ECOLOGY

Revealing pathways from payments for ecosystem services to socioeconomic outcomes

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Payments for ecosystem services (PES) programs have been widely implemented as a promising tool to conserve ecosystems while facilitating socioeconomic development. However, the underlying pathways (or processes) through which PES programs affect socioeconomic outcomes remain elusive, and existing literature provides little guidance to quantify them. By integrating linkages among PES programs, livelihood activities, and socioeconomic outcomes, we develop a framework to reveal pathways from PES programs to socioeconomic outcomes. We empirically demonstrate the framework's operationalization and uncover the pathways that lead to unexpected negative effects of two important PES programs on participating households' income. With improved understanding of the pathways (for example, the programs decreased income through reducing crop production), we provide recommendations to enhance the PES programs' outcomes in our demonstration site and beyond. Our study highlights the finding that elucidating the pathways from PES programs to their outcomes can help identify specific strategies to achieve ecosystem conservation and socioeconomic development simultaneously.

INTRODUCTION

The world is currently threatened by the unprecedented decline of ecosystem services that are essential for human survival (*1*). Meanwhile, poverty continues to plague many parts of the world (*2*). To eradicate poverty and conserve ecosystems, sustainable development—economic growth that is ecologically sound—has become a practical necessity and the central topic of the Millennium Development Goals of the United Nations and its successor, the Sustainable Development Goals, released in 2015 (*3*, *4*). However, activities that are desirable from the point of view of conservation are often unattractive to users of natural resources (for example, farmers, loggers, and fishers). To achieve sustainable development goals, there has been a growing search for possible solutions to the long-existing conflicts between ecosystem conservation and socioeconomic development, especially in rural areas that house a disproportionately large number of the world's poor and provide sanctuary for most of Earth's biodiversity.

Among the potential solutions, payments for ecosystem services (PES) programs have been widely implemented across the world (*5*–*7*). The central idea of PES is that conservation costs borne by communities in target areas should be compensated by beneficiaries outside conservation regions to avoid impeding socioeconomic development of those local communities. Normally, costs of conservation are not distributed in proportion to their gains. The gains of conservation (for example, enhanced water supply, wildlife habitat, and carbon sequestration) are often shared regionally or even globally, but the costs (for example, lost livelihood opportunities) are mostly borne by local communities (*7*). For example, forest conservation practices (for example, logging bans) upstream often bring benefits such as clean water to users downstream (for example, city dwellers). However, these conservation practices may worsen the livelihood of upstream land users (for example, farmers) because of sacrificed opportunities for productive use of the forest resources. By offering payments to participating households, it is hoped that PES programs can simultaneously facilitate ecosystem conservation and socioeconomic development in target areas (*7*).

To evaluate the effectiveness of PES programs in achieving their sustainability goals, a large number of studies have documented their effects on environmental and socioeconomic outcomes (*8*–*10*). Although it is important to capture these effects, such work offers little insight into the processes through which these effects occur (*11*, *12*). In conservation areas, PES programs often induce complex human-nature changes (for example, decrease in traditional livelihood activities) that may constitute pathways through which PES programs affect target outcomes (for example, household income) indirectly. Revealing these pathways is vital for conservation success in both theory and practice. One of the major goals of conservation research is to produce generalizable understanding of the effects of policy interventions. However, the effects of policies, including PES programs, often vary across different spatial and temporal contexts, which often make them not directly comparable (*13*). Uncovering the pathways underlying these effects will allow more specific explanations to why certain socioeconomic outcomes occur or fail to occur, thereby making different study results more comparable and facilitating the development of theories (*13*). In conservation practice, better understanding the failures or successes of existing PES programs is also crucial. Armed with such knowledge, conservation practitioners may be able to identify the pathways that have the potential to improve the socioeconomic outcomes of PES programs and design management strategies accordingly. However, the pathways through which PES programs affect socioeconomic outcomes have remained elusive, and existing literature offers little guidance to test and quantify them (*5*, *6*).

By integrating the linkages among PES programs, livelihood activities, and socioeconomic outcomes, we propose a conceptual framework for revealing the pathways through which PES programs affect socioeconomic outcomes. We then demonstrate the framework's operationalization using the structural equation modeling approach to analyze the pathways through which two PES programs affected the income of participating households in a demonstration site. On the basis of our findings, we provide recommendations to improve the socioeconomic outcomes of PES programs for rural communities in the demonstration site and beyond.

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Conceptual framework

Our conceptual framework (Fig. 1) includes three major interrelated components: PES programs, livelihood activities, and socioeconomic outcome. The linkages among them (the black arrows in Fig. 1) constitute pathways through which PES programs affect socioeconomic outcome.

Along each specified pathway, one or more livelihood activities work as intermediary variable(s) to transmit the effect of PES programs on socioeconomic outcome. This means that PES programs affect livelihood activities (for example, farming) first, which, in turn, affect the socioeconomic outcome. For example, PES programs often work by paying for land use changes (for example, cropland conversion to forests or grasslands) that are thought to increase ecosystem services (*7*). Experiences and lessons learned (*6*, *14*) over the past decades indicate that land use changes promoted by PES programs may reduce the benefits participating households could obtain from their previous livelihood activities (for example, agricultural production) and thus negatively affect socioeconomic outcome (for example, household income). Meanwhile, the resources (for example, surplus labor and payments) made available by PES programs to participating households may help them shift to alternative livelihood activities (for example, working in off-farm sectors). Benefits from these alternative livelihood activities may help compensate for the losses arising from participating PES programs and improve the socioeconomic outcome (*9*).

Because different livelihood activities might be interrelated, the linkages among them may constitute additional pathways to transmit the effects of PES programs on socioeconomic outcome. For example, for various reasons (for example, higher income and hardships of farming), off-farm jobs are usually more attractive to farmers in many rural areas around the world (*15*). Households that have access to off-farm employment may invest less labor in farming activities and thus reduce their agricultural production. Therefore, if a PES program can prompt participating households to find off-farm employments, then it may, in turn, reduce their agricultural production and ultimately change the socioeconomic outcome.

In reality, PES programs often affect socioeconomic outcome through many pathways, and some may be difficult to specify for practical reasons (for example, lack of data to describe related livelihood activities). In addition, the measurements used to characterize the specified livelihood activities may be unable to capture all dimensions of them (for example, measuring a household's participation in a livelihood activity with the number of laborers involved may not fully reflect the actual number of labor hours for that activity). Therefore, a direct linkage between PES programs and socioeconomic outcome (the blue arrow in Fig. 1) is used in our framework to represent the processes that are not specified, and this linkage is named "unspecified pathway."

To obtain reliable estimates of the linkages among these three components (that is, PES programs, related livelihood activities, and socioeconomic outcome), control variables should be properly considered in the analysis. In our framework, control variables refer to the factors that may affect (the red arrows in Fig. 1) one or more variables along the pathways. If not controlled, they can bias the estimates of the linkages that constitute the pathways connecting PES programs and socioeconomic outcome (the black arrows in Fig. 1). Examples of control variables may include those characterizing the socioeconomic, demographic, and biophysical conditions of analysis units (for example, households).

Demonstration of the framework's operationalization

Demonstration site and PES programs

We used two PES programs implemented in Wolong Nature Reserve (Wolong hereafter) to demonstrate the operationalization of the framework. Wolong is a flagship protected area in southwest China established mainly to protect the giant panda (*8*). Besides featuring rich biodiversity, Wolong is also home to about 4900 local residents, living in

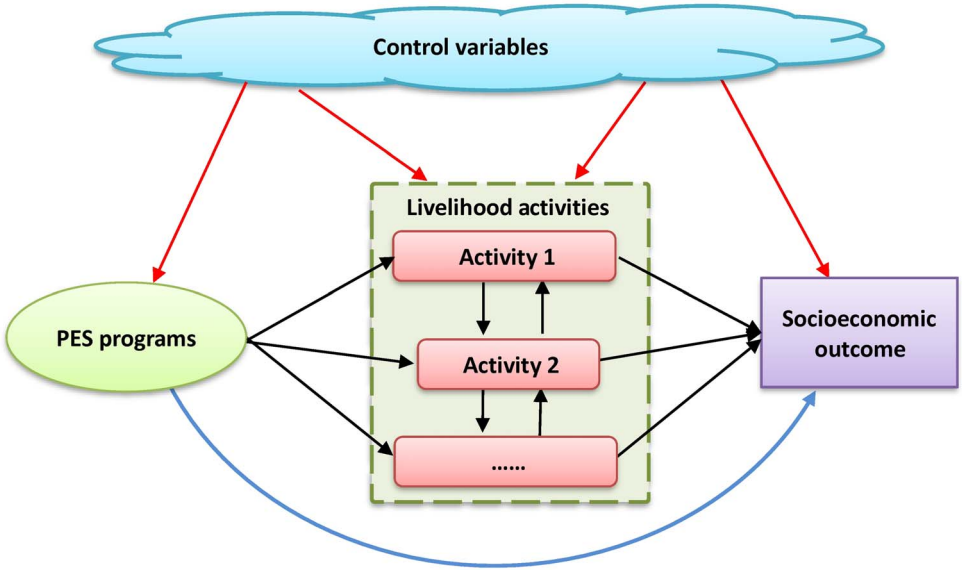

Fig. 1. Framework for analyzing the effects of PES programs on socioeconomic outcome through influencing different livelihood activities. An arrow represents a linkage through which the variable at the arrow tail affects the variable at the arrowhead. Black arrows are the ones that constitute the specified pathways linking PES programs and socioeconomic outcome. The blue arrow represents the unspecified pathway that links PES programs and socioeconomic outcome. Red arrows represent the linkages through which control variables affect other components in the framework. Different livelihood activities might be related, and the linkages among them may constitute additional pathways linking PES programs and socioeconomic outcome.

around 1200 households (*8*). The local residents mainly rely on crop production and livestock husbandry (*16*). Since the early 2000s, working in the local tourism industry and out-migrating to work in cities have become important income sources for some local households (see the Supplementary Materials for details of these livelihood activities in Wolong) (*15*, *17*).

As part of the effort to address the rapid degradation of panda habitat due to human activities (for example, agricultural expansion, timber harvesting, and fuelwood collection), two PES programs [the Grain-to-Green Program (GTGP, which is a national program and one of the world's largest PES programs) and the Grain-to-Bamboo Program (GTBP, which is a local program to grow bamboo on cropland for feeding pandas in captivity and for attracting tourists)] have been implemented in Wolong since 2000 and 2002, respectively (*8*). Under these programs, local households received payments annually from the government based on the amount of cropland they converted to forest land or bamboo land (see text description and table S1 for details). As a national conservation program, the GTGP also pays land owners to plant trees on barren land in some regions, but in Wolong, only cropland has been enrolled into the GTGP (*16*).

Specification of framework components

We are interested in the effects of GTGP and GTBP on household income and applied our framework to analyze how these effects occur through influencing different livelihood activities. Because the effects of these programs on household income through direct payment is evident and can be easily observed (for example, from official records), we used nonpayment income (income from sources other than direct payments from these two PES programs) as the indicator of socioeconomic outcome and focused on how these programs affect nonpayment income through different pathways. On the basis of our knowledge of Wolong, we selected three livelihood activities that might have worked as intermediary variables to transmit the effects of the GTGP or the GTBP on nonpayment income, including tourism participation (working in local tourism industry), labor migration (temporary out-migration to work in cities), and crop production.

Hypothesized pathways

On the basis of previous study results (*15*, *17*), we hypothesized that linkages among the PES programs, livelihood activities, and nonpayment income constitute different pathways through which the GTGP and the GTBP affected income (Fig. 2).

Specifically, we hypothesized that the GTGP and the GTBP provoked changes in each of these three livelihood activities, which then affected the nonpayment income. As previous studies (*15*, *17*) indicate, we first hypothesized that all the three livelihood activities can increase nonpayment income. We then hypothesized that both the GTGP and the GTBP had a positive effect on households' participation in the local tourism industry and labor migration. This is because previous studies (*9*, *14*) show that cropland reduction due to conservation policies could release rural labor from crop production and promote the shift from on-farm to off-farm activities such as working in the local tourism industry or out-migrating for jobs in cities. Furthermore, we hypothesized that both the GTGP and the GTBP had negative impacts on crop production because participating households converted parts of their cropland to forest or bamboo land. These hypothesized linkages can form two-step pathways through which the GTGP and the GTBP affected these three livelihood activities, which, in turn, affect nonpayment income (Fig. 2). For example, the GTGP may affect nonpayment income through the pathway in which the GTGP promotes participation in tourism, which then increases nonpayment income.

In addition, we hypothesized that these three livelihood activities were linked and that the linkages among them constituted longer pathways through which the GTGP and the GTBP affected nonpayment

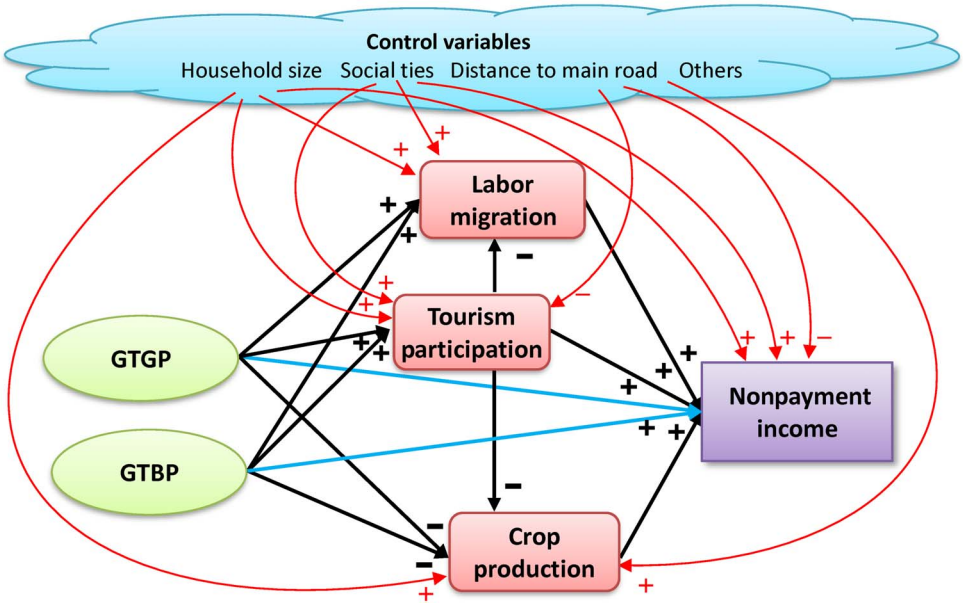

Fig. 2. Illustration of hypothesized linkages among PES programs, livelihood activities, control variables, and nonpayment income. We focused on analyzing the effects of the GTGP and GTBP on nonpayment income (income from sources other than direct payments from these two PES programs) because the direct contribution of payments from GTGP and GTBP to participating households' income can be directly observed. Arrows in the diagram represent linkages. "+" and "–" refer to hypothetical positive and negative effects of the linkage, respectively. The black arrows represent the ones that constitute the specified pathways that link the GTGP or the GTBP with nonpayment income. The two blue arrows represent the unspecified pathways that link the GTGP and the GTBP with nonpayment household income, respectively. A complete list of variables considered in the Wolong demonstration study is found in table S2.

income. For example, we hypothesized that tourism negatively affected crop production. This is because tourism activities (for example, operating a restaurant) are often labor-intensive (*18*). Households that participate in the local tourism industry may have less labor available for farming activities and thus may maintain less land for crop production. We also hypothesized that tourism had a negative influence on labor migration. Although both tourism and labor migration have the potential to increase rural household income, rural migrant workers in cities may lack health insurance coverage, face substantial educational expenses for their children, experience discrimination from urban residents, and suffer from high stress and depression (*19*). Therefore, local tourism jobs in Wolong are often more attractive than migrant jobs in cities. If a household has access to jobs in the local tourism industry, it is less likely to have labor migrants working in cities. These hypothesized linkages among different livelihood activities, as well as the aforementioned linkages between livelihood activities and the other two components (that is, PES programs and nonpayment income), constitute additional pathways through which PES programs affect household income (Fig. 2). For instance, the GTGP may affect nonpayment income through the pathway in which the GTGP promotes participation in tourism, which then decreases crop production and, in turn, nonpayment income.

To obtain reliable estimates of these hypothesized pathways, we considered a broad set of control variables to characterize the demographic (for example, household size), socioeconomic (for example, social ties to government), and biophysical (for example, distance to the main road) features of local households (table S2).

RESULTS

Our results show that the linkages among the two PES programs (the GTGP and the GTBP), livelihood activities, and nonpayment income constituted different pathways through which these programs affected household income (Fig. 3). For example, the GTBP negatively affected income through a pathway in which the GTBP boosted participation in the local tourism industry ($P < 0.1$), which led to decreased crop production ($P < 0.05$), and then a reduction in nonpayment income ($P < 0.01$).

The net effects on nonpayment income transmitted through tourism participation and labor migration are both positive (Table 1), but these effects are not statistically significant ($P > 0.1$) and smaller than the significant ($P < 0.01$) negative effect on nonpayment income transmitted through crop production (Table 1). In the case of the GTBP, the magnitude of the positive effects on income through promoting tourism participation and labor migration could offset only about 34% of the income loss due to reduced crop production. In the case of the GTGP, these positive effects could offset an even smaller portion (11%) of the loss due to reduced crop production.

For both PES programs, their effects on nonpayment income captured by the unspecified pathways are negative, although not statistically significant ($P > 0.1$) (Table 1). As noted in the "Conceptual framework" section, the coefficients of the two unspecified pathways represent effects of the GTGP and GTBP on nonpayment income through all other processes that are not specified in this study, respectively.

The total effects of the GTGP and the GTBP on nonpayment income have been negative and are statistically different from 0 ($P < 0.05$) (Table 1). The results suggest that 1.0% increase in cropland enrollment (as measured by percentage of cropland being enrolled) would decrease nonpayment income by 0.6% under the GTGP and 0.9% under the GTBP. Correspondently, for enrollment of 1 mu of cropland (1 mu = 0.067 ha), the average net loss after considering the direct payments local household received (estimated using Eq. 2) was 634 yuan for the GTGP and 194 yuan for the GTBP (1 yuan = US$0.122 in 2005). These negative effects on income indicate that the income level of participating households would be better off if they did not participate in these PES programs.

DISCUSSION

Poverty eradication and ecosystem conservation are among the major goals being targeted by the 2030 Agenda for Sustainable Development of the United Nations (*3*). To achieve these goals, scientists, policy-makers, and conservation practitioners need a better understanding of the underlying pathways through which conservation policies succeed or fail in generating desirable outcomes (*11*). Our study here illustrates that

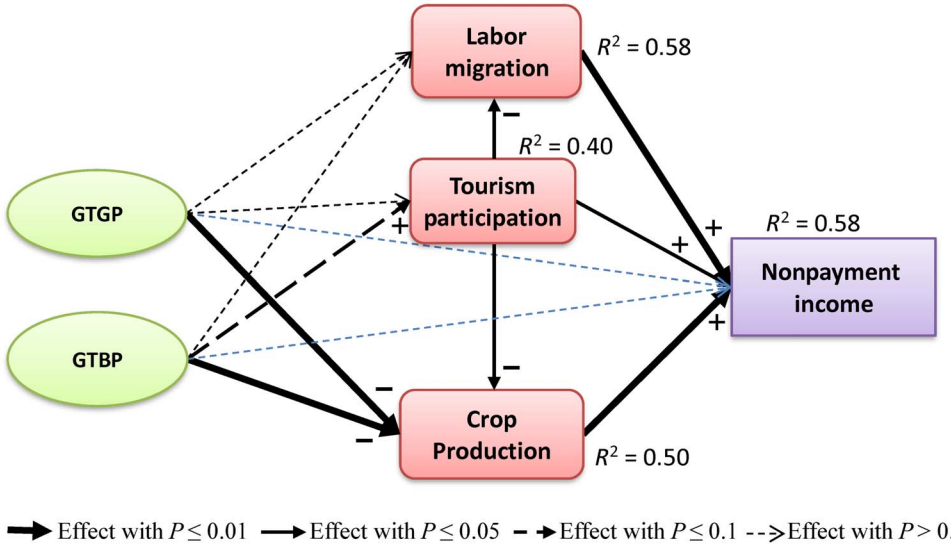

Fig. 3. Visualization of the structural equation model results. Arrows with different line types represent linkages whose effects are of different statistical significance levels. "+" or "−" indicates that the effect of the linkage is positive or negative. To keep clarity, the control variables were not presented in this diagram. Full model results are shown in table S4.

Table 1. The standardized coefficients of effects transmitted from the GTGP and the GTBP to nonpayment income in 2005 through different livelihood activities and other unspecified processes. The number of households included in the analysis is 202.

Livelihood activities/processes	Descriptions	Coefficients	
		GTGP	GTBP
Tourism participation	Whether the household has a member who directly participated in tourism activities in 2005: 1. Yes; 0. No	−0.664***	−0.563***
Labor migration	Whether the household had labor migrants in 2005: 1. Yes; 0. No	0.058	0.142
Crop production	Cropland devoted for crop production in 2005	0.009	0.048
Other unspecified processes†	Other livelihood activities that are not observed in this study and/or other dimensions of the observed activities (that is, crop production, tourism participation, and labor migration) that are not captured by their proxies above	−0.006	−0.477
Total	The sum of all the effects transmitted through all the three livelihood activities and other unspecified processes	−0.602*	−0.850**

*$P \leq 0.05$. **$P \leq 0.01$. ***$P \leq 0.001$. †The effect transmitted through unspecified processes is represented by the coefficient of the unspecified pathway.

integrated analysis of the linkages among PES programs, livelihood activities, and socioeconomic outcomes can help reveal the pathways from PES programs to socioeconomic outcomes.

In contrast to the positive effects of PES programs on income found in many other studies (*10*, *14*), we found that the negative effects of the GTGP and the GTBP outweighed their positive effects on income in our study site, even after these programs' payments were counted. These negative net effects on household income occurred perhaps because, as time went by, the fixed payments of the GTGP or GTBP failed to cover the growing gap between their positive and negative effects on income through different pathways. From 2000 to 2003, households in Wolong enrolled a large portion (about 66% on average) of their cropland into these two programs. However, the price of agricultural products in China has increased markedly since 2004 (*20*). Therefore, the strength of the pathway through which these programs negatively affect the income by reducing crop production was increased. Meanwhile, our results indicate that these programs' effects on prompting participating households to find off-farm employment in the local tourism industry or in cities were small, although these livelihood activities can significantly increase household income (Fig. 3). Therefore, the gap between the negative effect on income due to lost crop production and the positive effects on income through promoting off-farm employment increased after the implementation of the GTGP and GTBP. However, the fixed payment levels of these programs did not consider the possible changes in the opportunity costs borne by participating households and thus failed to cover the growing cost of lost crop production in the later years of our study period.

On the basis of the understood pathways, conservation practitioners may be able to identify the obstacles to improving the socioeconomic performance of PES programs and design effective management strategies accordingly. Our study results in Wolong show that both the GTGP and the GTBP had weak effects on promoting participation in the local tourism industry or labor migration. One major reason might be that the local households have limited access to the benefits brought by tourism development. For example, evidence from previous studies in Wolong (*17*, *21*) and other areas (*22*) suggests that a large portion of tourism revenue often goes to tourism development companies and the government. Local communities often receive only a small share of the benefits brought by tourism (<4% in Wolong) (*21*). In addition, although China has witnessed a marked increase of labor migrants [from only 2 million in the early 1980s to more than 150 million in 2010 (*23*)], many barriers that hinder labor migration remain. The major barriers include lack of skills, unequal educational opportunities for children of migrant workers in cities, and administrative restrictions on the shift from rural residence to urban residence (*24*). Because of these barriers, participating households may be unable to effectively use the payments and surplus labor made available by PES programs to participate in these off-farm livelihood activities. Therefore, management interventions that help overcome these barriers (for example, providing training to participating households to develop new skills and offering equal opportunities for migrant workers in urban areas) should be considered to increase the benefits participating households could obtain from these off-farm livelihoods and, ultimately, to improve the socioeconomic outcomes of these PES programs. Otherwise, higher payments should be offered to local households to cover the associated losses from participating in these programs, although it may put a heavier financial burden on governments.

Like any other conservation policy, PES programs' socioeconomic effects often vary across space and time. With a better understanding of the underlying pathways, we may be better positioned to explain and anticipate the socioeconomic outcomes of PES programs in different contexts. For example, PES programs similar to the GTGP and the GTBP have been widely implemented around the world, such as the Conservation Reserve Program in the United States (*25*), the Permanent Cover Program in Canada (*26*), the Common Agricultural Policy in Europe (*27*), the Pagos de Servicios Ambientales program in Costa Rica (*28*), and payment for afforestation programs in Bolivia (*29*) and Ecuador (*30*). Land owners participating in these programs receive payment to convert their cropland to vegetative land. Therefore, pathways as identified in our demonstration case may be applicable to explain the socioeconomic outcomes of these PES programs (for example, these programs may also negatively affect income through reducing crop production and positively affect income by prompting them to seek alternative livelihoods).

In addition, a better understanding of the pathways may help anticipate the dynamics of PES programs' socioeconomic outcomes across time. For example, the rapid economic growth in China's cities stimulates an ever-growing demand for laborers. In a number of coastal cities in China, many factories have been struggling with labor shortages in recent years (*31*). Meanwhile, the Chinese government has implemented a series of policies favorable for labor migrants to work in cities (for example, reform of the existing urban-biased residence registration system) (*32*). These changes may help rural households find off-farm

employments in cities and thus enhance the socioeconomic outcomes of the GTGP and the GTBP, which have released many rural laborers from farming activities. As urbanization continues at an increasing speed in the developing world (*33*), a similar trend in PES programs' effects on socioeconomic outcomes may also occur in other countries.

Although our framework was developed to analyze the socioeconomic outcomes of PES programs, it can be easily adapted for the analysis of other conservation policies (for example, protected areas) that also have complex socioeconomic effects by affecting different livelihood activities. Ultimately, to improve the socioeconomic outcomes of conservation policies, it is necessary to develop more elaborate theories [for example, metacoupling theory that integrates human-nature interactions across space (*34*)] to guide conservation practices that will enhance positive outcomes while mitigating negative ones. It is our hope that the framework proposed and its operationalization in this study will contribute to the construction of these theories and a collective base of evidence about the effects of pathways underlying conservation programs' socioeconomic outcomes. Armed with these theories and knowledge, scientists, policy-makers, and conservation practitioners may be able to better use conservation tools to achieve Sustainable Development Goals.

MATERIALS AND METHODS

Household surveys and measurements

In Wolong, households are usually the basic units of decision-making in most livelihood activities such as crop production, tourism participation, labor migration, and enrollment in the GTGP or the GTBP (*17*). Therefore, all measurements used in this case study were derived from data collected at the household level.

For this study, we mainly used data collected from surveys conducted in 1999 and 2006. In 1999 (before the PES programs were implemented), our research team conducted the first household survey in Wolong to collect data covering demographic (for example, household size, birth year, gender, and education level) and socioeconomic (for example, income sources, cropland area, and expenditures) information of individual households in 1998. A total of 220 households (about 20% of the total in Wolong) were randomly selected for surveys with strata based on administrative groups (the smallest administrative unit in China). These households sampled in 1999 were revisited for data collection in 2006, when the PES programs had already been implemented for several years. Besides collecting similar demographic and socioeconomic data to those in 1999, we added retrospective questions on households' involvement in tourism activities, labor migration, the GTGP, and the GTBP in previous years. Eighteen households were missing from the survey in 2006 for various reasons such as deaths, migration to outside areas, or temporarily working outside Wolong during the survey period. As a result, here, we used data from a total of 202 households surveyed in both years to examine the pathways through which PES programs affected household income. In addition to the household surveys, we measured the location of each household using a Global Positioning System device and calculated the distance of each household to the main road using the software ArcGIS 10.2 (ESRI Inc.). The survey instruments and data collection procedures we used in this study were reviewed and approved by the Institutional Review Board of Michigan State University (https://hrpp.msu.edu/).

Here, we measured the GTGP and the GTBP at household level with the proportions of cropland a household converted to forest land under the GTGP and bamboo land under the GTBP, respectively. We measured crop production in 2005 with the amount of cropland devoted to it. We measured labor migration and participation in the tourism industry in 2005 with two binary variables that indicate whether the household had members who temporarily out-migrate to cities for jobs or had members working in the local tourism industry, respectively. In addition, we generated a set of variables to characterize households' demographic, socioeconomic, and physical conditions that are commonly found to be relevant to household income or the livelihood activities mentioned above. Descriptive statistics of all these variables are shown in table S2.

Estimating the effects of different pathways

We tested the hypothesized linkages among PES programs, related livelihood activities, and nonpayment household income using the structural equation modeling method (*35*). Structural equation modeling is statistically unbiased and has been widely used in statistical inference literature (*35*).

Because all variables in this study can be reasonably treated as observable, we conducted path analysis using the structural equation modeling technique to test the hypothesized linkages among PES programs, related livelihood activities, and nonpayment household income, as shown in Fig. 2. The general matrix representation of the structural equation model with only observed variables is presented in Eq. 1

$$\mathbf{y} = \mathbf{B}\,\mathbf{y} + \mathbf{\Gamma}\,\mathbf{x} + \zeta \quad (1)$$

where $\mathbf{y}$ is the $p \times 1$ vector of endogenous variables, representing variables explained by the model; $\mathbf{x}$ is the $q \times 1$ vector of exogenous variables in the model (that is, variables not explained by the model); ζ is the $p \times 1$ vector of error terms; $\mathbf{B}$ is the $p \times p$ coefficient matrix describing the effects of endogenous variables on endogenous variables; $\mathbf{\Gamma}$ is the $p \times q$ coefficient matrix describing the effects of exogenous variables on the endogenous variables; p is the number of endogenous variables; and q is the number of exogenous variables. Because some endogenous variables are dichotomous (tourism participation and labor migration), we obtained the path coefficients in the model with the robust weighted least-square estimator.

We used a set of validation indices to test how well the data support the hypothesized pathways. All values of these indices indicated that our empirical data well supported the hypothesized pathways (table S3). After obtaining path coefficients (table S4), we calculated the effect of each pathway through which the GTGP or the GTBP affected the nonpayment income (table S5). On the basis of that, we further calculated the net effects transmitted through each observed livelihood activity in this study (crop production, tourism participation, and labor migration), the effect transmitted through unspecified processes (that is, effect captured by the unspecified pathway), and their total (Table 1). We conducted the statistical modeling and analyses using Mplus 7 (*36*).

Estimating net effects of PES programs on household income

On the basis of estimates of the total effect on nonpayment income and information on the direct payments, we calculated the net economic effect per unit area (mu) of cropland enrolled in the GTGP and the GTBP with the following equation

$$Net\ effect_i = \beta_i \times percentage_i \times nonpayment\_income/area_i + payment_i \quad (2)$$

where $i \in \{GTGP, GTBP\}$; β_i is the coefficient of the total effect of program i on the nonpayment income; $percentage_i$ is the average percentage of cropland enrolled in the program i (56% for the GTGP and 10% for the GTBP); nonpayment_income is the average nonpayment income (14,764 yuan) of local households in 2005; $area_i$ is the average cropland area enrolled in the program i (5.5 mu for the GTGP and 1 mu for the GTBP); and $payment_i$ is the average payment rate of program i (240 yuan/mu for the GTGP and 1060 yuan/mu for the GTBP).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/3/eaao6652/DC1

section S1. Description of the demonstration site

section S2. Model validation analysis

fig. S1. Wolong Nature Reserve in Sichuan Province, southwestern China.

table S1. General information about the PES programs and related livelihood activities under investigation in Wolong Nature Reserve.

table S2. Summary statistics of variables used in constructing the structural equation model.

table S3. Summary of validation results of the structural equation model.

table S4. Results of the structural equation model.

table S5. The effects of specified and unspecified pathways by which the GTGP and the GTBP affected nonpayment income.

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Acknowledgments: We thank S. Marquart-Pyatt, N. T. Krogman, and two anonymous reviewers for the valuable comments on an early version of the manuscript and S. Nichols for the editing of the manuscript. We also thank W. Liu, X. Chen, and L. An for their efforts in collecting the data used in this study. We appreciate H. Zhang at Wolong Nature Reserve and Z. Ouyang at the Chinese Academy of Sciences for their logistical support during the data collection processes. **Funding:** This study was funded by the NSF (grant no. 130313), the Ministry of Science and Technology of China (grant no. 2016YFC0503404), Michigan AgBioResearch, Michigan State University, and the National Natural Science Foundation of China (grant no. 41571517). **Author contributions:** H.Y., J.L., and W.Y. designed the research. H.Y., J.Z., and J.L. performed the research. H.Y., W.Y., J.Z., T.C., and J.L. analyzed the data and wrote the manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials and are also publicly available online at www.icpsr.umich.edu/icpsrweb/ICPSR/studies/34365. Additional data related to this paper may be requested from the authors.

Submitted 14 August 2017
Accepted 8 February 2018
Published 21 March 2018
10.1126/sciadv.aao6652

Citation: H. Yang, W. Yang, J. Zhang, T. Connor, J. Liu, Revealing pathways from payments for ecosystem services to socioeconomic outcomes. *Sci. Adv.* **4**, eaao6652 (2018).

Science Advances

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Sci Adv **4** (3), eaao6652.
DOI: 10.1126/sciadv.aao6652