

AGRICULTURE

Bigger is better: Improved nature conservation and economic returns from landscape-level mitigation

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Impact mitigation is a primary mechanism on which countries rely to reduce environmental externalities and balance development with conservation. Mitigation policies are transitioning from traditional project-by-project planning to landscape-level planning. Although this larger-scale approach is expected to provide greater conservation benefits at the lowest cost, empirical justification is still scarce. Using commercial sugarcane expansion in the Brazilian Cerrado as a case study, we apply economic and biophysical steady-state models to quantify the benefits of the Brazilian Forest Code (FC) under landscape- and property-level planning. We find that FC compliance imposes small costs to business but can generate significant long-term benefits to nature: supporting 32 (± 37) additional species (largely habitat specialists), storing 593,000 to 2,280,000 additional tons of carbon worth \$69 million to \$265 million (\$ pertains to U.S. dollars), and marginally improving surface water quality. Relative to property-level compliance, we find that landscape-level compliance reduces total business costs by \$19 million to \$35 million per 6-year sugarcane growing cycle while often supporting more species and storing more carbon. Our results demonstrate that landscape-level mitigation provides cost-effective conservation and can be used to promote sustainable development.

INTRODUCTION

Economic development creates numerous benefits but often comes at the expense of the environment. For example, business activities have been estimated to cause annual losses of \$7.3 trillion (\$ pertains to U.S. dollars) globally due to pollution and foregone ecosystem services (1). A main policy mechanism for countries to balance development with conservation and to reduce environmental externalities is impact mitigation (2, 3). Worldwide, mitigation policies strive for no net loss (or ideally net gain) to the environment by requiring that developers first avoid and minimize impacts and, if unavoidable, compensate (offset) for residual impacts (4). In practice, impacts on biodiversity are measured in terms of species and habitat attributes (5, 6), but there is growing interest to account for ecosystem services, such as water quality and carbon sequestration, along with human well-being (7–10).

Although the principles underlying mitigation policy are sound, its implementation is not without criticism. Mitigation has come under fire for burdening individual businesses or development sectors (11–13). It is also carried out on an ad hoc project-by-project basis that fails to account for cumulative and indirect impacts at a landscape scale and for larger-scale processes that influence economic activities, biodiversity, and ecosystem service provision (5, 14). Further, to achieve no net loss, mitigation activities (for example, restoration or protection) should provide conservation benefits that would not have otherwise occurred; yet, this condition of additionality is often not met (5). Thus, mitigation activities frequently result in highly dispersed conservation projects that have limited ecological effectiveness but impose substantial oversight burden on the regulatory community (12, 15).

To correct traditional project-by-project decision-making, unprecedented attention is now being given to the adoption of landscape (watershed or regional)–scale mitigation planning (12, 14, 15). The United States now officially espouses this new mitigation approach with the recent Secretarial Order [DOI (Department of the Interior), no. 3330, 2013], which calls for intra- and interagency mitigation processes to adopt landscape-scale planning (12, 16). Other countries, such as Colombia [MADS (Ministerio de Ambiente y Desarrollo Sostenible), Resolution 1517, 2012] and Peru [MINAM (Ministerio del Ambiente), Resolution 398, 2014], have followed suit (17). Although landscape-scale mitigation is expected to provide greater conservation benefits at a lower cost, empirical justification is still scarce (12).

Using commercial sugarcane expansion in a watershed in the threatened Brazilian Cerrado as a case study (Fig. 1), we apply economic and biophysical steady-state models to quantify the benefits of the Brazilian Forest Code (FC; Law no. 12,651, 25 May 2012) under different compliance scenarios: property (farm)–level (PL) and landscape (watershed)–level (LL) planning involving habitat protection and/or restoration. The Brazilian Cerrado biome is a global biodiversity hot spot (18): It is the world's most diverse tropical savannah but has lost more than 50% of its area in recent years because of agricultural conversion (19). With less than 2.2% under federal- or state-protected areas, the vast majority of remaining natural vegetation is on private lands and regulated by the FC, which currently has low compliance in the biome (13, 20). This policy intends to provide no net loss of habitat and ecosystem services by stipulating that a minimum portion of natural vegetation be maintained on individual properties (13). Although compliance is traditionally met at the property scale, farms are allowed to offset their legal requirements by protecting or restoring habitats on other properties within the same biome (20). The choice of mitigation action (habitat protection or restoration) can also influence the extent to which mitigation provides conservation gains (21, 22) and can affect compliance costs (11, 13).

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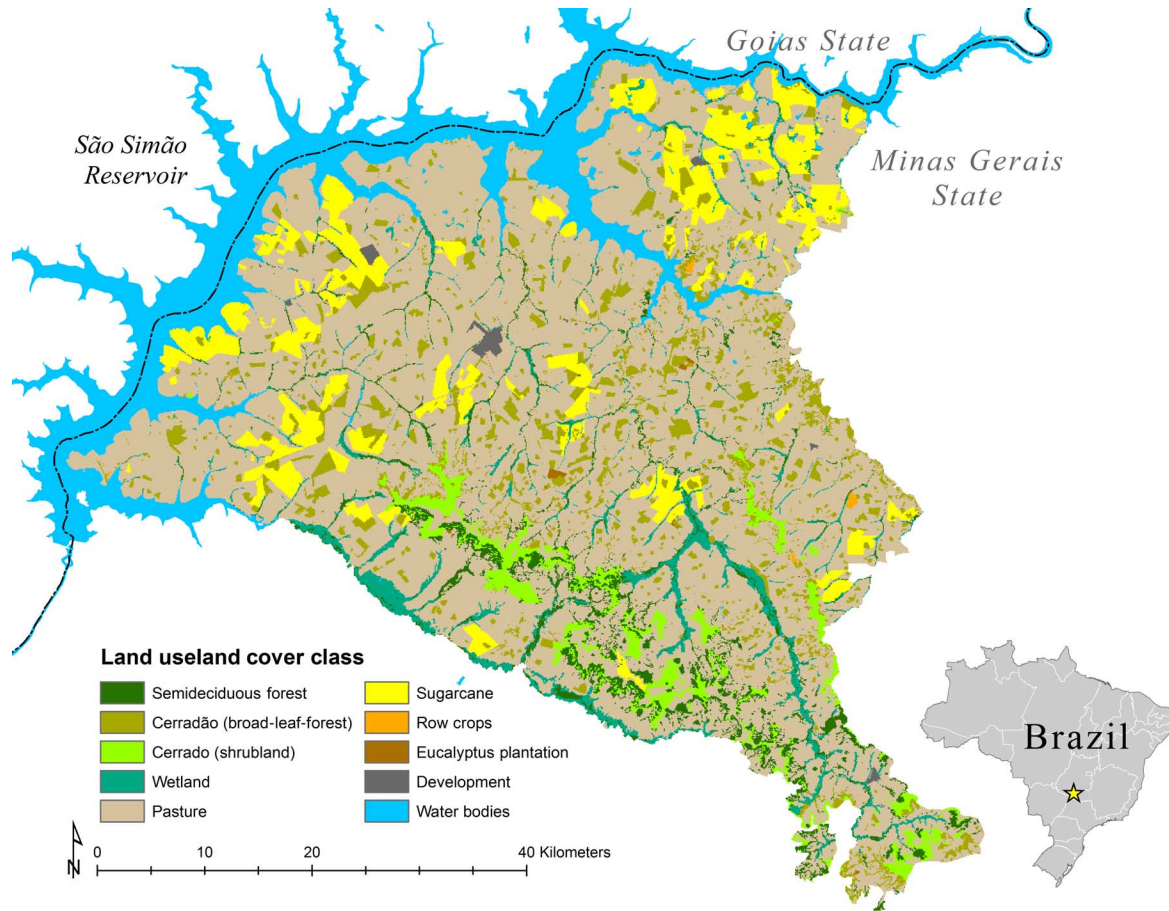


Fig. 1. Current land cover and land use in the study region. Current distributions of land cover and land use for the Ribeirão São Jerônimo watershed in the Brazilian Cerrado in southeastern Brazil.

Here, we assess how the aggregate long-term performance of the FC can be improved in a cost-effective way. We focus on the steady-state economic costs and environmental outcomes (biodiversity, water quality, and carbon sequestration) of different mitigation planning options for a large commercial sugarcane producer that is expanding production in the study region. In all of our scenarios, planning is based on minimizing the costs of environmental compliance and sugarcane production to mimic what is known to occur in practice (23, 24). The objective of our study is to show how planning for commercial production can be improved, in a way that benefits local ecosystems, while providing incentives (in the form of cost savings) for commercial producers to comply with the law at the same time. Because FC compliance is yet to be achieved in the region, we evaluate potential outcomes using empirically based models with spatially explicit parameters adapted to the local context as well as exceptionally detailed cost data from a local commercial agricultural producer.

RESULTS

Mitigation benefits can outweigh costs to business

FC compliance requires that some land be taken out of production and be placed under natural vegetation. Depending on the sugarcane pro-

duction target, compliance is likely to affect 4.2 to 8.4% of the study region and require only 15 to 22% of the area to be in natural vegetation (Fig. 2A and table S5). We find that compliance is likely to increase annual costs to a commercial grower by only 4.5 to 8.2%, because of the costs associated with FC compliance and increases in the transportation, leasing, and transaction costs (see the “Production and FC compliance costs across mitigation scenarios” section in the Supplementary Materials). However, compliance is expected to generate significant benefits in the long run: supporting, on average, about 32 (± 37) additional species (largely forest and cerrado specialists) and ~74% ($\pm 8\%$) of all possible bird and mammal species in the region (tables S11 and S12). It could also store an additional 3 to 12% (593,000 to 2,280,000 tons) of carbon worth \$69 million to \$265 million using the social value of avoided CO₂ emissions (table S14). Marginal improvements of ~3% ($\pm 0.47\%$) in the aggregate surface water quality could also be gained (table S16). It should be noted that the impacts of the FC depend on the sugarcane production goal: The larger the agricultural area needed to meet the sugarcane target, the larger the benefits (tables S11, S14, and S16).

LL mitigation is cost-effective

Compared to PL compliance, LL mitigation is expected to generate cost savings of \$19 million to \$35 million (mean = \$29 million \pm \$9 million) in a 6-year sugarcane production cycle to a large agricultural producer

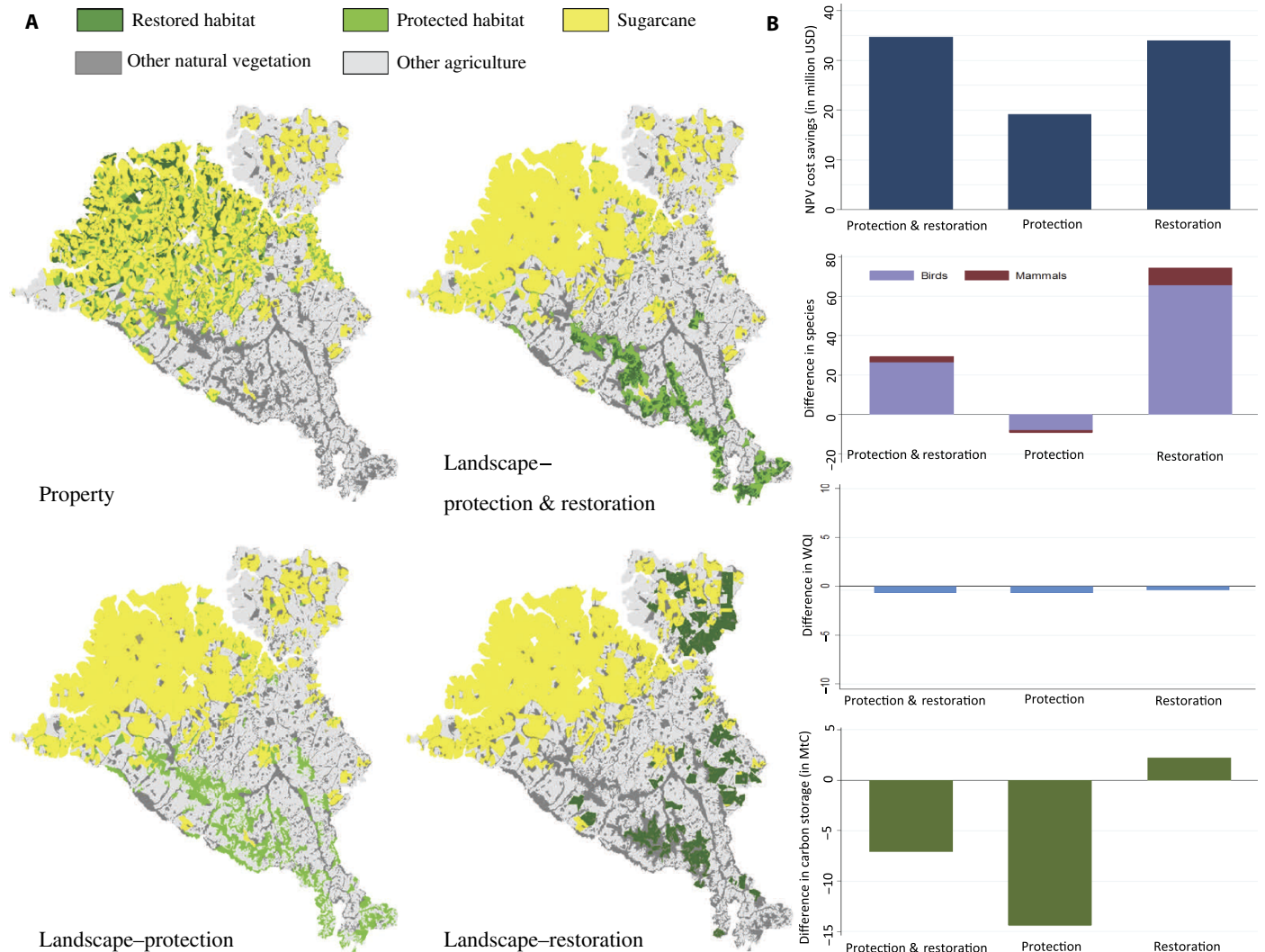


Fig. 2. Comparison of the property (farm)-level and landscape (watershed)-level planning based on economic modeling of sugarcane expansion. (A) Landscape outcomes for the modeled watershed based on an 8.5-million ton sugarcane production target from profit maximization and FC compliance based on PL and LL mitigation planning with combined habitat protection and restoration (LL-PR), protection only (LL-P), and restoration only (LL-R). (B) Difference in cost savings [net present value (NPV) in million U.S. dollars], long-term species richness (number of bird and mammal species), water quality index (WQI), and additional mean carbon storage [in megatons of carbon (MtC)] for LL planning relative to PL planning. See the Supplementary Materials for additional results.

regardless of whether the FC requirements are met via habitat restoration, protection, or a combination thereof (Fig. 2B and fig. S5). Reduced transportation costs are the largest, most consistent source of cost savings; leasing and habitat restoration cost savings are also substantial in certain LL scenarios (fig. S6). Coordination across farms allows for the most profitable land to be put into agriculture, with the habitat required for compliance located in unsuitable or less profitable areas in the region (Fig. 2A). In contrast, PL mitigation often necessitates that profitable land within leased farms be set aside for FC compliance. Thus, more farms (30 to 69 additional farms) and more land (116 to 119 additional hectares) are needed to meet the sugarcane production targets (fig. S7). For our study area, this means that 30 to 69 farms will be taken out of cattle ranching and put into sugarcane production under PL planning relative to LL planning.

Relative to PL compliance, LL compliance is also expected to increase net biodiversity in a steady-state equilibrium (Fig. 2B, fig. S12, and table S11),

resulting in an additional 32 (± 34) species on average, which are largely bird and habitat specialists (table S12 and fig. S13). For every 1000 ha of protected or restored habitat in the watershed, there is an expected addition of 15 species under LL planning relative to the 8 species under PL planning. Notably, these environmental benefits are achieved, although PL compliance consistently results in 11,500 (± 2600) more hectares of restored/protected land than LL compliance on average (table S5 and fig. S7). The reason is that LL planning reduces habitat fragmentation (tables S6 and S7 and fig. S10) and produces fewer small patches ($-24 \pm 5\%$), less edge area ($-32 \pm 4\%$) across all scenarios, and more core area ($+25 \pm 15\%$) with restoration (fig. S9). Steady-state LL compliance can also generate additional storage of 151,000 tons of carbon ($\sim 1\%$ increase) in the habitat restoration scenario (Fig. 2B and table S14).

PL and LL compliance result in similar aggregate surface water quality for the region (Fig. 2B, figs. S15 to S17, and table S16). In general,

slightly lower total amounts of nitrogen and phosphorus are predicted for the watershed under PL mitigation relative to LL mitigation (fig. S16). The reason is that PL planning results in more natural vegetation being placed close to riparian areas and retains more wetlands, both of which reduce nitrogen and phosphorus loading. In contrast, LL planning targets natural vegetation, particularly cerrado, located on higher slopes that have higher erosion rates (fig. S8 and table S5). For this reason, it can result in lower sediment loadings (fig. S17 and table S14).

Mitigation action affects the outcomes

Complying with the FC at landscape scales through a combination of habitat protection and restoration (LL-PR) produces the greatest cost savings in the long run (Fig. 2B and fig. S5). In contrast, only restoring habitat (LL-R) produces slightly smaller monetary benefits but generates the greatest predicted ecological gains (figs. S12, S14, S16, and S17). In our models, FC compliance based solely on habitat protection (LL-P) underdelivers in both economic and environmental terms. The reason behind this is that remaining vegetation is scarce within the watershed (Fig. 1); thus, there are few options for patches that can be protected. All LL mitigation results in vegetation being protected or restored in less economically productive areas, with preference given to protecting existing habitat because it tends to be located in cheaper, unproductive lands. When faced with a choice between restoration and protection, the sugarcane producer in our model resorts to restoration only after cheaper existing habitat becomes unavailable (see the “Changes in habitat area” section in the Supplementary Materials).

DISCUSSION

This study provides an evaluation of the FC to inform ways to improve its aggregate long-term impact before compliance is achieved on the ground. Contrary to concerns about the potential cost burden of the FC on agricultural producers (11, 25), we find that compliance imposes relatively small costs to a commercial producer but generates substantial conservation benefits by supporting greater biodiversity, storing additional tons of carbon, and marginally improving surface water quality. Further, we find that in a steady state, FC compliance provides greater biodiversity and carbon storage benefits in a more cost-effective way when it is implemented at a landscape scale relative to the traditional property scale. The reason is that in addition to providing new natural habitat, it allows for better natural habitat configuration (that is, less fragmentation). Our results are consistent with those of previous studies that underscore the strong impacts of the spatial patterns of agricultural expansion and habitat conversion on both biodiversity and ecosystem services (26, 27).

The benefits of LL mitigation

The steady-state benefits we detect from LL mitigation are likely to hold in other similar settings (see the “Generalizability of the results” section in the Supplementary Materials). Cost savings are expected under LL planning relative to PL planning because expanding the spatial scale provides additional options for the placement of crops for production and natural vegetation for mitigation. The only exception is the case where all the profitable land is used under PL planning, such that there is no difference in costs across the different scales. However, this case is only applicable where there is very little land available and suitable for agriculture or where the agricultural commodity is consumed only by

the household that has produced it (and not traded on a market). In real life, these situations are uncommon.

Long-term ecosystem services and biodiversity benefits are likely due to LL planning when their biophysical requirements operate at large geographic extents (for example, larger than a farm) and are unevenly distributed across a landscape (28–30). When mitigation compliance leads to landscapes composed of larger, more intact, and more connected patches that are farther from human disturbance, as in our landscape scenarios, species diversity at regional (or gamma) scales and carbon storage have been shown to improve (31, 32). Better landscape configuration may also enhance the provision of other ecosystem services, such as nutrient cycling and the provision of nontimber forest products (31, 33). In contrast, services, such as pollination and soil retention that can operate at smaller spatial scales and that can be managed in agricultural mosaics (34), may not substantially benefit from landscape-scale mitigation practices unless they are specifically targeted. For example, in our planning scenarios, the aggregate surface water quality was determined by the location of the natural vegetation with respect to steep slopes, erodible soils, and waterways. When mitigation planning takes into account the requirements of such locally supplied services, they can be enhanced with cross-property landscape management that targets the spatial configurations of habitats (29). Ultimately, the net impacts of landscape mitigation on biodiversity and ecosystem services will depend on the starting conditions (for example, the initial amount, diversity, and configuration of habitat types in a landscape), the traits of the target species, the spatial distributions of the biophysical attributes that determine ecosystem function, and the amount of natural habitat targeted by the policy in any given setting.

Hurdles to implementing LL planning

Although our analysis predicts multiple benefits from LL mitigation in the long run, this approach is currently not targeted by the FC (13). Reasons may include lack of flexibility in implementing regulations, logistical hurdles to multi-landowner coordination, lack of large-scale assessments and clear land tenure, and potential spatial mismatch between the perceived beneficiaries and those bearing the costs of compliance. Overcoming these obstacles requires a viable institutional framework to provide credible assessments, sufficient compensation, and incentives for coordination across farms (29, 35, 36). Such conditions are often not in place, although the FC allows for landowner compensation through offsets (where landowners pay others to meet their natural vegetation requirements) (13). Although this mechanism may promote cost-effectiveness, it will have limited conservation benefits if there is no coordination on where the offsets are allocated. In the case of large-scale commercial agricultural production, these hurdles may be more easily overcome because the producer has an incentive to coordinate among small holders and to compensate them for the cost of using their land.

The right mitigation action?

Our results demonstrate that the mitigation actions undertaken influence the additionality of offsets and can differentially affect biodiversity and ecosystem services. We find that under landscape mitigation, protection may be allocated to lands that are not profitable and are therefore not under threat from development. Such findings raise concerns about the additionality (37) and, hence, the impact of FC compliance that gives preference to protecting existing habitat (20) and reduces restoration requirements (13).

Globally, there is considerable variability in how mitigation is implemented. The U.S. wetland and stream mitigation programs (4), Mexico’s

offset law (17), and Brazil's Atlantic Forest Restoration Pact (38) favor habitat restoration. In contrast, Germany's Impact Mitigation Regulation is designed to protect existing natural lands and thus favors preservation (6). Some countries demonstrate no clear preference (for example, Colombia and Peru) as long as mitigation guarantees effective preservation or restoration of an area equivalent to that which is affected (17). On the basis of our findings, we emphasize that mitigation policies should require compensation methods that provide the greatest additionality of the impacts of offset actions and that can benefit both biodiversity retention and ecosystem service provision.

Important caveats to our conclusions are that our models assume instantaneous growth and full restoration success and thus do not distinguish between old-growth and newly restored habitat. The choice of the appropriate mitigation action in practice should consider the temporal lag between development impacts and offset actions and the quality and recoverability of destroyed habitats versus restored ones. Restored sites, particularly in complex natural systems and in degraded landscapes, can fail to recover lost biodiversity or do so only after long time lags (ranging from a few decades to hundreds of years) (21, 39, 40) and under active management (21, 22). Although the costs of terrestrial restoration are found to be variable, they can be substantial: ranging from \$300/ha to more than \$200,000/ha, depending on the location, habitat type, and management activities, among other factors (41). Thus, in cases of low restoration success, long time lags to habitat maturity, and substantial restoration costs, habitat protection may be preferred. Furthermore, unless restoration precedes development and protection provides additionality (that is, would not have occurred without the development offset), temporal losses in biodiversity and ecosystem services are expected (5).

Expanding the scope and assessments of mitigation policy impacts

Mitigation policies should consider impacts on all stakeholders in an affected region (10) to balance the costs and benefits of development and prevent the displacement or "leakage" of agricultural activities to other locations (42, 43). Although our analysis quantifies the aggregate net benefits of planning at landscape scales, it does not account for human welfare, distributional issues, or the displacement of land conversion (see the Supplementary Materials for further details). Previous studies provide evidence that conservation may also generate benefits in terms of improved water availability (44), reduced disease burden (45, 46), and reduced poverty (47). We provide the first step in highlighting how to improve existing land use policies by showing that planning at larger scales may provide long-term environmental benefits in a cost-effective way. An important future extension of our work is the empirical validation of the predictions after FC compliance is achieved on the ground as well as the modeling and evaluation of the policy in terms of welfare impacts (47). The modeling work presented here can inform the design and data collection of such studies (48).

CONCLUSION

Many countries, such as Brazil, are at a tipping point, struggling to balance accelerating development pressures with dwindling natural resources. Improving the effectiveness of mitigation to balance economic development with nature conservation is now pivotal (9, 10, 49), given accelerating large-scale development from sectors such as agri-

culture, energy, mining, and transportation that affect vast lands across the globe (50, 51). Advancing mitigation by adopting multiobjective landscape planning can promote cost-effective conservation and more sustainable development trajectories. It can also complement the growing global and national commitments to the large-scale restoration of degraded lands by directing and consolidating mitigation efforts to restore priority areas for biodiversity and ecosystem services (52, 53). Although recent policies and voluntary commitments by governments, businesses, and financial institutions are positioned to enable and incentivize private developers to adopt the principles of landscape-scale mitigation in their planning and practice (7, 8, 12), this approach is not yet widely implemented (10). Our analysis underscores that LL planning can improve the long-term performance of land use policies for conservation in a cost-effective way. Because the magnitude of benefits may depend on the specific context (for example, scale and type of development, the biophysical linkages between land use change, biodiversity, and ecosystem services), it will be critical to conduct rigorous empirical impact evaluations from multiple contexts to strengthen the evidence base for business, conservation, and people. Empirical assessments, such as those proposed for the landscape-scale infrastructure initiatives under new U.S. mitigation strategies (12, 16) and for restoration efforts on large versus small landholdings under the Atlantic Forest Restoration Pact (38, 54), are essential to quantify on-the-ground outcomes. Information on time and cost savings as well as on the benefits to nature and people from LL mitigation will help to overcome political, institutional, and logistical barriers to seeing its widespread adoption.

MATERIALS AND METHODS

Study region, FC requirements, and mitigation scenarios

Our study area encompasses the Ribeirão São Jerônimo watershed, an approximately 400,000-ha area in Minas Gerais State, southeastern Brazil. This region is currently largely composed of pasture that is being converted to sugarcane fields (19, 43). Less than 20% of the natural habitat remains and consists of four dominant vegetation types (4% cerrado, 7% cerrado, 3% semideciduous forests, and 4% wetlands) (Fig. 1, fig. S2, and table S1). All remnant vegetation resides on private land holdings and is regulated by the Brazilian FC (13, 20).

We used a 25% natural vegetation FC requirement at the PL and at the LL. Because FC compliance is generally low for small holders in our study area (13, 20), we assumed that only the commercial sugarcane producer would comply with the FC. All land that was not rented for sugarcane production or FC compliance remained unchanged. Thus, in all scenarios, we assumed that 25% of the farm area rented for sugarcane production must be placed under natural vegetation. This percentage is consistent with the natural vegetation requirements in the region: both in Legal Reserves, which target ~20% natural area set-asides anywhere on farms to protect biodiversity, and in Permanent Protected Areas, which target ~5% of vegetation to be placed along stream banks and steep slopes to protect water quality. Given the resolution of our data (90-m pixels), our models did not distinguish between Legal Reserves and Permanent Protected Areas and instead combined the required natural areas, which could be allocated anywhere within the watershed. See the "FC requirements and mitigation compliance options" section in the Supplementary Materials for further details.

The natural area requirement were met via the protection or restoration of the cerrado habitat types historically found in the region

(see the “Physiogeographic characteristics” section in the Supplementary Materials). For PL planning, the choice between restoration and protection depended on the proportion of natural habitat currently on the farm. For LL planning, we considered three cases for compliance: (i) the protection of existing natural remnants and no restoration (LL-P), (ii) the restoration of nonnatural vegetation (for example, pastures) to natural habitat types (LL-R) and no protection, and (iii) the protection and restoration of natural habitats (LL-PR). By assumption, the protection or restoration of habitat holds in perpetuity, as required by federal law. Further, because of the lack of studies on cerrado habitat types that would allow us to differentiate between different types of restoration (55), we assumed one-time investments in active restoration, instantaneous vegetation growth, and perfect and uniform restoration success for all natural habitat types (see the Supplementary Materials for further details). Thus, our results pertain to a steady-state (long-run) equilibrium; we did not model the transitional dynamics.

To calculate the additional impacts of the FC, we used a baseline scenario that modeled agricultural production in the absence of the law (that is, no habitat is protected or restored). In all of our scenarios, planning minimized the costs of environmental compliance and sugarcane production to a large commercial producer while meeting a production target.

We modeled two annual production targets—2.5 million tons (low target) and 8.5 million tons (high target)—to reflect the average current and projected sugarcane processing capacities, respectively, of sugarcane mills in Brazil (table S2). Because the results for the two targets exhibited consistent directional trends (as described in the Supplementary Materials), we present the results only for the larger production target in the main text. We quantified the long-term biodiversity, water quality, and carbon benefits from the landscapes that met the sugarcane production and FC compliance targets at the lowest cost.

Sugarcane profit modeling

The decision of where to grow sugarcane was based on a static and deterministic model that balances the revenue from growing sugarcane with the costs of production and FC compliance. We modeled the production decisions of a large agricultural producer based on a spatially explicit sugarcane production model that incorporates the revenue from sugarcane (the product of the price of sugarcane and predicted yield) and the costs associated with production (soil preparation, sowing, harvesting, fertilization, transportation, leasing, clearing, management, and transaction costs) and FC compliance (transaction, restoration, and leasing costs) (table S3). The exceptionally detailed cost data were obtained from a local commercial sugarcane producer in our study region. In our economic models, we did not consider the potential benefits to sugarcane production from natural vegetation (for example, pest control, soil fertility and stability, and water availability for irrigation) (56) because these have been traditionally very difficult to quantify and are not typically considered in status quo business decision-making. The differences in production and compliance costs between the different planning scenarios are presented in terms of NPV (in million U.S. dollars) and were calculated for a standard sugarcane production cycle of 6 years, with a discount rate of 10.32%. See the “Sugarcane production model” section in the Supplementary Materials for further details.

Land use optimization

The goal of the optimization procedure was to generate landscapes that maximized the net returns from sugarcane production subject to (i)

meeting the sugarcane production target and (ii) meeting the requirements of the FC. Under the assumption of exogenous yield, the decision variables were at the extensive margin (that is, which pixels to select for sugarcane production and FC compliance and, having allocated those, which farms to lease). We did not model decisions at the intensive margin (that is, how much sugarcane to produce on a given pixel by varying the production inputs). We used an integer programming branch-and-bound algorithm to select the pixels and farms in a static framework (57). We did not model the potential displacement of cattle ranching due to sugarcane expansion in the study area. See the “Landscape optimization” section in the Supplementary Materials for more details.

The optimization procedure generated partial landscapes that indicated which farms should be leased and, within those farms, which pixels should be allocated to sugarcane production and FC compliance or which should remain under different uses. To produce a final landscape, we used local raster tools in ArcGIS and assigned the land cover/land use currently found in the region if the pixel was not selected for sugarcane production or natural habitat for FC compliance. Where restoration of natural habitat was predicted by the optimization, we used the predicted vegetation layer (fig. S2) to assign a natural habitat type.

Biodiversity, water quality, and carbon sequestration models

We assessed the profit-maximizing landscapes under the different planning scenarios in terms of their potential to support biodiversity, water quality, and carbon storage. To quantify the expected number of mammal and bird species, we applied the model from Polasky *et al.* (58) that predicts the probabilities of species persistence based on the habitat area required for a breeding pair, the relative suitability of all land cover types, and the ability of species to disperse among patches in the landscape. Focusing on 407 terrestrial bird and 132 mammal species, we assessed how species richness, composition, and habitat specialization shift across the planning scenarios. Owing to the lack of relevant studies from our study region, we did not consider different habitat successional stages and attributed a single value per habitat type for all parameters. See the “Biodiversity modeling” section in the Supplementary Materials for further details.

To quantify the water quality benefits, we used the terrestrial nutrient and sediment models from InVEST 2.5.6 (59) and calculated the total annual predicted loadings of nitrogen (N), phosphorus (P), and sediment (S) reaching the waterways in the study area. The N, P, and S loadings were then converted into predicted concentrations and combined into a WQI (60). The WQI scale ranges from 0 to 100, with an index change of at least 10 points required for water quality status to shift between categories (very good, good, fair, poor, and very poor), depending on the starting value. See the “Water quality surface models” section in the Supplementary Materials for further details.

To quantify the long-term carbon sequestration benefits, we used values from published studies for the amount of carbon stored in above-ground and belowground biomass and soil in steady-state systems in the Cerrado biome. For each scenario, we determined the additional mean carbon storage potential per planning scenario and monetized the value of the ecosystem services using prices from the voluntary carbon market as a lower bound and recent estimates of the social value of avoiding damages from carbon emissions as an upper bound. See the “Carbon valuation” section in the Supplementary Materials for further details.

Whenever possible, all biophysical models used spatially explicit data and parameters from previous studies conducted in the biome.

We found that the predictions from our biophysical models were consistent with those from published studies on the Cerrado or deemed reasonable by expert review when studies were not available (see the Supplementary Materials for further details).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/2/7/e1501021/DC1>

Supplementary Materials and Methods
Supplementary Results

fig. S1. Study area in relation to major ecological biomes of Brazil.
fig. S2. Distributions of natural vegetation types predicted for our study area.
fig. S3. Distributions of soil types for our study area.
fig. S4. Optimized landscapes corresponding to each mitigation scenario.
fig. S5. Cost savings for LL mitigation relative to PL mitigation.
fig. S6. Sources of cost savings for LL mitigation relative to PL mitigation.
fig. S7. Area of natural habitat across the mitigation scenarios.
fig. S8. Types of natural habitat restored or protected under the PL and LL scenarios.
fig. S9. Changes in habitat fragmentation for LL mitigation relative to PL mitigation.
fig. S10. Patterns of habitat fragmentation for the different mitigation scenarios.
fig. S11. Changes in fragmentation by habitat type for LL mitigation relative to PL mitigation.
fig. S12. Changes in the expected number of bird and mammal species for LL mitigation relative to PL mitigation.
fig. S13. Changes in the expected number of species by habitat specialization for LL mitigation relative to PL mitigation.
fig. S14. Changes in the predicted carbon storage for LL mitigation relative to PL mitigation.
fig. S15. Changes in WQI for LL mitigation relative to PL mitigation.
fig. S16. Changes in the average predicted nitrogen and phosphorus concentrations and total loadings for LL mitigation relative to PL mitigation.
fig. S17. Changes in average predicted turbidity and total sediment loading for LL mitigation relative to PL mitigation.
table S1. Land cover types and definitions for the study area.
table S2. Final yield for each scenario.
table S3. Summary of the parameters used in the agricultural profit optimization models.
table S4. Definitions of the parameters used in the agricultural profit optimization equations.
table S5. Amount of habitat restored or protected under each mitigation scenario.
table S6. Fragmentation metrics for patches of all natural habitat types grouped together.
table S7. Fragmentation metrics for patches by habitat type.
table S8. Data sources used to determine relevant species by taxonomic group.
table S9. Average (\pm SD) habitat suitability values for land cover types in our study region.
table S10. Average (\pm SD) parameters by trophic level used in the biodiversity model.
table S11. Expected number of species based on the biodiversity model across mitigation scenarios.
table S12. Expected number of species by habitat specialization for each mitigation scenario.
table S13. Aggregated values for carbon storage per land cover/land use category for our study area.
table S14. Additional carbon storage provided by each mitigation scenario.
table S15. Minimum and maximum values for nitrogen (TN), phosphorus (TP), and turbidity concentrations in pristine areas in the Cerrado biome.
table S16. WQI across mitigation scenarios.
Additional Supplementary Material for this article is available at <http://nature.org/TNC-Dow-Brazil>.
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