agricultural frontier (Nepstad et al 2014, Davidson et al 2012, Foley et al 2007). We use recently developed high-resolution, spatially-explicit ecological datasets (Hiederer and Kochy 2012, Powers et al 2011, Del Grosso et al 2008, Clark et al 2012, Aide et al 2013, Feeley et al 2012a, Baccini et al 2012, INPE 2012, LAPIG-UFG Databases 2012, Anderson-Teixeira et al 2012, Mueller et al 2012) to assess how geographic variation in potential future agricultural expansion may affect the delivery of four ecosystem services associated with environmental goals in Amazonia: agricultural production, carbon storage, provision of high-biodiversity habitat, and biophysical climate regulation. We then quantify tradeoffs between increased agricultural production via agricultural expansion and each individual environmental goal. Finally, we use a simple optimization model to conduct a series of simulations of 'least harm' agricultural expansion while shifting the priority placed on different environmental goals to explore alternate strategies for protecting multiple ecosystem services in tandem.

2. Methods

2.1. Study system

This analysis is completed for Amazonia, which we define here as the combination of the Amazon River and Tocantins River watersheds (figures 1–2). The region spans several ecological and biophysical gradients (e.g. precipitation and elevation), but functions hydrologically and climatically as an interconnected system (Davidson et al 2012). Croplands and pasturelands have rapidly expanded, and some areas are now intensively managed for dramatically higher crop yields (Ray et al 2013, Richards et al 2015). Agricultural expansion has had substantial impacts on individual ecosystem services: carbon emissions (Harris et al 2012, Baccini et al 2012, Soares-Filho et al 2010, Fujisaki et al 2015), habitat for biodiversity (Feeley and Silman 2009, Soares-Filho et al 2006, Lenzen et al 2012, Steege et al 2015), hydropower services and freshwater availability (Stickler et al 2013, Coe et al 2009, Castello and Macedo 2015) and biophysical climate regulation (Oliveira et al 2013, Silvério et al 2015, Lima et al 2014). The ecological heterogeneity, globally significant agricultural production and ecosystems, and a rapidly transforming agricultural frontier make Amazonia an ideal region for assessing and managing tradeoffs among multiple ecosystem services.

2.2. Potential agricultural yield

We estimate the attainable yield of soybean cultivation across Amazonia by comparing Amazonia’s agriculture with high-performing regions in analogous climates (Mueller et al 2012). We estimate attainable pasture-fed beef yield across Amazonia by linking a model of non-tree aboveground net primary productivity (del Grosso et al 2008) to intensified stocking densities (head of cattle per hectare of pasture) reported in the literature for Amazonian pasture systems (see supplemental methods available at stacks.iop.org/ERL/13/064008/mmedia). Soybean and beef attainable yields are converted to kilocalories per hectare for direct comparison (supplemental methods).

2.3. Carbon stock losses

We derive a map of above-ground carbon contained in natural vegetation by combining a year 2008 map of live woody biomass carbon (Baccini et al 2012) with a year 2008 map of natural vegetation developed by combining three high-resolution land cover datasets (INPE 2012, LAPIG-UFG Databases 2012, Aide et al 2013, Clark et al 2012). We estimate soil carbon emissions post-clearing using a map of soil organic carbon stocks in the top 30 cm of soil (Hiederer and Kochy 2012) and a spatially-explicit map of soil carbon stock change factors (Powers et al 2011). We calculate a bootstrapped 95% confidence interval around the mean carbon loss from vegetation and soil carbon post-land use change across Amazonia (supplemental methods).

2.4. Relative species richness

The loss of biodiversity-rich habitat impacts global genetic diversity, ecotourism, and other ecosystem services (Chazdon 2008). We used range maps of Amazonian plant, mammal, and bird species (supplemental methods) to estimate relative local diversity as a proxy for habitat quality. We define relative species diversity as the number of overlapping species ranges in each 5 arc-minute by 5 arc-minute grid cell.

We searched online databases of vascular plant, mammal, and bird herbarium and museum collections tied to georeferenced data to compile presence/absence
observations for Amazonian plant, mammal and bird species. In the case of mammal and bird species, those geolocated presence/absence data are combined with mean annual temperature, maximum climatological water deficit (a measure of water stress and precipitation regime), and ecoregion identity (serving as a proxy for non-climatic factors such as soil type) to model the distribution of each species using a simple species distribution model (Feeley et al. 2012). Plant species’ ranges were estimated using a maximum entropy approach due to artificial diversity patterns that emerged when linking plant observations and ecoregion identity (supplemental methods). We further explored habitat quality patterns by using a cumulative rarity index that accounts for range size, based on the formula for Simpson’s D (a biodiversity index that measures species evenness in a community), for the three taxa groups considered. Our rarity index was defined as:

\[ D = \sum_{i=1}^{n} \frac{1}{p_i^2} \]

where \( n \) is the number of species of plants, birds or mammals, and \( p_i \) is the number of cells in our estimated range for that species.

2.5. Biophysical climate regulation
Agricultural expansion can alter regional climate (Anderson-Teixeira et al. 2012) through changes in surface energy balance, i.e. flows of heat and water from the land to the atmosphere, potentially affecting local (Oliveira et al. 2013), downwind (Bagley et al. 2012) or downstream ecosystems, including by altering agricultural yields (Oliveira et al. 2013), increasing local temperature (West et al. 2011) or shifting water resource availability (Stickler et al. 2013). We used Agro-IBIS, a process-based ecosystem land-surface model, to simulate the effects of replacing natural vegetation with agricultural lands on local atmospheric temperature and moisture; Agro-IBIS was previously calibrated for use in Amazonia (Anderson-Teixeira et al. 2012).

We modeled the net radiation, latent heat flux, and sensible heat flux across Amazonia for three land cover types: natural vegetation, grass, and soybean cultivation (supplemental methods, supplementary figure S4). We calculate the effects of land use change on energy balance as the difference in energy fluxes between the natural vegetation and the agricultural simulations. We then convert the energy balance impacts of land use change into impacts on local air temperature and atmospheric moisture sensu West et al. (2011).
2.6. Tradeoffs associated with agricultural expansion

We experimentally double the land dedicated to agriculture as of 2008 in order to quantify and map environmental tradeoffs associated with land use change. New hectares of agriculture are allocated to locations where land clearing would lead to the least environmental harm, defined as a composite index of harm via carbon emissions, loss of habitat with high relative species richness, and potential disruption to local biophysical climate regulation. We use a simple model to determine where land conversion leads to the 'least combined environmental harm':

\[ V_{ij} = \sum_{k=1}^{N} w_k D_{kij}p_{ij} \]

Here, \( V \) is the value placed on a parcel of land remaining in natural vegetation, \( w_k \) is the weight, or human preference/priority, given to each ecosystem property, \( D_{kij} \) is the delivery of the ecosystem property, \( k \) is an index for each ecosystem property (e.g., potential agricultural yield, carbon storage, etc.) being incorporated into \( V \), \( p_{ij} \) indicates whether locations are to be \textit{a priori} protected, and \( ij \) points to the grid cell.

Each grid cell is assigned a combined environmental value \( V \), which depends on the relative weights (\( w \)) assigned to each ecosystem service and maps of potential agricultural yield and non-agricultural ecosystem service delivery (\( D_{kij} \), figure 1); a cell’s value is determined by the ability of that cell to provide each ecosystem property and the relative weight, or priority, of each of those properties. Deforestation is simulated with perfect efficiency (i.e. cells with low \( V \) values are converted to agriculture in rank order). The relative weights (\( w \)) between factors was varied across each simulation systematically in 5% increments (\( w_1 = (1.0, 0, 0) \), \( w_2 = (0.95, 0.5, 0) \), ...) for \( n = 441 \) in order to search for non-linearities in response variables. For instance, in one simulation lowering carbon emissions could receive 55% of the priority, protecting high numbers of species could receive 30% priority and limiting changes to regional climate regulation could receive the final 15% priority.

Each simulation was run such that current Amazonian protected areas (World Database on Protected Areas, supplemental methods) were or were not eligible for conversion to agriculture (via \( p_{ij} \); total \( n = 882 \)). One optimization was run without regard to protected areas, showing the theoretical boundaries of efficient land use change. A second simulation did not allow any land use change within protected areas, to approximate efficiency within current bounds. While these simulations are not meant to be realistic future Amazon land use change scenarios, they allow us to explore broad patterns in balancing multiple landscape goals in heterogeneous systems as conservation priorities vary.

3. Results

3.1. Agricultural production

We estimate the range of attainable soybean yield to be 10.755 ± 0.837 million kilocalories (kcal) hectare\(^{-1}\) (mean ± standard deviation), which is similar to estimated attainable yields in Central Brazil (Foley \textit{et al} 2012, Ray \textit{et al} 2013). For pasturelands, we estimate attainable annual yields to be 0.053 ± 0.009 million kcal hectare\(^{-1}\) (mean ± standard deviation figure 1).

3.2. Carbon storage

We find that, across all cells, agricultural expansion in the Amazon leads to the release of carbon in the range of 214.0 ± 98.0 tonnes per hectare (mean ± standard deviation, Mg C ha\(^{-1}\), figure 1, supplementary figure S1, supplementary methods). The tradeoff between the carbon lost and agricultural yield gained (Mg C kcal\(^{-1}\)) from agricultural expansion shows a distinct spatial pattern across Amazonia (figure 2). This heterogeneity is driven primarily by variation in dominant natural vegetation. For example, conversion of savanna in southeastern portion of Amazonia releases fewer Mg C ha\(^{-1}\) than does clearing forest in the Andes portion of the basin. Because western and northeastern forests are carbon-rich and still relatively intact, additional food production in these regions has disproportionately large impacts on carbon storage.

3.3. Biodiversity

Average relative diversity in a 5 arc-minute by 5 arc-minute area is 1026 ± 560 species (499 ± 505 for plants, 79 ± 16 for mammals, 449 ± 91 for birds, figure 1, supplementary figure S2). The largest tradeoff between habitat for biodiversity and increased agricultural production (species kcal\(^{-1}\), figure 2) is in the Andes-Amazon region of the western Amazon. The Andes-Amazon region not only features the highest average relative diversity, but also the highest cumulative rarity/Simpson’s D diversity indices (supplementary figure S3).

3.4. Regional climate regulation

Model results find that deforestation leads to annual regional warming of 0.33 °C ± 0.29 °C and regional atmospheric drying due to a decrease in atmospheric moisture loading from vegetation (i.e. lower evapotranspiration rates) of 0.84 ± 0.31 mm H\(_2\)O per day (figure 1). The spatial pattern in the tradeoffs between regional climate regulation and agricultural production (figure 2) is driven by higher impacts in regions with more pronounced climate seasonality in the south and east. These areas have a lengthy dry season, during which relatively short-rooted crops (e.g. soybean and pasture grass) have dramatically reduced evapotranspiration rates in comparison to deep-rooted forest vegetation that can more readily access deep soil water...
Figure 2. Potential ecosystem service cobenefits of avoided agricultural expansion. Highlighted areas are locations that store vegetative and soil carbon, provide biodiversity-rich habitat or regulate biophysical climate in the top 25% of cells for each ecosystem service (figure 1). Non-natural vegetation as of 2008 or areas of open water are indicated in grey (supplementary methods).

3.5. Single- and multi-service tradeoffs

To detect locations where preventing deforestation would secure multiple environmental benefits, we identified locations with the greatest potential to store carbon, provide species-rich habitat, and regulate regional climate per unit of agricultural production foregone (figure 2). We calculated the ratio between potential agricultural production and each ecosystem service and mapped the top 25% of cells, or the locations where removing natural vegetation for agricultural does the most environmental harm. The top performing areas for each of the three non-agricultural ecosystem services are clustered, indicating that protecting the provision of each ecosystem service could be achieved by targeting particular regions within Amazonia.

However, the top performing areas for the delivery of each non-agricultural service are not geographically aligned: protecting eastern Amazonia is most important if the conservation priority is regulating regional climate, but protecting western Amazonia is most important if the conservation priority is maintaining biodiversity. Consequently, there are limited opportunities to simultaneously protect both regional climate and biodiversity in the same location. Prioritizing carbon stocks provides more opportunity for simultaneously protecting two or more ecosystem services at once, e.g. ‘cobenefit’ protection (Mukul et al 2016). If left in forest, areas with high carbon stocks cover a swath from western to eastern Amazonia that intersects with areas of high relative biodiversity in the west and some portions of high-performing climate regulation areas in the northeast (figure 2).

Qualitative comparison indicates that a targeted land conservation strategy can be effective at protecting the provision of a single ecosystem service in the face of agricultural expansion. Limiting the tradeoffs for multiple ecosystem services at once in geographically variable regional contexts may require difficult decisions about how to balance different environmental goals. To explore this tension, we use land use optimization simulations to assess (1) the effects of different spatial locations of deforestation on ecosystem services and (2) how prioritizing environmental goals in relation to one another shifts ecosystem service delivery, even under ‘best-case-scenario’ land use expansion (supplementary methods). In each simulation \( n = 882 \), we experimentally double Amazonia’s agricultural footprint at the least combined environmental harm—which we refer to below as ‘efficient’ expansion—while varying the priority given to carbon storage, habitat provision, and regional climate regulation.

Our simulations deliver similar amounts of additional agricultural output, but their environmental impacts vary considerably (figure 3). As higher priority is placed on either carbon storage, habitat provision,
Figure 3. Variation in environmental impacts for land use simulations in which Amazonia’s agricultural footprint was doubled at the least combined environmental harm; simulations apply different levels of environmental priority to the three ecosystem services of interest: minimizing impacts to carbon storage, habitat provision and regional climate regulation is balanced according to priority ‘weights’ which add up to 100% (supplementary methods). As the priority given to a given service rises (x-axis), the impact of agricultural expansion on that service decreases while the impacts on the remaining services rise, though often with substantial spread (e.g. panel 3a (C emitted decreases when C priority increases) versus panel 3c (regional climate impacts increase as C priority increases)). Agricultural ‘optimal expansion’ scenarios were optimized when strictly avoiding protected areas (blue data points, $\rho_{\text{prot}}$) and without avoiding protected areas (black data points, $\rho_{\text{all}}$); qualitative trends hold regardless. Trend lines are Loess local regressions and marked as significantly different from zero as $^{***}$ when $p$-value $<0.001$, $^{**}$ when $p$-value $<0.01$ and $^*$ when $p$-value $<0.05$. Regional climate index is the mean of the normalized deviations in heat and moisture regulation after land use change where $+1.0$ is a large amount of biophysical climatic deviation.

or regional climate regulation (from 0%–100% priority for each), agriculture expands optimally into areas that emit less carbon, affect fewer species, or cause less disruption to regional climate after land use change (figures 3(a), (e) and (i)). The Pearson’s correlation coefficients ($\rho$) between carbon storage priority level and total carbon emitted, habitat priority level and species ranges affected, and regional climate priority level and the regional climate index are $-0.78$, $-0.57$ and $-0.93$, respectively ($p$-values all $<0.001$), indicating strong negative correlations. By contrast, the impacts on services not targeted rise as the priority is shifted increasingly towards a single environmental goal: as carbon priority increases from 25%–75%, the mean regional climate index increases from $0.43$–$0.58$ (figure 3(c)). Similarly, as regional climate priority rises from 25%–75%, carbon emissions increase by $>100\%$ and the number of species ranges affected rises by 35% (figures 3(g)–(h)).

There are large differences in outcomes across the scenarios for the two ‘non-prioritized’ ecosystem services. Balancing multiple ecosystem service goals requires placing value judgments on the second and third service under consideration. Those relative priorities in some cases lead to large variation in the scale of relative impact on secondary and tertiary environmental goals. For instance, even when habitat conservation is given 75% of the environmental
priority, simulations in which regional climate regulation is the second priority have a regional climate index $\sim 40\%$ lower than simulations that value carbon storage highly (figure 3(f)). Explicit conservation goals can produce sizeable positive environmental impacts for the primary environmental goal under consideration, as well as secondary goals.

3.1. 3-dimensional efficiency frontier

Land use expansion simulations indicate that, at a given priority level for each ecosystem service, delivery of the balance between the remaining services could vary widely. We plotted each land use simulation as a point on a 3-dimensional efficiency frontier (figure 4), which shows the upper limit service delivered from the landscape given defined constraints (here, agricultural expansion area). We see that a swath of ‘Goldilocks’ land use arrangements do appear on the frontier: simulations where a medium number of species ranges are affected, regional climate is moderately disrupted, and a relatively small amount of C is emitted. By contrast, we found few clear ‘win-win’ land use arrangements, where a simulation with low total C emissions appears along the efficiency frontier between habitat and climate regulation (i.e. points towards the upper right quadrant, figure 4).

4. Discussion

Our results suggest that even if agricultural lands expanded via a ‘least harm’ pathway in the Amazon, in ecologically heterogeneous regions, large and differential effects of this expansion on the earth system can result depending on the particular environmental goals. Including additional ecosystem services, such as those related to disruptions to water or nutrient cycles, further complicates our ability to design land use strategies that maximize both agricultural and multiple environmental benefits. For this reason, a ‘one-size-fits-all’ land conservation strategy in the Amazon that attempts to simultaneously achieve multiple environmental goals by managing for any particular ecosystem service is unlikely to be effective. Instead, a ‘portfolio’ approach that strategically targets different regions of Amazonia to achieve different environmental outcomes could be a way forward; the current arrangement of protected areas in Brazil approaches this strategy in portions of the Amazon.
(Soares-Filho et al. 2010), which is part of the reason why our simulations that consider or do not consider protected areas are qualitatively similar (figure 3).

Balancing multiple ecosystem services can be navigated despite spatial heterogeneity in a modeling context that is free from socio-economic constraints including environmental governance, land markets, and geo-spatial limitations on the location’s near-term agricultural expansion (e.g. transport infrastructure). It is possible that ‘optimal’ land use allocation now could change in the future and need to be reevaluated because the impact of land use expansion on ecosystem services will vary under future climates and agricultural practices, or because future policy makers choose to address a broader set of ecosystem services. Exploring tradeoffs under efficient, optimal conditions allows us to determine the outer bounds of what would be possible were environmental goals determined, stated, and pursued without inefficiencies. However, even under these unimpeded conditions, balancing multiple ecosystem services proves a challenge at the regional scale.

Yet several realities of modern conservation, and their associated challenges, merit discussion. Conservation strategies and priorities are not determined by a single actor, and instead competing interests—including those of farmers, ranchers, corporations, environmentalists, indigenous peoples, and regional and national government agencies—all influence the pattern and rate of agricultural expansion and have different priorities that operate at different scales (Garrett and Rausch 2016, Lenzen et al. 2013, Fuchs et al. 2011, Soares-Filho et al. 2016, Gibbs et al. 2015, Cord et al. 2017, King et al. 2015). Agricultural expansion often follows the spatial configuration of roads or waterways (Soares-Filho et al. 2006, Fearnside 2007) or the availability of suitable forestland for conversion, whose suitability depends on the constraints of the agriculturalist and the crop they aim to produce (Ordway et al. 2017), which in turn is dependent on local, regional and global market demand for food, fuel and fiber (Pacheco 2012, DeFries et al. 2010). Additionally, the benefits of grown calories via agricultural production can accrue to distant stakeholders; for instance, many of the calories embodied in Amazonian soybean production are consumed as inputs by livestock (DeFries et al. 2010, Cassidy et al. 2013); ecosystem service management more broadly often contends with tensions between beneficiaries and those bearing costs. Ecosystem services frameworks at this spatial scale also face challenges in incorporating services that do not have readily available, public datasets, leading to systematic emphases on readily-quantifiable services.

Bearing those caveats in mind, comparing our land use simulations with the current strengths and weaknesses in Amazonia’s protected lands highlights potential areas of focus. Large protected areas in the Brazilian states of Pará and Mato Grosso (supplementary figure S7) overlap extensively with the high-delivering areas for biophysical climate regulation highlighted in figure 2. Western Amazonas state (Brazil) and two large protected areas in Peru overlap extensively with areas of biodiversity-rich habitat, and in some cases with both high performing biodiversity-rich habitat areas and high-performing carbon storage areas. Protected areas in northwest Amazonas also protect carbon-rich forests. Broadly, current protected areas, particularly in the north and west of the Brazilian Legal Amazon (Soares-Filho et al. 2010), are distributed across space and do overlap with portions of all three high-delivering ecosystem service regions (figure 2). Indeed, the Brazilian Amazon’s protected areas are key to ecosystem service protection (Soares-Filho et al. 2010) and Brazil’s protected areas maintain low deforestation rates because of a multi-pronged set of government, private sector and non-governmental organization initiatives to limit Amazonian deforestation (Nepstad et al. 2014).

Notably, the eastern Amazon and cerrado biome in Brazil have a more limited protected area network, as well as the region’s highest levels of deforested land (figure 2), despite this region’s importance for climate regulation. Deforestation-driven changes in regional climate regulation may already be underway. For example, precipitation extremes in Amazonia are increasingly common (Gloor et al. 2013), and the interaction of drought and landscape level changes to energy balance could have large effects on forest function (Gatti et al. 2014) and fire regimes (Alencar et al. 2015). Regional atmospheric warming and drying could have significant impacts on agriculture and ecosystems in Amazonia (Oliveira et al. 2013), northern Argentina, and central and southeastern Brazil (Bagley et al. 2012, Pires and Costa 2013), as well as on hydropower (Stickler et al. 2013) and urban water supplies (Setälä et al. 2014), suggesting that regional biophysical climate disruption is an environmental tradeoff that ought to be considered in tandem with the biogeochemical effects of greenhouse gas emissions on the global climate. In addition, our modeled estimates of the tradeoff between agriculture and regional climate regulation are conservative, incorporating neither climate-agriculture feedbacks (e.g. any post-clearing reduction in agricultural yields due to local climatic disruption) nor the influence of larger regional circulation changes, which likely make some areas more prone to regional climatic disruption than our results indicate (Malhi et al. 2008, West et al. 2011, Oliveira et al. 2013).

Amazonia differs from other areas that may be subject to regionally-based conservation strategies in several ways. Amazonia spans several ecological gradients (e.g. precipitation and elevation), but functions hydrologically and climatically as an interconnected system (Davidson et al. 2012). Compared to other agricultural expansion frontiers in the tropics, Amazonia has relatively stringent environmental restrictions.
imposed by both governments and corporations, as well as high levels of enforcement (Garrett et al 2016). Although there are clear gradients in the provision of the investigated ecosystem services across the region (e.g. see figure 1), even the relatively low values of these services within Amazonia are relatively high at a global level. For instance, even regions of the Amazon with low plant, bird or mammal biodiversity would be considered a biodiversity hotspot at the global scale (Dirzo and Raven 2003).

When developing a comprehensive conservation agenda for a landscape, or when exploring the implications of future land use decisions on multiple ecosystem services, optimization models, like the model presented here, can identify efficient outcomes across a wide variety of values. A key finding is that slight shifts in preference generated significant differences in earth system impacts with agricultural expansion. This sensitivity shows that this approach and similar analyses can be useful at the regional scale to inform conservation priorities. However, such a framework can complement, and not replace, careful consideration of the social and political context on top of the local ecology. In some contexts, it could be preferable to consider service delivery across time instead of space, to use a financial valuation instead of a qualitative priority metric from 0–1 (e.g. prices in place of weights $w_k$), or to estimate tradeoffs for individual stakeholder groups. We declined to set weights using prices in this case study in order to investigate the full suite of simulations irrespective of uncertainties in ecosystem service pricing, but as such this approach provides information less rooted in socioeconomic. Ecosystem service optimization models are also highly influenced by which services are included. Analytical decisions require subjective decisions about environmental and economic priorities in individual land use contexts when undertaking actions that may affect provision of these services, such as setting land use and road-building policies and expanding private land holdings.

We show that, in geographically heterogeneous systems, including Amazonia, land use decisions that aim for the provision of multiple ecosystem services hinge on value-laden tradeoffs not only between food and the environment, but between different ecosystem services. As such, balancing multiple ecosystem services must be an explicit, targeted environmental goal as land resources become increasingly valuable. A purposefully-adopted scheme of complementary conservation strategies across large, interconnected ecosystems would be a massive conservation undertaking. But broadly, sustainable land use strategies will increasingly require a multi-dimensional, quantified approach to explicitly account for these tradeoffs as the Earth system remains under pressure to provide agricultural and environmental output across the planet.

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