Quantifying causal mechanisms to determine how protected areas affect poverty through changes in ecosystem services and infrastructure

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To develop effective environmental policies, we must understand the mechanisms through which the policies affect social and environmental outcomes. Unfortunately, empirical evidence about these mechanisms is limited, and little guidance for quantifying them exists. We develop an approach to quantifying the mechanisms through which protected areas affect poverty. We focus on three mechanisms: changes in tourism and recreational services; changes in infrastructure in the form of road networks, health clinics, and schools; and changes in regulating and provisioning ecosystem services and foregone production activities that arise from land-use restrictions. The contributions of ecotourism and other ecosystem services to poverty alleviation in the context of a real environmental program have not yet been empirically estimated. Nearly two-thirds of the poverty reduction associated with the establishment of Costa Rican protected areas is causally attributable to opportunities afforded by tourism. Although protected areas reduced deforestation and increased regrowth, these land cover changes neither reduced nor exacerbated poverty, on average. Protected areas did not, on average, affect our measures of infrastructure and thus did not contribute to poverty reduction through this mechanism. We attribute the remaining poverty reduction to unobserved dimensions of our mechanisms or to other mechanisms. Our study empirically estimates previously unidentified contributions of ecotourism and other ecosystem services to poverty alleviation in the context of a real environmental program. We demonstrate that, with existing data and appropriate empirical methods, conservation scientists and policymakers can begin to elucidate the mechanisms through which ecosystem conservation programs affect human welfare.

parks | mediator | impact evaluation | quasi-experimental | matching

Scholars and practitioners have begun to more carefully assess the causal effects of ecosystem conservation programs on environmental and social outcomes (e.g., land cover and local livelihoods; reviews in refs. 1–5) and how these effects vary spatially (6, 7). However, we still know very little about why these effects occur or fail to occur (8).

Consider, for example, a bulwark of ecosystem conservation: the creation of protected area networks, like parks and reserves. Governments often establish these networks on marginal lands in rural areas where poor households reside (9–12). The effects of protection on poverty in neighboring communities are thus a subject of much concern and debate (text and references in refs. 12 and 13). Recent studies have estimated that protected areas reduced poverty in neighboring communities in Bolivia, Costa Rica, and Thailand (12, 14, 15). These studies, however, do not elucidate the specific mechanisms through which the protected areas reduced poverty.

Understanding the mechanisms through which environmental programs work is crucial for sustainability science and practice. Armed with such knowledge, decision makers can design programs that foster the mechanisms that alleviate poverty and mitigate the mechanisms that exacerbate poverty. The ecosystem conservation literature, however, offers little guidance on how to empirically estimate the impacts of these mechanisms. To show how the causal mechanisms of protected areas (or of any environmental program) can be identified, we use data from Costa Rica and quantify the proportion of Andam et al.'s (12) estimated poverty reduction that can be attributed to changes in infrastructure, tourism services, and other ecosystem services.

Ecosystem services are important in the lives of the rural poor (16, 17), and some have proposed that there may be strong links between protecting ecosystem services and sustainable development (18). In an essay on the relationship between ecosystem conservation and the Millennium Development Goals, the authors argue that, "[a]ction is urgently needed to identify and quantify the links between biodiversity and ecosystem services on the one hand, and poverty reduction on the other" (ref. 19, p. 1502). We agree, but argue that the focus should not be on poverty's links to biodiversity and ecosystem services per se, but rather on poverty's links to programs that aim to maintain or enhance biodiversity and ecosystem services. Although studies have tried to estimate the value of ecosystem services to the poor (for example, references in refs. 17 and 20), these studies do not measure the impacts of changes in ecosystem services that result from actual policies and programs.

Conservationists cannot induce changes in ecosystem services by magic; they must use policies and programs. There is a difference between the statements "poor people depend on ecosystem services" and "poor people would be better off with a specific conservation program" (ref. 21, p. 1137). Poor people may indeed derive value from ecosystem services, but a protected

Significance

Scholars are accumulating evidence about the effects of environmental programs on social outcomes. Quantifying these effects is important, but to design better programs we need to understand how these effects arise. Little is known about the mechanisms through which ecosystem conservation programs affect human welfare. Our study demonstrates that, with existing data and appropriate empirical designs, scientists and policymakers can elucidate these previously unidentified mechanisms. We estimate how Costa Rica's protected area system reduced poverty in neighboring communities. Nearly two-thirds of the impact is causally attributable to opportunities afforded by tourism. The rest is attributable to unobserved mechanisms. Changes in infrastructure or land cover contributed little, on average, to poverty reduction.

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area program, for example, may affect the poor very differently than a payment for environmental services program would affect them. The effects may differ because the programs operate through different mechanisms or affect the same mechanisms to different degrees. Our study seeks to measure the poverty impacts of changes in ecosystem services that result from an actual conservation program.

Our study also measures the contribution to poverty alleviation from protected area-based ecotourism at a national scale. In December 2010, the United Nations General Assembly unanimously adopted a resolution stating that "ecotourism can … contribute to the fight against poverty, the protection of the environment and the promotion of sustainable development." [Resolution 65/173, entitled "Promotion of ecotourism for poverty eradication and environment protection" (http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/65/173).] However, the hypothesis that nature-based tourism can benefit the rural poor has been vigorously debated (9, 10, 22–25), and the empirical evidence for or against it is weak. In one review, the authors note that "there is no way to know the extent of changes in poverty … that can be attributed to a specific ecotourism project because none of the studies provided baseline measures or established specific causal mechanisms to relate the implemented program with observed outcomes" (ref. 8, p. 21). Our study does both.

Mechanisms

Andam et al. (12) estimate that the establishment of protected areas before 1980 in Costa Rica caused a 16% reduction in poverty in neighboring census tracts by the year 2000 (12). We decompose this impact into its constituent mechanism effects; i.e., we clarify the causal pathways through which this reduction in poverty was achieved. We consider three of the most widely hypothesized mechanisms.

Tourism and Recreational Services. The provision of tourism and recreational services is a widely cited mechanism through which protected areas could affect the poor (9, 10, 22–24, 26). The empirical evidence for or against ecotourism's poverty-reducing powers typically comprises selective accounting of jobs lost and gained, expenditures made, or local prices changed. Such accounting, however, cannot hope to capture the myriad direct and indirect channels through which ecotourism can affect poverty (it will also often capture the effects of other mechanisms). No study has tried to estimate the causal effect on poverty in the communities around protected areas from the additional tourism caused by protection.

Costa Rica's stable government, rich biodiversity, and protected area system make the country a popular destination for ecotourists (27). Approximately half of its international tourists visit a protected area (28). Indirect evidence for the potential poverty-reducing effects from Costa Rican ecotourism comes from three sources. First, a review of ecosystem service valuation studies found that over half of the well-designed tourism and recreational service studies were from Costa Rica (2). Each study estimated substantial economic value, albeit not directly for the poor. A second study estimates that reductions in poverty from the establishment of protected areas were largest at intermediate distances from cities, where one finds the national parks that receive the most tourists (6). A third study estimates that workers near park entrances work in higher-paid, nonagricultural activities than workers in similar communities farther from park entrances (29). Despite these suggestive results, other studies have questioned whether ecotourism in Costa Rica has much local development benefit (30).

We cannot observe changes in tourism services directly and instead must identify a strong correlate of them. Our correlate is the establishment of a formal entrance for the protected area. In other words, we assume that poverty-relevant increases in tourism activity arise only after the establishment of a formal entrance through which tourists can pass. We believe this assumption is reasonable because an estimated 96% of visitors to protected areas in 2007 visited a protected area with a formal entrance (Table S1) (see *SI Text* for an explanation of why recent visitation data cannot be used).

Other Ecosystem Services. By restricting land cover change, protected areas may maintain or enhance other ecosystem services, such as pollination or hydrological services (31, 32), which are important in the lives of the rural poor (16, 17, 19). However, these same restrictions can also have detrimental effects on the poor. For example, they stop profitable agricultural and forestry activities and enable wildlife-related crop damage and depredation of livestock (20, 33).

We cannot observe the individual effects, salutary or detrimental, that arise from forest use restrictions. Instead we estimate the net effect on poverty from the changes in forest cover caused by protection between 1960 and 1986. This net effect is policy relevant: It matters little to the poor if they benefit from some changes in ecosystem services caused by restrictions on forest use if the net effect of the restrictions is an increase in poverty. [Although we believe that future studies should attempt to decompose this mechanism into its constituent mechanisms, doing so may be difficult if protected areas' effects on the constituent mechanisms are highly correlated (e.g., when one observes large impacts on hydrological services, one also observes large impacts on pollination services and foregone agricultural production).]

Infrastructure. Protected areas can affect poverty through mechanisms other than changes in ecosystem services. The most plausible mechanism is changes in infrastructure. Infrastructure may be enhanced or blocked by the establishment of protected areas. For example, protected area rules may limit road development in an area or, because of anticipated needs by law enforcement or tourists, they may encourage road development. Road networks are important because they greatly affect the costs of inputs, outputs, and consumption goods for the rural poor (34). They are also a good indicator of the broader level of infrastructure development. [Based on the World Bank's 2009 World Development Indicators (http://data.worldbank.org/indicator), the correlations between paved road networks (percentage of country) and access of rural populations to improved water sources (percentage of population), access to improved sanitation services (percentage of population), access to mobile phones (subscriptions per 100 people), and access to electricity (percentage of population) are 0.67, 0.72, 0.53, and 0.68, respectively.] We use changes in roadless volume (35) between 1969 and 1991 to capture the impact of protected areas on road infrastructure. Higher values of roadless volume imply a smaller road network within a given area (i.e., less infrastructure).

Our three mechanism variables do not capture all possible mechanisms or even all dimensions of our three hypothesized mechanisms. Roads could, for example, be improved through improved surfacing, which may or may not be strongly correlated with roadless volume. Levels of ecosystem services, to cite another example, are affected by more than just changes in forest cover, and tourism and recreational opportunities are surely not completely captured by the presence of a park entrance. We do not, however, need an exhaustive set of mechanism variables. Our design, which is described in greater detail in the next section, decomposes the total treatment effect into the three mechanism effects and the effect of unidentified mechanisms. This latter effect includes effects from other mechanisms and from dimensions of our three mechanisms that are not captured by changes in park entrances, forest cover, or roadless volume.

Study Design

To measure poverty, Andam et al. (12) create an asset-based poverty index from the 1973 and 2000 Costa Rican censuses. To measure the effect of protected areas on this index, they use the quasi-experimental design depicted in the directed acyclic graph

(DAG) (36) in Fig. 1*A*. The black arrow connecting protection to poverty, labeled "average treatment effect on the treated (*ATT*)," represents the causal effect of protected areas (treatment) on people living around protected areas (the treated). Estimating the *ATT* is made difficult by confounding variables: factors that affect where protection is assigned and that also affect poverty (e.g., low agricultural productivity). These confounding variables can mask or mimic the effects of protection on poverty. By controlling for, or blocking, the effects of these confounding variables (represented by the red broken single-headed arrows in Fig. 1*A*), one can identify the causal effect of protection on poverty. Andam et al. (12) show that failure to control for confounding variables leads to dramatically different conclusions about protection's effects on poverty.

Mechanisms can be viewed as intermediate outcomes in a causal pathway: A mechanism is an outcome that, once affected by the treatment, affects the final outcome of interest. The DAG in Fig. 1*B* depicts this refinement of the Andam et al. (12) causal pathway (Fig. 1*A*). Each pathway that links protection to poverty through one of the mechanisms represents a mechanism average treatment effect on the treated (*MATT*). (We adapt the ideas and terminology from ref. 37 to develop these concepts.) For instance, the tourism *MATT* is the proportion of the total impact of protected areas on poverty (the *ATT*) that comes from the change in tourism induced by protection (the top pathway in Fig. 1*B*: Protection → Tourism → Poverty). The *MATT* can be viewed as the difference between the total effect of protection on poverty and the effect of protection on poverty when the mechanism is absent. To further clarify the *MATT* concept, we introduce the following thought experiment that describes an experimental design that would allow one to estimate the mechanism effect from changes in tourism (an experiment that would be impossible to run in practice). The design comprises two experiments that are run sequentially. In the first experiment, protection is randomly assigned to areas from a pool of eligible candidate forests, after which the average impact of protection on poverty in neighboring census tracts is estimated. The second experiment starts with a clean slate and assigns protection to the same areas. In this second experiment, however, the effect of protection on tourism is blocked; i.e., tourism is allowed only to the extent that it would exist if there were no protected area. The average poverty in protected census tracts includes all of the effects of protection except those that arise from changes in tourism. The difference in the average poverty within protected census tracts in the first and second experiments is the tourism *MATT*.

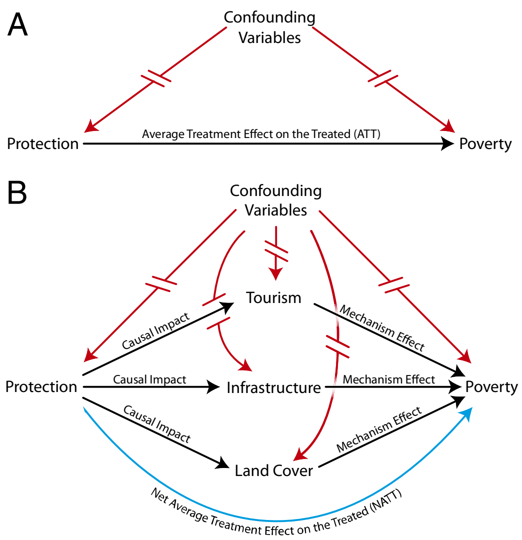

Fig. 1. Directed acyclic graphs (DAGs) depict the empirical strategy for estimating causal mechanism effects. A single-headed arrow (→) represents a causal link or pathway between two variables. (*A*) Design to estimate average treatment effect on the treated (*ATT*), which is protection's effect on poverty in communities around protected areas. (*B*) Design to decompose *ATT* into mechanism average treatment effects on the treated (*MATT*) and a net average treatment effect on the treated (*NATT*).

One cannot, of course, run such experiments. To estimate the *MATT*s using nonexperimental data, one must answer the following question: What level of poverty would have been observed in protected census tracts had the census tracts been exposed to protection, but had protection not affected the mechanisms? The DAG in Fig.1*B* illustrates that, in principle, this estimation can be carried out in a two-step process.

First, one estimates the causal effect of protection on the mechanisms (Protection → Mechanism). Second, one estimates how the change in the mechanisms due to protection affects poverty (Mechanism → Poverty). [Mechanisms are, by definition, affected by the cause (e.g., protected status). Thus, simply controlling for mechanisms within, for example, a single-equation regression framework will generally make the regression estimator biased (38).] Fig. 1*B* also illustrates the obstacles in this two-stage process. First, one must control for (break the link between) confounding variables that jointly affect the establishment of protected areas, the mechanisms and poverty. Second, one must model the effect of protection on poverty in the absence of the mechanisms. To address these two issues, we extend the matching design of Andam et al. (12), using a two-stage framework developed by Flores and Flores-Lagunes (37). This design yields an estimate of the counterfactual poverty in each protected census tract, had protection not affected the mechanisms; in other words, had the mechanisms in the protected tracts taken on the values observed in their matched unprotected tracts, holding all other relevant covariates constant. For each mechanism, the *MATT* is the difference between the average poverty level in the protected census tracts and the average counterfactual poverty level with the mechanism blocked. We conduct several robustness checks and explore how violations of our underlying assumptions can affect our results. See *Materials and Methods* and *SI Text* for full exposition of methods, including details on the controls for confounding variables.

If we were able to account for, and measure, all of the mechanisms through which protection affects poverty, the sum of all of the *MATT*s would equal the *ATT*. As noted in the *Mechanisms* section, however, our set of mechanisms is not exhaustive. The proportion of the total *ATT* that stems from mechanisms other than the ones we measure is defined as the net average treatment effect on the treated (*NATT*). See *SI Text* for a formal exposition of *MATT* and *NATT*.

Results

Andam et al. (12) estimate that poverty indexes were, on average, 2.39 points lower in protected census tracts than they would have been in the absence of protection ($P < 0.01$). This reduction is equivalent to 0.27 SD of the poverty distribution among the matched unprotected tracts (i.e., effect size = 0.27). Fig. 2 summarizes how much of this *ATT* is accounted for by each of our mechanisms.

The tourism and recreational service mechanism has the largest *MATT* ($P < 0.01$; *Materials and Methods*). It thus accounts for the greatest proportion of the total poverty reduction that comes from the establishment of protected areas. Were the mechanism blocked, the estimated poverty reduction would have been about 70% smaller.

Protection induced more forest cover than would have been present in the absence of protection. The estimated *MATT*, however, is small, positive (the mechanism increases poverty), and not statistically different from zero ($P > 0.2$). Thus, we find no evidence that restricting land cover change in protected forests either reduced or exacerbated poverty around protected areas, on average.

Although the development of road networks in protected census tracts reduces poverty (Table S2), the establishment of protected

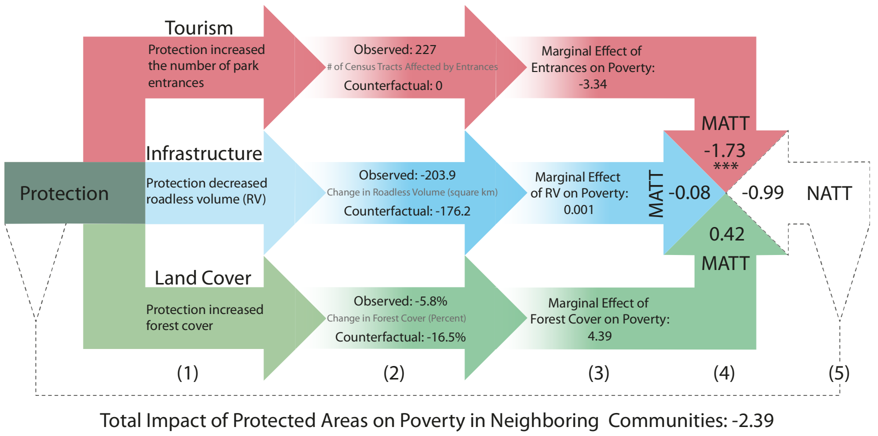

Fig. 2. Estimated mechanism average treatment effects on the treated (*MATT*) and net average treatment effect on the treated (*NATT*) for Costa Rica's protected area network. Depicted are (*1*) the qualitative impact of protection on each of the mechanisms, (*2*) the estimated causal impact of protection on each of the mechanisms, (*3*) the estimated impact on poverty due to a 1-unit change in the value of each mechanism (marginal effect), (*4*) the estimated *MATT* for each mechanism, and (*5*) the amount of the original *ATT* for which our mechanisms do not account (the *NATT*). See Table S2 for full results, including SEs.

areas did not have a substantial impact on the development of road networks (roadless volume decreased by 16%). Thus, the estimated *MATT* on poverty is small (3% of the *ATT*) and not statistically different from zero ($P > 0.5$).

Unidentified mechanisms account for about one-third of the estimated poverty reduction. These unidentified mechanisms may include mechanisms other than the three we identified or include pathways not captured by our mechanism proxies (e.g., tourism opportunities unaffected by the presence or absence of a park entrance).

Robustness Checks and Rival Explanations. We explore the sensitivity of the results to changes in methodology and then consider potential hidden bias in our estimators (i.e., unobserved confounding variables in Fig. 1*B*). First, we rerun all of the analyses using 1973 census tract boundaries, instead of the 2000 boundaries. The estimates are nearly identical; given there are fewer units, the precision of the estimates is lower (Table S3). Second, we reestimate all mechanism effects, using a more traditional system of structural equations (39, 40), which indirectly accounts for counterfactual outcomes under certain assumptions (*SI Text*). The estimated mechanism effects are similar: Tourism accounts for more than half of the poverty reduction and the other two mechanisms account for little of it (Table S4). One important difference in this alternative analysis is that the modest poverty exacerbation effect of the change in forest cover in Fig. 2 is statistically significant. Third, we use an alternative technique to recover the tourism *MATT* through the estimation of a local *NATT* (37). This approach requires fewer assumptions, but to recover the *MATT*, it assumes that the *NATT* is constant across protected tracts (i.e., no heterogeneity in responses to nontourism mechanisms). The *MATT* estimate is larger, but qualitatively similar, at −2.14 (see *SI Text*, *Local NATT* for details). Fourth, rather than use roadless volume as a proxy for changes in infrastructure, we use the number of health clinics and schools (Table S5). The estimated *MATT*s are smaller than the estimate using roadless volume and not statistically different from zero ($P > 0.5$).

Another concern is that our mechanisms may not be isolated from each other. In other words, they may affect each other and thus parts of one mechanism effect could be embedded in the estimate of another. If true, however, we would expect that there would be strong correlations among our mechanism variables. We would also expect a large difference, due to multicollinearity, between estimated *MATT*s when we estimate them jointly (as in Fig. 2) vs. separately. In contrast, the correlations among our mechanism variables are relatively low (Table S6) and the estimated *MATT*s are similar whether estimated jointly or separately (Table S2).

To consider the potential that our results arise from hidden sources of bias, we identify the most serious potential sources of bias and discuss their likely effects on our estimators. For the tourism mechanism, the biggest threat comes from unobserved factors that are positively correlated with park entrance placement and negatively correlated with poverty (i.e., negative selection bias in the second stage of our two-stage approach). For example, the government may have systematically protected locations with high expected future economic development, using characteristics that were unobservable to us. Such targeting would bias our estimator toward finding a poverty-alleviating effect from tourism. For the infrastructure mechanism, the main threat comes from factors that are positively correlated with where protection is assigned and negatively correlated with infrastructure development (i.e., negative selection bias in the first stage of our two-stage approach). For example, unobservable local political power may make infrastructure development more likely and the nearby establishment of a protected area less likely. Such power would bias our estimator toward finding no poverty-alleviating effect from infrastructure development. For the land cover mechanism, the main threat comes from factors that are positively correlated with forest cover change and poverty (i.e., the second stage). For example, protection may be most effective at inducing additional forest cover in areas that are politically the least powerful and thus less likely to economically develop. Such a phenomenon would bias our estimator toward positive numbers.

These three rival explanations require the presence of unobservable sources of heterogeneity in economic development potential and local political power that are only weakly correlated with our control variables. Our control variables comprise the main factors that affect agriculture, and thus economic growth, in rural areas. Therefore, although we cannot prove the absence of important unobservable sources of heterogeneity, we do not know from where they could arise. Moreover, if the first and third rival explanations were both true, an unusual pattern of hidden bias would have to exist: One mechanism (tourism increase) is more likely in communities that have higher expected potential poverty reduction in the absence of the mechanism, whereas the other mechanism (forest cover increase) is more likely in exactly the opposite type of communities. Furthermore, to reverse our conclusion about the effect of changes in forest cover and instead conclude that the increase in forest cover induced by protection contributed to a modest proportion (10%) of the reduction in poverty, the coefficient in our second-stage estimation procedure (i.e., relationship between changes in forest cover and poverty) would have to change by more than 9 SDs. We find such a degree of hidden bias implausible. These conclusions are supported by an alternative approach to examining the sensitivity of our results developed for systems of structural equations (40) (Table S4). [Another rival explanation is that changes in the mechanisms led to emigration of the poor or immigration of wealthier households, thereby mimicking a reduction in poverty. Andam et al. (12) addressed this rival explanation and we revisit their analysis in *SI Text*.]

Discussion

The Durban Accord at the Fifth World Parks Congress proclaimed that the establishment of protected areas should strive to reduce, and in no way exacerbate, poverty. To achieve this goal, the conservation community needs a better understanding of the mechanisms through which protected areas affect poverty. Our analysis suggests that nearly two-thirds of the poverty reduction associated with the establishment of Costa Rican protected areas is causally attributable to tourism. Changes in infrastructure and changes in forest cover account for little or none of the estimated poverty reduction. The mechanism effect of infrastructure is small because, although infrastructure development reduces poverty, protected areas had little effect on infrastructure development. In contrast, protected areas did increase forest cover, but this change had no detectable average effect on poverty.

As noted in *Mechanisms*, protected areas' effects on forest cover may have both salutary and detrimental effects on the rural poor. The DAG in Fig. 3 depicts these elaborated causal pathways. As reported in other studies (12, 41), the change in forest cover caused by protected areas in Costa Rica comes from both reduced deforestation and increased forest regrowth. These land cover changes have three potential mechanism effects on poverty. First, they can increase salutary regulating and provisioning ecosystem services, which in turn reduce poverty. Second, they can increase detrimental ecosystem services (or reduce salutary services), which in turn increase poverty. Third, they can decrease production/extraction activities and thereby increase poverty. We estimated only the net effect of these three potential effects and thus cannot discriminate between two potential inferences: (*i*) On average, the three mechanisms have no effect on the poor (all three mechanism effects are zero) or (*ii*) on average, the salutary and detrimental effects are nonzero, but are of opposite sign and approximately equal, thus canceling each other out.

Future studies that have precise measures of ecosystem service flows and foregone productive activities may be able to discriminate between these rival explanations. However, if one were willing to make the plausible assumption that restrictions on forest use had some negative effects on the poor, then one could infer that the salutary effects from regulating and provisioning ecosystem services provide a countervailing weight against these negative effects (i.e., accept inference *ii* above).

About one-third of the estimated reduction in poverty comes from unidentified mechanisms, which may include mechanisms other than the three we identified (e.g., changes in social capital) or dimensions of our mechanisms not captured by our proxies (e.g., changes in ecosystem services that are weakly correlated with changes in forest cover). To further decompose the total effect of protection in Costa Rica and elsewhere, future studies should seek richer measures of mechanisms. For example, through which mechanisms precisely did tourism reduce poverty in Costa Rica? Unlike other countries (e.g., Madagascar), Costa Rica has no system of revenue sharing with local communities. Thus, tourism likely reduced poverty in Costa Rica through market channels.

Costa Rica is a country renowned for its public and private ecotourism investments (42). Thus, one should be cautious about extrapolating our results to other countries. Furthermore, we do not claim that our study is the last word on estimating causal mechanism effects, for protected areas or any other conservation initiative. To truly understand the mechanisms through which ecosystem conservation policies affect poverty, we need to build the evidence base on a policy-by-policy and country-by-country (or region-by-region) basis. To generate this evidence, interdisciplinary teams of scientists need to collect the right data and analyze them within designs that help isolate mechanism effects.

Despite its limitations, our study creates a unique path of inquiry that can yield policy-relevant evidence. For example, the debate about the role of ecotourism in poverty alleviation is unresolved. We believe our study highlights unique avenues for tourism research through the use of strong empirical designs aimed at identifying the causal effects of policy-supported tourism.

Ultimately, the conservation science community wants fully elaborated theories and structural empirical models. With these theories and models, we can better understand the multiple causes of environmental and social outcomes and the trade-offs among different policies. At this time, however, we are far from realizing this goal. As noted in a previous study (4), our best hope in the short term is to develop better theory and empirical evidence about the effects of individual causes (e.g., protected areas, incentives, and decentralization), the heterogeneity of these effects (including interactions with other causes), and the mechanisms through which these effects are realized. With this new theory and evidence, scientists, policymakers, and practitioners can design better policies for achieving environmental and social goals.

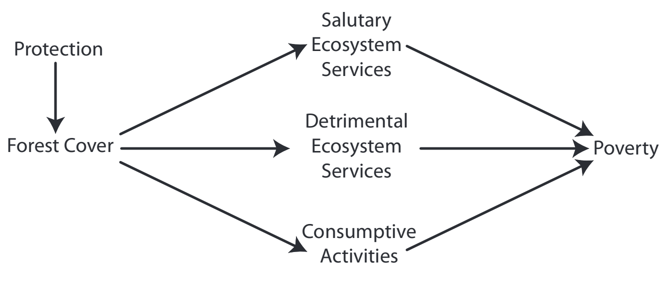

Fig. 3. Elaborated causal pathway for the land cover mechanism average treatment effect on the treated (*MATT*). For example, in our study, Protection → Forest Cover → Salutary Ecosystem Services → Poverty describes the pathway in which protection causes an increase in forest cover, which leads to an increase in salutary ecosystem services, which then reduces poverty. We are unable to quantify the mechanisms that lie between forest cover and poverty; therefore our estimated *MATT* for changes in forest cover captures all these potential pathways.

Materials and Methods

Unit of Analysis. The socioeconomic data come from the 1973 and 2000 censuses used in ref. 12. Our unit of analysis is based on the 2000 census tract (*segmento censal*) boundaries. We use areal interpolation to rectify differences in census tract boundaries between 1973 and 2000 (*SI Text*). In 2000, Costa Rica contained 17,239 census tracts with an average size of 2.95 km^2.

Treatment. To determine whether a census tract is considered protected for the analyses, a layer containing all protected areas established before 1980 is overlaid with the census tracts. During the study period, protected areas were in International Union for Conservation of Nature (IUCN) categories Ia, I, II, IV, and VI. As in ref. 12, a census tract is considered protected if at least 10% of its area is occupied by protected land of any IUCN category. A 10% threshold was chosen because protecting 10% of the world's ecosystems was the goal of the Fourth World Congress on National Parks and Protected Areas (12). Conversely, any census tract that contains less than 1% protected land is considered unprotected. Of the 17,239 census tracts, 483 are protected (treated) before 1980 and 16,249 are potential counterfactual observations. To avoid bias in the analyses, 507 tracts with protection between 1% and 10% are dropped from the analysis.

Poverty. For each census tract, a poverty index for the baseline (1973) and endpoint (2000) year is derived from census data following ref. 43. Higher levels of poverty are associated with greater poverty index values (negative index values indicate low levels of poverty).

Tourism Mechanism. The locations of entrances are derived from global positioning system (GPS) data (source, ref. 29). Of Costa Rica's 39 protected areas that were established before 1980, 19 received at least one park entrance before 2000 (total of 23 entrances). A protected census tract is considered exposed to a park entrance if it is occupied by a protected area in which at least one entrance was established. According to this definition, 227 census tracts are exposed to a park entrance.

Land Cover Mechanism. Using the forest cover layers from ref. 44, we measure the percentage of forest cover within each census tract in 1960 and 1986 (see Table S7 for baseline and mechanism measurements of forest cover).

Infrastructure Mechanism. We quantify infrastructure development using change in roadless volume between 1969 and 1991. Roadless volume is the sum of the product of area and distance to the nearest road for every 1-ha parcel within the census tract and is calculated as in ref. 12 (Table S7).

Two-Stage Estimation Procedure. The confounders in Fig. 1*B* that we seek to control are the same variables postulated to jointly affect protection and poverty in previous studies (6, 12, 45): baseline poverty, forest area, agricultural productivity classes, roadless volume, and distance to markets (see *SI Text* for definitions and sources and *Table S7* for descriptive statistics). To estimate counterfactual poverty and mechanism values, we match census tracts on these characteristics (i.e., find unprotected census tracts that are observably similar to protected tracts). In the first stage, we select the matching algorithm that achieves the best covariate balance for our sample: one-to-one Mahalanobis nearest-neighbor covariate matching with a bias-adjustment procedure (46) for imperfect matching in finite samples (see *SI Text* for details; Table S8 has covariate balance results). The difference in poverty between the matched protected and unprotected tracts yields the *ATT* of Andam et al. (12). The matched unprotected units also provide an estimate of counterfactual mechanism values for protected units (i.e., the value of the mechanism in the absence of protection). In the second stage, we estimate the counterfactual poverty for protected census tracts had protection not impacted the mechanism. We use a regression technique suggested by ref. 37, which is similar to the regression bias-adjustment techniques of refs. 46 and 47. First, the effects of the mechanisms on poverty are estimated in a regression framework. The estimated regression coefficients capture the influence of the mechanisms, and of the observable covariates used in the first stage, on poverty in the protected census tracts (Tables S2, S3, and S9). Then the observable covariate values and the counterfactual mechanism values (estimated in the first stage) are plugged into the estimated regression equation, which provides an estimate of poverty for each protected census tract had the mechanisms taken on the values of their matched unprotected tracts, holding all other relevant covariates constant. The difference between this estimated counterfactual poverty level value and the observed average poverty level in the protected census tracts is the *MATT*. In *SI Text*, we present *MATT*s estimated with and without bias adjustment. To calculate the precision of our *MATT* estimates, we base our SE estimator on the heteroskedasticity robust matching-based estimator suggested by ref. 46. Author-created code for all estimators, programmed in R 2.15.1, is available upon request.

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