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Optimizing land use decision-making to sustain Brazilian agricultural profits, biodiversity and ecosystem services

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A B S T R A C T

Designing landscapes that can meet human needs, while maintaining functioning ecosystems, is essential for long-term sustainability. To achieve this goal, we must better understand the trade-offs and thresholds in the provision of ecosystem services and economic returns. To this end, we integrate spatially explicit economic and biophysical models to jointly optimize agricultural profit (sugarcane production and cattle ranching), biodiversity (bird and mammal species), and freshwater quality (nitrogen, phosphorus, and sediment retention) in the Brazilian Cerrado. We generate efficiency frontiers to evaluate the economic and environmental trade-offs and map efficient combinations of agricultural land and natural habitat under varying service importance. To assess the potential impact of the Brazilian Forest Code (FC), a federal policy that aims to promote biodiversity and ecosystem services on private lands, we compare the frontiers with optimizations that mimic the habitat requirements in the region. We find significant opportunities to improve both economic and environmental outcomes relative to the current landscape. Substantial trade-offs between biodiversity and water quality exist when land use planning targets a single service, but these trade-offs can be minimized through multi-objective planning. We also detect non-linear profit-ecosystem services relationships that result in land use thresholds that coincide with the FC requirements. Further, we demonstrate that landscape-level planning can greatly improve the performance of the FC relative to traditional farm-level planning. These findings suggest that through joint planning for economic and environmental goals at a landscape-scale, Brazil's agricultural sector can expand production and meet regulatory requirements, while maintaining biodiversity and ecosystem service provision.

1. Introduction

An additional 1 billion ha of agricultural land are predicted to be necessary to meet future demands for food, fiber, and fuel (Tilman et al., 2011). Much of this expansion in cropland and pastureland is taking place in forest-rich tropical regions: >80% of new agricultural land between 1980 and 2000 came at the expense of tropical forests (Gibbs et al., 2010); over 34% of recent global tropical deforestation (2000 − 2012) occurred in Brazil (Hansen et al., 2013). Agricultural expansion in tropical regions negatively impacts natural habitats and the ecosystem services they provide: e.g., regulating and purifying water (Power, 2010), regulating climate through carbon storage (Baccini et al., 2012), and supporting the majority of the world's biodiversity (Jenkins et al., 2013). On the other hand, agricultural expansion is important to food security and economic development (Ramankutty et al., 2008). As a result, planning strategies are needed that can increase

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agricultural production while sustaining local biodiversity and ecosystem services provision.

Previous studies have tackled this challenge by spatially mapping ecosystem services under alternative land use scenarios (e.g., Bateman et al., 2013; Koh and Ghazoul, 2010; Law et al., 2015; Nelson et al., 2009; Qiu and Turner, 2013). Importantly, their findings reveal that landscapes that maximize only commodity production provide smaller net social and environmental benefits than landscapes that also prioritize other ecosystem services (e.g., water quality, carbon sequestration). Further, they demonstrate that it is possible to provide high levels of multiple services by considering land-use trade-offs and carefully targeting the allocation of land use activities across a region. The majority of research, however, tends to be limited by considering only current landscape conditions or a few pre-selected scenarios, and by evaluating outcomes based on a limited range of values ascribed to different services. As such, potential thresholds in ecosystem service provision or the most efficient land-use options for multiple services may go undetected. Expanding upon existing work, we model a range of land-use scenarios and map efficient combinations of agricultural land and natural habitat across varying levels of agricultural production (expansion) under different service values. We apply this approach to a watershed in the Brazilian Cerrado to inform landscape design that can sustain economic activities together with biodiversity and ecosystem services in the face of agricultural expansion.

1.1. Case study in the Brazilian Cerrado

The Cerrado biome harbors some of the highest levels of species richness and endemism in the world, but has lost more than half of its original extent due to cattle ranching and expansion of cash crops, such as sugarcane and soybeans (Klink and Machado, 2005). With absolute deforestation rates in the Cerrado now surpassing those in the Amazon (Soares-Filho et al., 2014) and with habitat loss projected to continue (Lapola et al., 2010), the remaining natural vegetation and ecosystem services that they support are at risk (Klink and Machado, 2005). Thus, strategic land-use planning is needed to support livelihoods while also protecting unique habitats for biodiversity and providing clean surface water.

Current land use planning in the region is governed by Brazil's Forest Code (FC): a federal policy that targets the protection of biodiversity and hydrological services by mandating that a portion of natural vegetation be maintained on private lands (Soares-Filho et al., 2014). Farm-by-farm planning is required for FC compliance (Soares-Filho et al., 2014; Sparovek et al., 2012a), but planning at a larger (e.g., watershed) scale may better capture economies of scale for both agricultural production and ecosystem services provision (Swift et al., 2004), and thereby improve the impact of the FC (Kennedy et al., 2016). Brazilian states and licensing agencies can influence the location of protected and restored habitats and promote landscape planning, for example, by requiring consideration of habitat connectivity in the placement of required natural vegetation (Silva et al., 2012). To assess the potential benefit of such larger-scale FC compliance, we model the outcomes for agricultural production and environmental quality in a Cerrado watershed at two scales, property (farm)-level (PL) and landscape-level (LL).

1.2. Multi-service spatial optimization

We apply a spatial optimization approach to examine the trade-offs and thresholds in the provision of agricultural profit (AP) and ecosystem services (ES), proxied by freshwater quality (WQ) and biodiversity (BD). For brevity, we collectively refer to BD and WQ as ES. Although food production is an ES by many classification schemes, we distinguish AP from BD and WQ in our assessment to evaluate the trade-offs between marketed and non-marketed services (given that the former are often produced at the expense of the latter) (Carpenter et al., 2009).

We integrate detailed spatially explicit models of AP (cattle ranching and sugarcane production), BD (number of bird and mammal species) and WQ (nitrogen, phosphorus, and sediment retention) to construct efficiency (or production possibility) frontiers (Figs. 1, 3) (*sensu* Polasky et al., 2008) that map efficient combinations of agricultural land and natural habitat, so that no increase in a service is possible without decreasing another. We generate separate frontiers for each of the combinations between AP and the ES, using a range of weights (as described below). Varying the weights placed on BD and WQ allows us to evaluate a range of predicted landscape outcomes under different service preferences without imposing any assumed social value. To compare the effects of planning at different scales, we generate efficiency frontiers 1) with no restriction on the amount or location of habitat or agriculture (referred to as "unconstrained"); 2) enforcing a 25% habitat constraint on each farm (referred to as "property-level" or PL, mimicking the Forest Code); and 3) enforcing a 25% habitat constraint across the entire landscape (referred to as "landscape-level" or LL, the whole-landscape comparison to FC) (see Table 1).

Our approach is a methodological advance from previous ES optimizations, which have been based on simplified or artificial landscapes at small spatial scales (e.g., 1 km^2) (e.g., Cong et al., 2016; Groot et al., 2007) or have targeted only BD (e.g., Polasky et al., 2008) or a single service like pollination (e.g., Brosi et al., 2008) or timber production (e.g., Lichtenstein and Montgomery, 2003), but have not considered more than two ES objectives. We build upon these efforts by optimizing land uses for multiple ES across an entire watershed and accounting for the spatial dependencies of ES dynamically in land cover optimizations. Further, we vary the importance for BD and WQ to assess their trade-offs at a watershed-scale, and vary the planning scale (PL vs. LL) to evaluate the benefits of spatial coordination of land use. Our aim is to demonstrate the theoretical potential of land-use planning approaches under varying service preferences at different planning scales to improve agricultural production and to sustain multiple ecosystem services.

In contrast to the more commonly applied scenario-based assessments (e.g., Bateman et al., 2013; Koh and Ghazoul, 2010; Law et al., 2015; Nelson et al., 2009; Qiu and Turner, 2013), the efficiency frontiers allow us to (1) assess whether current land use planning and policies like the Forest Code are efficient or whether improvements can be made to increase both agricultural production and ecosystem service provision, (2) examine the inherent complementarities and trade-offs between the environmental and economic objectives, and (3) identify potential thresholds in ES provision along a continuum of possible efficient combinations of land use. Thus, this approach has significant implications for improving agricultural and conservation policies in hotspots like the Brazilian Cerrado.

2. Methods

2.1. Study area and forest code requirements

Our study area encompasses the ~400,000 ha Ribeirão São Jerônimo watershed in Brazil's southeastern agricultural region (Fig. S1). It is currently comprised of mainly pasture that is being converted to sugarcane (Klink and Machado, 2005; Lapola et al., 2010). <20% of the natural habitat, made up of four dominant vegetation types (cerrado, cerradão, semi-deciduous forests, and wetlands) remains (Fig. S2, Table S1). All remnant natural vegetation is on private lands and is regulated by the FC. In our region, this law requires that each farm maintains ~25% of its area in natural vegetation. This percentage is based on our assessment of the FC requirements using publicly available farm boundary maps combined with field surveys. For the PL scenarios, 25% of a farm's area is placed under natural vegetation; for the LL scenarios, 25% of the total area of the watershed, regardless of land tenure, is allocated across the watershed. This percentage requirement is composed of both 1) Legal Reserves (LRs), which require ~20% natural area set-asides