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A Spatially Explicit Estimate of Avoided Forest Loss

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Abstract: *With the potential expansion of forest conservation programs spurred by climate-change agreements, there is a need to measure the extent to which such programs achieve their intended results. Conventional methods for evaluating conservation impact tend to be biased because they do not compare like areas or account for spatial relations. We assessed the effect of a conservation initiative that combined designation of protected areas with payments for environmental services to conserve over wintering habitat for the monarch butterfly (*Danaus plexippus*) in Mexico. To do so, we used a spatial-matching estimator that matches covariates among polygons and their neighbors. We measured avoided forest loss (avoided disturbance and deforestation) by comparing forest cover on protected and unprotected lands that were similar in terms of accessibility, governance, and forest type. Whereas conventional estimates of avoided forest loss suggest that conservation initiatives did not protect forest cover, we found evidence that the conservation measures are preserving forest cover. We found that the conservation measures protected between 200 ha and 710 ha (3–16%) of forest that is high-quality habitat for monarch butterflies, but had a smaller effect on total forest cover, preserving between 0 ha and 200 ha (0–2.5%) of forest with canopy cover >70%. We suggest that future estimates of avoided forest loss be analyzed spatially to account for how forest loss occurs across the landscape. Given the forthcoming demand from donors and carbon financiers for estimates of avoided forest loss, we anticipate our methods and results will contribute to future studies that estimate the outcome of conservation efforts.*

Keywords: avoided deforestation, matching estimators, Mexico, monarch butterfly habitat, payment for environmental services, REDD, spatial analysis

Una Estimación Espacialmente Explícita de la Pérdida de Bosque Evitada

Resumen: *Con la expansión potencial de programas de conservación de bosques estimulados por los acuerdos de cambio climático, es necesario medir el alcance de los resultados de tales programas. Los métodos convencionales para evaluar el impacto de la conservación tienden a ser sesgados porque no comparan áreas similares ni consideran relaciones espaciales. Evaluamos el efecto de una iniciativa de conservación que combinó la designación de áreas protegidas con pagos por servicios ambientales para conservar el hábitat invernal de la mariposa monarca (*Danaus plexippus*) en México. Para ello, utilizamos un estimador espacial que combina covariables entre polígonos y sus vecinos. Medimos la pérdida de bosque evitada (perturbación y deforestación evitadas) mediante la comparación de cobertura forestal en tierras protegidas y no protegidas que eran similares en términos de accesibilidad, gobernabilidad y tipo de bosque. Mientras las estimaciones convencionales de pérdida de bosque evitada sugieren que las iniciativas de conservación no protegieron la cobertura forestal, encontramos evidencia de que las medidas de conservación están preservando la cobertura forestal. Encontramos que las medidas de conservación protegieron entre 200 y 710 ha (3-16%)*

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de bosque que es hábitat de alta calidad para las mariposas monarca, pero tuvieron menos efecto sobre la cobertura forestal total, preservando entre 0 y 200 ha (0–2–5%) de bosque con cobertura de dosel >70%. Sugerimos que estimaciones futuras de la pérdida de bosque evitada deben ser analizadas espacialmente para explicar como ocurre la pérdida de bosques en el paisaje. Dada la futura demanda de estimaciones de pérdida de bosque evitada por parte de donantes y financiadores de proyectos de carbono, anticipamos que nuestros métodos y resultados contribuirán a futuros estudios que estimen el resultado de esfuerzos de conservación.

Palabras Clave: análisis espacial, deforestación evitada, estimadores pareados, hábitat de mariposa monarca, México, pago de servicios ambientales, REDD

Introduction

Conservation practitioners and policy makers need to understand the extent to which their programs succeed or fail (Ferraro & Pattanayak 2006; Kapos et al. 2008). Yet reliable estimates of the effects of conservation programs remain elusive. Conservation programs are often evaluated by comparing areas subject to a conservation effort, such as legal protection, with areas that are not affected by the effort (Naughton-Treves et al. 2005; Figueroa & Sánchez-Cordero 2008). This approach may not yield accurate results because the methods used to select protected areas may bias the comparison (Mas 2005; Andam et al. 2008; Sims 2010). Lands that are protected may be less susceptible to some types of environmental change; therefore, a comparison would overestimate the effect of protection. To overcome such biases one must consider realistic counterfactual scenarios (Ferraro 2009). We use the term *counterfactual* to describe what would have happened to a defined area in the absence of the conservation program. Policy makers use the terms *avoided deforestation* and *additionality* to describe the outcome of a conservation program relative to the counterfactual situation.

The United Nations program for Reducing Emissions from Deforestation and Degradation (REDD) pays countries for reduced carbon emissions resulting from forest protection (Harvey et al. 2010). The REDD program is predicated on the assumption that it is, or soon will be possible to, measure avoided deforestation resulting from specific policies. Calculations of avoided deforestation will have considerable effects on the payments received by countries and forest communities. Countries that can demonstrate their conservation programs effectively protect forest cover will receive financial compensation for that success. This global scheme has intensified the demand from decision makers and climate-change specialists for studies on avoided deforestation (Combes Motel et al. 2009).

Few evaluations of conservation programs have included methods that remove sources of bias or that offer convincing counterfactual scenarios. And results of the few studies in which such methods have been applied are inconsistent. In an assessment of Costa Rica's payment for environmental services (PES) program Sánchez-Azofeifa et al. (2007) used a linear regression model to compare deforestation rates in areas managed by communities that did and did not participate in PES programs and controlled for slope, distance to cities, and ecological zones. They found that deforestation rates in participating areas are not significantly lower than deforestation rates in nonparticipating areas and concluded that forests in areas with PES programs probably would have remained forest in the absence of the program. In a follow-up study, Pfaff et al. (2008) used 2 matching estimators that compared land included in a PES program with land not included in a PES program, and their findings were consistent with Sánchez-Azofeifa et al. (2007).

Results of other assessments show that conservation programs can preserve forests. Using a probit regression, Muñoz-Piña's (2010) results suggest that Mexico's Payment for Hydrological Environmental Services Program has prevented deforestation of 13,000–18,000 ha. Similarly, results of another study in which the same PES program in Mexico was evaluated show the program is associated with a 6–10% reduction in the probability of deforestation (Alix-Garcia et al. 2010). In a comprehensive, quantitative evaluation of protected areas in Costa Rica, Andam et al. (2008) compared similar forest patches inside and outside protected areas and found that approximately 10% of forest in Costa Rica's parks would have been deforested had it not been for legal protection.

These recent evaluations do not account for the relative locations of forest patches. Accounting for spatial factors is critical because forest loss does not occur everywhere with equal probability (Lorena & Lambin 2009) and decisions about where to log are a function of the larger spatial context of forest management (Alix-Garcia 2007). For example, areas are more likely to be logged if they are adjacent to deforested areas or close to logging roads (Coffin 2007). Therefore, we estimated the effect of conservation measures on protected forest when accounting for the characteristics of neighboring forest.

We estimated avoided forest loss (avoided disturbance plus deforestation) that resulted from the enlargement of a protected area when combined with a PES program. These conservation efforts were jointly designed and implemented by the Mexican federal government and a coalition of conservation organizations in late 2000 with the objective of protecting the overwintering habitat of the monarch butterfly (*Danaus plexippus*).

Every autumn (September to November), millions of monarch butterflies migrate to a few mountain tops in central Mexico that contain the forest and climate conditions necessary for their winter survival (Brower et al. 2008). This migration motivated UNESCO (United Nations Educational, Scientific and Cultural Organization) to list the Monarch Butterfly Biosphere Reserve as a World Heritage Site in 2008 (UNESCO 2009). Intact forest cover at the overwintering sites protects the butterflies from precipitation, wind, and cold (Calvert & Brower 1981). Wet monarch butterflies have a higher probability of mortality from freezing, which means forest canopy is critical to the butterflies' survival (Anderson & Brower 1996).

Legal protection of the overwintering sites began in 1986, when the Mexican government outlawed logging in 4514 ha. By the late 1990s, experts on the species proposed enlarging the reserve because critical habitat for the butterflies remained unprotected and had a high probability of being logged (Missrie & Nelson 2007). These experts designed an expansion of the reserve on the basis of watershed boundaries, slope, elevation, and aspect. In 2000 the Mexican government used their design as a template for expanding the reserve to 56,259 ha; logging was prohibited in 13,551 ha.

The legal protection of additional monarch butterfly habitats in 2000 was accompanied by a financial incentive for communities to abstain from felling timber. The Monarch Butterfly Conservation Fund is a PES scheme that pays landowners who lost timber rights (Missrie & Nelson 2007). The fund was created with a US$5 million grant from the David and Lucile Packard Foundation that was later matched by contributions from the Mexican federal and state governments. The fund is managed by WWF Mexico and the Mexican Fund for the Conservation of Nature. After 10 years of operation, the fund has disbursed US$3.3 million to participating forest communities. Communities are paid between US$10 and $12/ha of conserved forest and $18/m^3 of forfeited timber. The program has monitored changes in forest cover to inform payment decisions, and, when necessary, withheld payment from noncompliant communities (Honey-Rosés et al. 2009).

Both the PES program and the protected area were designed to reverse a trend of rapid deforestation and disturbance. We define *deforestation* as the conversion of forest to a nonforest land cover and *disturbance* as a reduction in the percent cover of the forest canopy (FAO 2004). In Mexico approximately 0.25% and 0.7–3.5% of temperate forests are being deforested and disturbed per year, respectively (Mas et al. 2004). In the Monarch Butterfly Biosphere Reserve deforestation rates are 0.1%/year (Ramírez et al. 2003; Figueroa & Sánchez-Cordero 2008) and forest disturbance is between 1.3% (Ramírez et al. 2003) and 3.2%/year (Brower et al. 2002).

Methods

Study Area

To estimate avoided forest loss (avoided deforestation and disturbance) while accounting for the spatial dynamics of deforestation and disturbance, we modified a method used in the social sciences that applies matching estimators (Abadie & Imbens 2006) to isolate the causal relation between a program and its outcome. This method has been used to evaluate the effect of conservation programs on forest cover and poverty (Sims 2010; Andam et al. 2010).

We analyzed deforestation and disturbance in a 343,249-ha region surrounding the Monarch Butterfly Biosphere Reserve in central Mexico (Fig. 1). This area is part of the Mexican Neovolcanic mountain range and characterized by coniferous (*Abies, Pinus,* and *Cuppressus*) and broad-leaved trees (*Quercus, Alnus,* and *Arbutus*). In the absence of disturbance, these forests are dense (>70% canopy cover) (Madrigal 1967; Giménez et al. 2003). The area covers 12 municipalities in the states of Michoacan and Mexico. Ownership of the reserve is divided among over 100 community-owned properties (hereafter *ejidos*) and indigenous, private, and government properties.

Spatial Data

We generated a spatial dataset of unique forest units (polygons) in a geographic information system (ESRI ArcMAP 9.3) by overlaying attributes from 4 data layers: property boundaries, land cover class in 1986, protected-area boundaries in 1986 and 2000, and municipal boundaries (Supporting Information). We intersected these layers to create a mosaic of 9441 polygons of irregular size and shape, each representing a stand of trees or vegetation in a specific human community and under specific conservation regulations. Thus, our spatial unit of analysis diverges from other assessments in which uniform cells were selected randomly from a grid (e.g., Sánchez-Azofeifa et al. 2007; Andam et al. 2008; Muñoz-Piña 2010). Use of regularly shaped cells from a grid as the unit of analysis is disadvantageous in that different property owners, forest attributes, or other features might occur within a single cell. Our approach allowed us to create counterfactual scenarios that controlled for factors owners are likely to consider when making timber-harvesting decisions such as species composition, tree density, elevation, slope, aspect, road access, and protection status. Therefore we believe our unit of analysis more closely reflects the decision-making unit of a forest owner.

Measures of Forest Change

We used 2 measures of forest change per polygon: percent conserved forest (>70% canopy cover) and percent

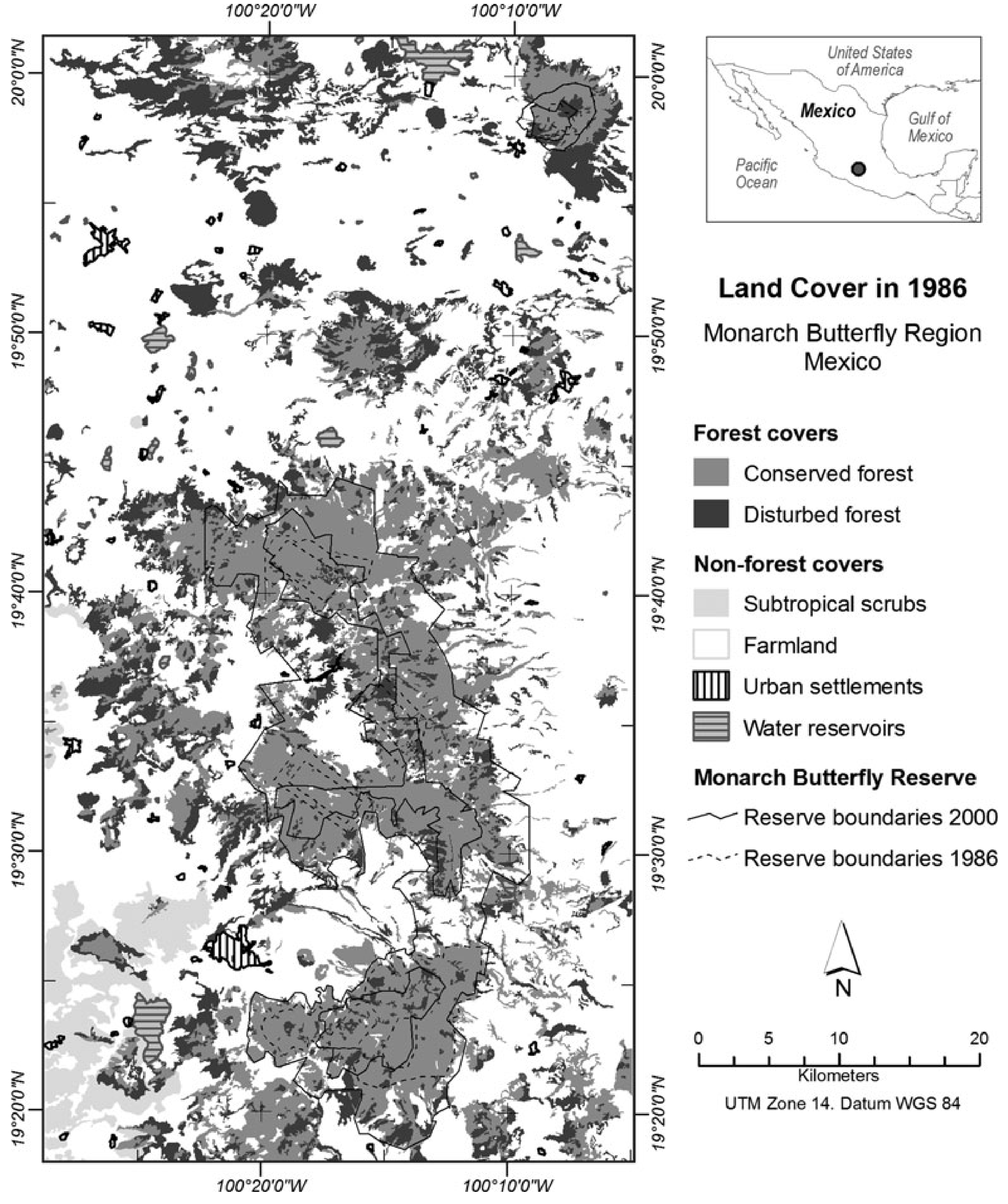

Figure 1. Land cover in the study area surrounding the Monarch Butterfly Biosphere Reserve in our baseline year of 1986.

forest cover (conserved forest + disturbed forest). We based these canopy-cover thresholds on dominant tree species and tree density in 1986 (Madrigal 1967) and on FAO's (Food and Agriculture Organization) classification scheme for tropical forests (FAO 1996). These continuous variables capture more information than a binary measure of forest and nonforest. Furthermore, given that much of this region is selectively logged, a binary measurement of forest would underestimate changes in landcover. For each polygon, we calculated changes in the percent conserved forest and percent forest cover with data from Ramírez et al. (2007, 2008). We restricted our analyses to polygons that were forest in 1986 and larger than 0.1 ha, which left us with 4623 polygons covering 97,409 ha.

We compared conserved forest and forest cover in 1986 with conserved forest and forest cover from 1993 to 2009. We selected 1993 as our measure of deforestation before the program to avoid capturing deforestation conducted in anticipation of possible logging restrictions. We weighted each polygon by its land area.

Models

We defined treatment polygons as forested areas with legal protection that were part of the PES program. Control polygons were forested areas not subject to the legal protection or the PES program (Fig. 2b). We did not include polygons subject to only legal protection or the PES program in our analyses. Excluded polygons included government properties not eligible to receive PES payments and polygons whose owners did not participate in the PES program. Our final data set consisted of 425 treatment polygons (8472 ha) and 3778 control polygons (79,305 ha) (median = 5.44 ha; mean = 20.81 ha; minimum = 0.1; maximum = 1443 ha) (Fig. 2a).

MODEL 1: DIFFERENCE IN DIFFERENCES

We used 4 approaches to estimate avoided forest loss associated with legal protection and PES. First, we conducted a simple difference in differences (DinD) comparison between treatment and control polygons. This method allowed us to control for time-specific changes (e.g., fluctuating timber prices or national conservation policies) that affected treatment and control polygons equally. It also let us control for unobserved characteristics that differed between treatment and control polygons but did not change during the study. Our assumption in the difference-in-differences approach was that the treatment and control polygons have equal changes in deforestation and disturbance over time in the absence of the treatment. This method may produce biased results if control polygons are systematically different from treatment polygons (Ferraro 2009).

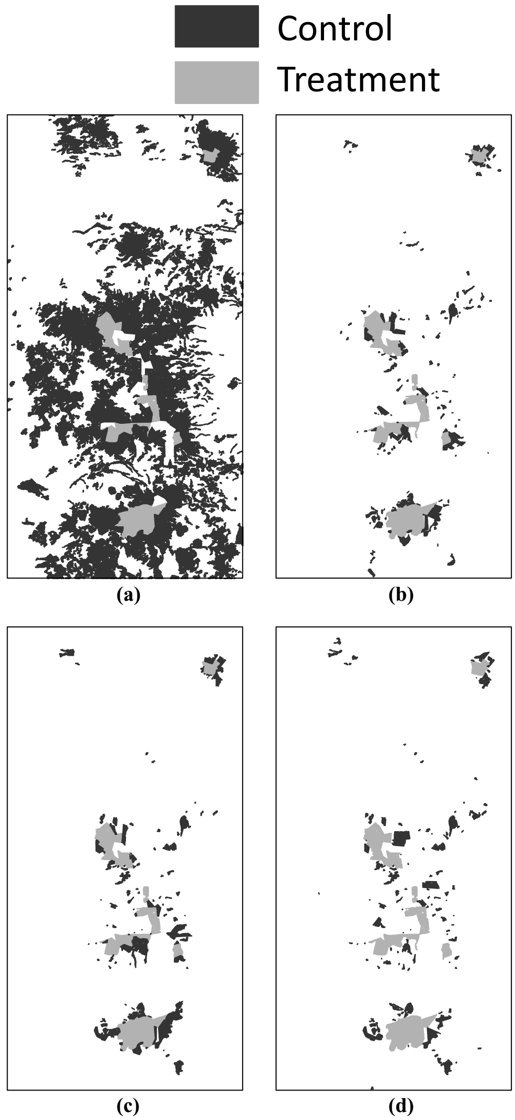

Figure 2. Treatment and control polygons used to estimate avoided deforestation (conversion of forest to nonforest land cover) and forest disturbance (reduction of canopy cover below 70%) resulting from the protected area and PES program in (a) model 1 (difference-in-difference comparison of means before and after in treatment versus control polygons), (b) model 2 (treatment and control polygons matched over their own covariates), (c) model 3 (treatment and control polygons matched over their own and their neighboring covariates), (d) model 4 (matching process in model 3 but without control polygons adjacent to the treatment area).

MODEL 2: MATCHING ESTIMATORS

To control for differences in the physical and governance characteristics of our forest polygons, we used a matching estimator (Abadie & Imbens 2006). The matching process paired polygons with similar, time-invariant characteristics representing accessibility (polygon size, slope, aspect, elevation, and distance from perimeter to the nearest road); forest type (dominant tree species and tree density in 1986); governance (ownership: ejido, private, indigenous community; state: Michoacan or Mexico), and existence of land-use restrictions prior to 2000. For example, to identify a counterfactual scenario for a south-facing polygon of pine at 2500-m elevation in the reserve,

Table 1. Mean (SE) values of model variables for treatment and control groups across 4 models of avoided forest loss.

		Control polygons			
Covariate	*Treatment polygons*	*model 1 difference in differences*	*model 2 matching*	*model 3 spatial matching*	*model 4 spatial matching without spatial bias*
Conserved forest (%)	0.87	0.68 (6.70)	0.87 (−0.19)	0.89 (−0.70)	0.89 (−0.83)
Slope (%)	39.07	33.35 (7.61)	38.99 (0.11)	38.90 (0.23)	39.80 (−1.00)
Elevation (m)	2990	2601 (19.69)	2951 (2.60)	2959 (2.09)	2914 (5.38)
Mean distance from perimeter of polygon to roads (m)	5685	4633 (5.33)	5446 (1.51)	5698 (−0.08)	5555 (0.79)
Aspect (°)	194	191 (1.10)	188 (1.89)	190 (1.47)	189 (1.62)
Pine cover (ha)	35.56	117.69 (−7.13)	24.64 (2.81)	30.23 (1.20)	30.29 (1.34)
Fir cover (ha)	69.78	23.01 (8.09)	54.32 (2.41)	41.56 (4.60)	37.06 (5.35)
Indigenous ownership[b]	0.31	0.07 (9.26)	0.31 (0.00)	0.31 (0.08)	0.26 (1.46)
Private ownership[b]	0.08	0.06 (1.11)	0.08 (0.00)	0.08 (0.11)	0.08 (0.09)
Michoacan	0.66	0.64 (0.53)	0.65 (0.20)	0.67 (−0.31)	0.61 (1.46)
Core and buffer 1986	0.70	0.08 (24.07)	0.69 (0.26)	0.68 (0.41)	0.63 (2.16)
Spatial W[a] agriculture (ha)	0.38	254.77 (−5.64)	16.11 (−2.00)	5.22 (−5.94)	9.39 (−9.50)
Spatial W slope (%)	36.11	26.62 (15.88)	35.82 (0.47)	35.78 (0.56)	35.83 (0.47)
Spatial W elevation (m)	2982	2580 (20.00)	2936 (3.10)	2934 (3.28)	2904 (5.66)
Spatial W pine (ha)	19.05	23.97 (−1.35)	26.96 (−2.78)	24.29 (−2.61)	26.58 (−3.91)
Spatial W fir (ha)	25.32	6.27 (11.21)	32.75 (−3.29)	22.65 (1.31)	23.84 (0.71)
Spatial W aspect (°)	186	178 (3.45)	177 (3.75)	183 (1.32)	181 (2.14)
Spatial W unit area (ha)	45.81	300.58 (−5.63)	77.77 (−3.80)	53.94 (−2.98)	61.95 (−6.23)

[a] *Spatial W are mean values of the covariate for neighboring polygons from a queen spatial weights matrix, which defines neighboring polygons as those that share a continuous boundary.*
[b] *Binary variable.*

the estimator identified the polygon that best matched those characteristics from among the set of control polygons outside the reserve. We then compared the level of deforestation and disturbance between the matched polygons to estimate the effect of the program. We assessed the quality of the matches by comparing summary statistics of the covariates of our treatment polygons and the selected controls (Table 1). When covariates in treatment and control units are very similar, the matching process mimics random assignment of treatment and control categories ex post facto (Ho et al. 2007).

We sought appropriate matches only for our treatment polygons and did not force the estimator to find matched treatment polygons for all control observations. We matched at least 5 controls to each treatment polygon to prevent our results from being driven by idiosyncratic matches and used the bias correction developed in Abadie and Imbens (2006) to control for match fit. The bias adjustment estimates the effect of covariates on the expected outcome with linear regression and corrects for differences in the covariates for each matched pair with the estimated coefficients.

MODEL 3: SPATIAL MATCHING

We expected forest loss to be influenced by the physical attributes of neighboring polygons in addition to the characteristics of the polygon itself. To test for spatial correlation we used Moran's I. We then refined our estimate of avoided forest loss by including spatially weighted covariates to account for spatial spillovers (forest loss occurring in neighboring polygons). We created a weights matrix in a spatial-statistics software package (Open GeoDa 0.9, GeoDa Center for Geospatial Computation and Analysis, Tempe, Arizona) that identifies the set of polygons that share a boundary. The software uses the weights matrix to quantify the attributes of neighboring polygons for each treatment polygon. Because deforestation is not restricted to polygon boundaries, we used a queen contiguity-based spatial weights matrix to calculate the characteristics of all neighboring polygons (i.e., the spatial covariates). Our spatial covariates were the average hectares of adjacent agricultural land, fir and pine forest, and the slope and elevation of neighboring polygons. The spatial-matching model compared polygons with respect to the spatial variables and the characteristics included in model 2.

MODEL 4: SPATIAL MATCHING WITHOUT SPATIALLY BIASED CONTROLS

The protection of one area may mean environmentally damaging human activities that occur elsewhere. This process has been referred to as "leakage" (Engel et al. 2008). If leakage were occurring, our control polygons adjacent to treatment polygons would have an increased probability of deforestation or disturbance (Supporting Information). Therefore, in model 4, we removed control polygons where forest changes could be affected by their proximity to the reserve. A leakage effect could lead us to overestimate the effect of a conservation policy. But the proximity of control polygons to the reserve could cause the opposite effect as well. Communities may be hesitant to log near a protected area if the boundaries of protection are undefined and logging near the protected area may disqualify them from receiving conservation payments. Regardless of the direction of the bias, we did not expect control polygons adjacent to treatment polygons to be unaffected by protection measures in a neighboring polygon. To correct for this bias, we ran a spatial-matching model that removed control polygons that bordered treatment polygons.

To assess the quality of our estimates, we compared the covariates' balance between control and treatment polygons throughout our modeling progression (Table 1). We also tested that our results were robust to modeling assumptions pertaining to the number and quality of matches and to temporal specifications. Because the covariate balance can change from model to model, we selected a fixed goodness-of-fit level that corresponded to the 95th percentile of matches in model 2, our least restrictive matching model. We then recalculated the estimated effect of the combined PES programs and logging ban for each model by removing polygons for each model for which any matches had goodness-of-fit values that were less than this fixed level. In a second test of robustness, we excluded the 5% poorest matches on the basis of covariate balance. To ensure that repeated use of some polygons as controls did not bias our estimates in favor of the initiative, we inspected the control polygons used repeatedly as matches. We also ran the model matching with 1 and 2 control polygons to each treatment. We also tested various temporal specifications. We compared the average percent forest cover for all periods, before 1993 & 2000 and after the creation of the protected area and PES program (2003, 2006, and 2009). As a test of robustness of the matching approach, instead of comparing the average difference between the paired polygons, we regressed the percent forest and percent conserved forest on our covariates using the control groups generated by our matching estimators.

Results

In the difference-in-differences comparison (model 1) neither legal protection nor the PES program were associated with the maintenance of forest cover. To the contrary, logging was more intense in treatment polygons following the implementation of conservation measures, with 11% more disturbance and almost 6% more deforestation inside treatment areas (Table 2). This comparison erroneously assumed that treatment and control polygons were the same in terms of accessibility, forest type, and governance (Table 1).

In the comparison of similar forest polygons (model 2), there was 4.8% more disturbance and 6.5% more deforestation in treatment polygons than in control polygons. However, model 2 still did not account for the spatial relation between forest polygons.

In the spatial model (model 3), deforestation was correlated with the percentage of deforestation in neighboring polygons at a 0.001% level of significance. Once we accounted for the spatial relation between forest polygons in model 3, treatment polygons showed a 3.3% increase in conserved forest relative to the counterfactual scenario. However, these same areas did not differ significantly in deforestation relative to the counterfactual scenario (−0.5%).

When we eliminated spatially biased control polygons (model 4), treatment polygons were associated with higher levels of conserved forest and total forest protection and with an 11.6% decrease in disturbance and a 2.6% decrease in deforestation (Table 2 & Fig. 3), although only the reduction in disturbance was significantly different from zero. This result implies that over 700 ha of

Table 2. Estimated avoided forest loss under different estimation models (SE).

	Model 1 difference in differences	*Model 2 matching*	*Model 3 spatial matching*	*Model 4 spatial matching without spatial bias*
Avoided disturbance[a]	−11.0 (0.1)	−4.8 (2.9)	3.3 (3.9)	11.6 (5.0)
Avoided deforestation[b]	−5.9 (0.1)	−6.1 (1.5)	−0.5 (1.8)	2.6 (2.1)
Avoided disturbance (ha)	−673.7 (6.4)	−292.1 (179.3)	204.4 (239.9)	711.2 (306.8)
Avoided deforestation (ha)	−444.4 (4.0)	−457.3 (110.6)	−35.8 (133.9)	198.2 (155.2)
Number of polygons	4203	4203	4203	4009
Average distance between matched treatment and control[c]	NA	2.15	5.67	6.83

[a] *Percentage of 2009 forest with canopy cover >70%.*
[b] *Percentage of 2009 forest cover.*
[c] *Sum of the weighted difference in the covariates between each matched treatment and control polygon; reflects a measure of the covariate balance and is inherently smaller when matching over fewer covariates.*

conserved forest would have been disturbed and 198 ha would have been deforested without the conservation initiative. Model 4 showed that the conservation measures protected between 200 and 710 ha, or between 3% and 16% of forest with >70% canopy cover, but had a smaller effect on total forest cover, preserving between 0 and 200 ha (2.5%).

The covariate balance in model 2 was more balanced than in model 1 (Table 1). We also saw that model 2 accurately identified control polygons with characteristics that matched the characteristics of treatment polygons, but did not match polygons within the spatially weighted covariates. The spatial-matching estimator in model 3 corrected for this difference. In contrast, the covariate balance was lower in model 4.

When we removed matches that were not in the 95th percentile of the matches in model 2, we found our estimated difference in deforestation and forest disturbance was essentially unchanged (Supporting Information). When we excluded the 5% poorest matches, we

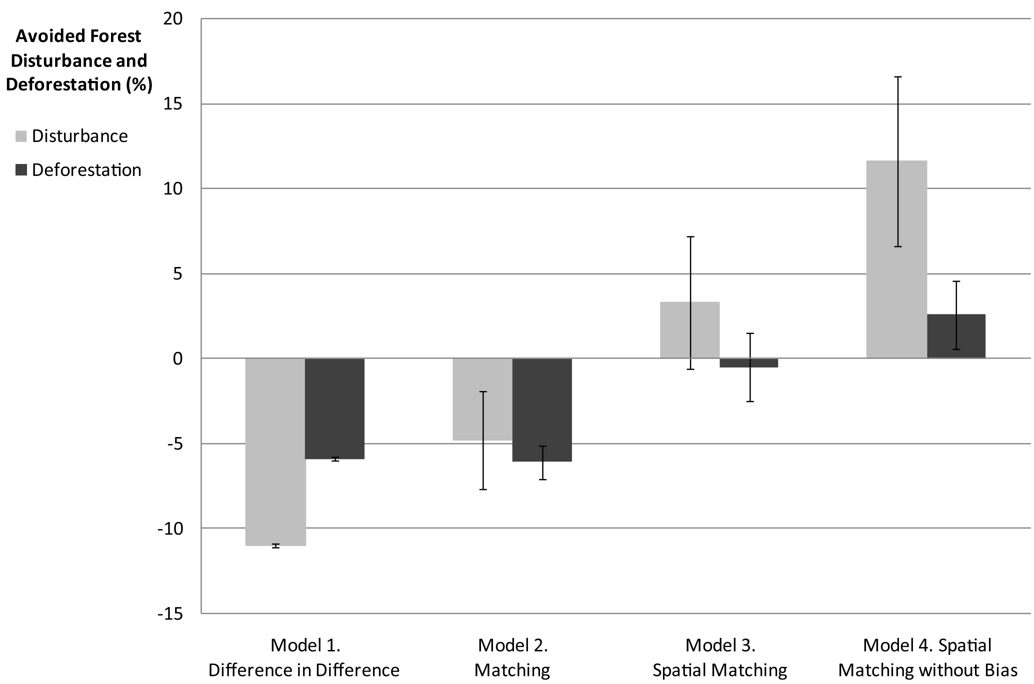

Figure 3. Estimates of avoided deforestation (conversion of forest to nonforest land cover) and avoided forest disturbance (reduction of canopy cover below 70%) resulting from the legal protection and payment for environmental services program in the Monarch Butterfly Biosphere Reserve. Lines extending out from bars are standard errors.

again found the estimated difference in deforestation and forest disturbance was qualitatively unchanged. Polygons used repeatedly as matched controls did not include heavily deforested areas (Fig. 2). In addition, estimated deforestation and disturbance were not substantially different when we matched 1 and 2 polygons to each treatment polygon.

When we used all years in our analysis, we observed a similar pattern of effects in that the conservation effect increased when we incorporated spatial considerations (Supporting Information). Due to a smoothing effect, the estimated effect of the program was slightly smaller when we used the average over all years. When we performed a linear regression, the effects of treatment on forest loss were similar to what we observed in our matching models (Supporting Information).

Discussion

We found evidence that the combination of legal protection and financial incentives has helped protect forest habitat for the monarch butterfly in Mexico. Although 9% of areas with a logging ban have been deforested since 1993 and 15% of the forest with dense canopy has been lost, without the joint conservation initiative, those losses would have been almost 3% and 11% higher respectively (Fig. 4). We believe model 4 represented the most accurate estimate of the conservation program's effectiveness because it removed potentially biased control polygons. At the same time, we expected lower covariate balance in model 4 because the elimination of polygons was not random. Rather, control polygons affected by leakage are, by definition, neighbors of treatment polygons and therefore more likely to have similar features. Potential bias introduced by differences in covariates between treatment and control polygons was also corrected by the bias-adjustment procedure.

Our assessment captured how deforestation and disturbance occurred across the landscape. We believe spatial covariates should be included in evaluations of conservation programs because the location of deforestation is a function of ecological and management characteristics in neighboring forest areas. Including characteristics of neighboring polygons significantly changed the estimated conservation effect, and excluding control

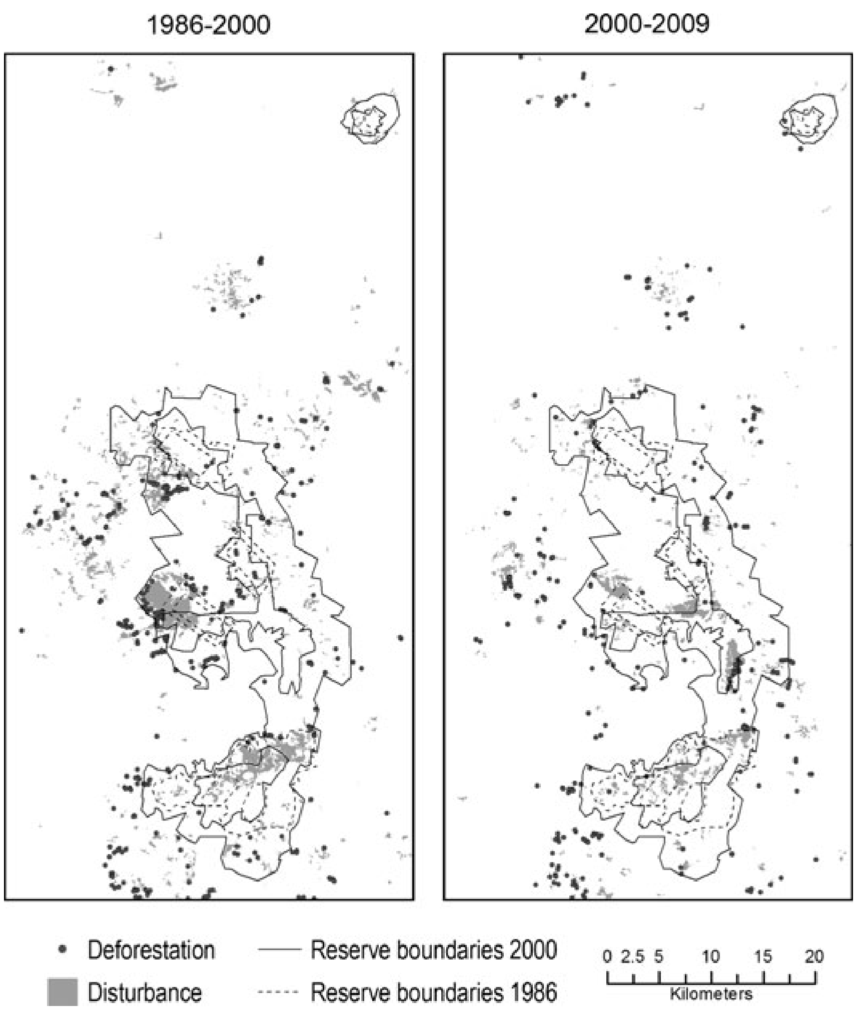

Figure 4. Observed deforestation and disturbance in the study area surrounding the Monarch Butterfly Biosphere Reserve in Mexico.

polygons that were biased by their location further affected results. The relatively larger estimate of avoided forest loss in model 4 suggests that the reserve helped conserve adjacent forest. It appeared that areas adjacent to treatment polygons contained preserved forest; thus, we observed what has been called negative leakage. Possible reasons for the conservation spillover include ambiguously marked reserve boundaries and increased monitoring.

Our research differs from existing evaluations of conservation programs because our study area is under considerable logging pressure, rather than pressure from agricultural expansion or livestock grazing. The high level of deforestation and disturbance in the reserve suggests that the protection measures targeted lands with a high probability of logging, not areas of low economic value for logging, as has been the case with many protected areas (Andam et al. 2008) and PES programs (Sánchez-Azofeifa et al. 2007). Thus, unlike conservation areas where logging pressure is low, in this region, simple inside-outside comparisons would under estimate the program's effectiveness.

We also focused on a relatively small geographic region. This extent of analysis allowed us to control for community and polygon characteristics. In addition, we captured both deforestation and disturbance dynamics. We propose that the discussion on avoided deforestation shift to avoided forest loss, which we define as the sum of avoided disturbance and deforestation. Avoided forest loss provides a more accurate measure of carbon content and preservation of forest ecosystems. Relying on only avoided deforestation as a measure of conservation underestimates total forest change (Htun et al. 2010). We also considered the effect of a PES program and legal protection as a single joint treatment. Evaluating the effect of these measures together is likely to become more common in the future.

One limitation of our study is that we were unable to account for community governance when devising our estimate of avoided forest loss. We ran a spatial-matching model that removed communities that did not adhere to the program and found considerable improvements in program effectiveness (Supporting Information). We interpret this as evidence that community dynamics and a community's ability to enforce its decisions has a large effect on the effectiveness of the conservation program (Honey-Rosés 2009). Thus, we suspect that deforestation may reflect weak community governance rather than merely the outcome of biophysical characteristics (Klooster 2000). We believe work is needed to understand how communities can take effective collective action through trust building, governance, and social capital (Agrawal 2001). Our estimate of avoided forest loss, although useful, does not capture many of these social dynamics that may help explain ecosystem change.

The sparse number of evaluations of conservation initiatives contrasts with the growing demand for research of this type. For example, the successful implementation of REDD will depend on methods that can quantify the avoided forest loss resulting from a set of policy interventions. Yet it remains unclear how countries will establish reliable counterfactual scenarios to estimate avoided forest loss (Combes Motel et al. 2009; Oestreicher et al. 2009). Nevertheless, implementation of REDD is moving forward. Norway has committed US$1 billion to purchase avoided deforestation credits from Indonesia under the REDD framework (CIFOR 2010), and experts are planning for billions more to be transferred to nations that can demonstrate reduced carbon emissions through forest protection (Harvey et al. 2010). Furthermore, REDD payments will rely on quantitative assessments of counterfactual scenarios regardless of the particular forest-protection strategy chosen by the national government, be it traditional protected areas, financial incentives, or community forestry. Each intervention must produce reliable estimates of how much forest was protected as a result of the policy.

We have observed a gap between the speed and extent of REDD implementation globally and the ability of policy makers to made credible decisions about whether countries have fulfilled their conservation commitments. Our results suggest that accurate estimates of avoided forest loss (e.g., additionality) will require the careful estimation of counterfactual scenarios that consider the physical characteristics of a forest polygon and its surrounding spatial context. Common evaluation methods that do not incorporate spatial covariates are likely to present misleading results, which, if used in a program such as REDD, could lead to an inefficient distribution of financial resources and complicate one's ability to know whether environmental targets have been achieved.

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Supporting Information

A description of the spatial data (Appendix S1), more details on leakage (Appendix S2), the matching method (Appendix S3), additional results (Appendix S4), and more details on robustness tests (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries should be directed to the corresponding author.

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