Yang, H., T. Dietz, Y. Li, Y. Dou, Y. Wang, Q. Huang, J. Zhang, M. Songer, and J. Liu. 2022. Unraveling human drivers behind complex interrelationships among sustainable development goals: a demonstration in a flagship protected area. Ecology and Society 27(3):15. https://doi.org/10.5751/ES-13275-270315

Research

Unraveling human drivers behind complex interrelationships among sustainable development goals: a demonstration in a flagship protected area

Hongbo Yang [1,2,3], Thomas Dietz [2,4], Yingjie Li [2], Yue Dou [5], Yujun Wang [6], Qiongyu Huang [3], Jindong Zhang [6], Melissa Songer [3] and Jianguo Liu [2]

ABSTRACT. The transformational potential of the United Nations' 2030 Agenda for Sustainable Development Goals (SDGs) lies in effective efforts to reconcile the conflicts and maximize the synergies among the interrelated SDGs. Previous research on the interrelationships among SDGs often focused on depicting the degree to which different goals reinforce or hamper each other; however, drivers behind these interrelationships have rarely been evaluated. We developed a novel approach to unraveling the impact of human activities on the complex trade-offs and synergies among SDGs. We used the approach to assess the impacts of four globally common livelihoods, including cropping, local off-farm labor work, labor migration, and livestock husbandry, on the interrelationships among SDG 1 (no poverty), SDG 3 (enhance human well-being), and SDG 15 (protect life on land) in a demonstration site. The results show that our approach can be very useful in informing coherent governance and facilitating progress toward SDGs across social, economic, and environmental dimensions simultaneously.

Key Words: *conservation; poverty alleviation; sustainable development goals; synergies; trade-offs*

INTRODUCTION

To facilitate progress toward sustainability across social, economic, and environmental dimensions simultaneously, the member states of the United Nations adopted the 2030 Agenda for Sustainable Development in 2015, which aims to achieve 17 Sustainable Development Goals (SDGs) by 2030 (United Nations 2015). The 17 SDGs are "an integrated and indivisible whole" of global objectives designed to catalyze coherent governance and avoid "sustainability solutions" in one system causing deleterious effects in others (Colglazier 2015). But operationalizing the 2030 Agenda on the ground is far from straightforward. The grand challenges facing humanity, from poverty, water scarcity, and food insecurity to climate change and biodiversity loss, are closely intertwined (Griggs et al. 2017, Liu et al. 2018). The linked challenges, however, have often been managed in silos and critical interrelationships among them are largely ignored (Zhao et al. 2021), often with counterproductive consequences for sustainability (Fader et al. 2018, Wong and van der Heijden 2019). For example, biofuels were proposed as part of the solution to CO_2 emissions from burning fossil fuels (Rulli et al. 2016). Despite its potential to mitigate climate change (promoting SDG 13), the biofuel approach in many cases unintentionally threatens biodiversity and increases water and food shortages (undermining SDG 2, SDG 6, and SDG 15) because a large amount of land and water was diverted for biofuel production (Renzaho et al. 2017, Pörtner et al. 2021).

Knowledge of the SDG interrelationships and drivers behind them is key to addressing such challenges (Guerry et al. 2015, Nilsson et al. 2016, 2018). Armed with such knowledge, policy makers may identify and strengthen actions that facilitate progress toward different goals simultaneously and avoid unintended trade-offs (Xu et al. 2020). However, the nature and strengths of the interrelationships among SDGs are largely context specific and rely on the development strategies chosen to pursue them (Moallemi et al. 2020). This makes the evaluation of interrelationships among SDGs and the drivers behind them challenging (Tosun and Leininger 2017) and encourages a growing call for understanding the complex interrelationships among different goals (McGowan et al. 2019).

Evaluations of SDG interrelationships are still nascent (Fu et al. 2019). Previous studies about SDG interrelationships often focused on the pattern of the relationships using expert knowledge and syntheses of the literature. For example, Nilsson et al. (2016) proposed a rating system to depict the extent to which different SDGs are linked to each other based on expert knowledge of the possible influence of gain in one goal on the other goals. Tosun and Leininger et al. (2017) evaluated the linkages among SDGs based on overlaps among the descriptions of the 169 specific targets of the 17 SDGs. McGowan et al. (2019) used a formal systems analysis approach and quantitatively assessed the relationships among the 17 SDGs, also based on expert knowledge. Certainly, it is important to characterize patterns of the interrelationships among SDGs. But to understand why these linkages occur is also essential; that is we have to understand the drivers of the SDGs to identify where common drivers lead to the emergence of positive or negative linkages across SDGs. Such linkages can facilitate or hamper achieving the goals as a whole. A poor understanding of the drivers can often result in puzzling SDG interrelationships that beg for explanations (McGowan et al. 2019) and failures in identifying ways to maximize the reinforcing relationships among the goals and minimize the conflicting ones.

We offer an analysis of how common forms of human livelihoods impact several SDGs, thus showing how human activities drive

[1]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China, [2]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA, [3]Smithsonian's National Zoo and Conservation Biology Institute, Front Royal, VA, USA, [4]Department of Sociology and Environmental Science and Policy Program, Michigan State University, East Lansing, MI, USA, [5]Natural Resource Department, Faculty of Geo-information Science and Earth Observation (ITC), University of Twente, [6]Key Laboratory of Southwest China Wildlife Resources Conservation, China West Normal University, Ministry of Education, Nanchong, Sichuan Province, China

the emergence of trade-offs and synergies across SDGs in a particular context, the Wolong Nature Reserve (Wolong hereafter; Ouyang et al. 2001). Our results help explain important dynamics in the system we study. The four livelihoods we consider, (1) cropping (Linderman et al. 2005a), (2) local off-farm labor work (Zhang et al. 2018), (3) labor migration (temporary out-migration to work in cities, [Yang 2018]), and (4) livestock husbandry (Wang et al. 2021), are very common across the globe (Carter et al. 2014, Chung et al. 2018). Because of this commonality, the kinds of interactions we find in our study are also likely to occur beyond our study area. We consider three SDGs: SDG 1 (no poverty), SDG 3 (enhance human well-being), and SDG 15 (protect life on land; see Indicators for SDGs). On the basis of the findings from our study site, we provide suggestions on how to harmonize the livelihood impacts on the SDGs in Wolong. Although details will vary across contexts, we hope our methods and results can serve as a working model that can be tailored for studying drivers behind complex SDG interrelationships in other contexts (e.g., Carter et al. 2015).

CONCEPTUAL FRAMEWORK AND EVALUATION METHOD

Conceptual framework

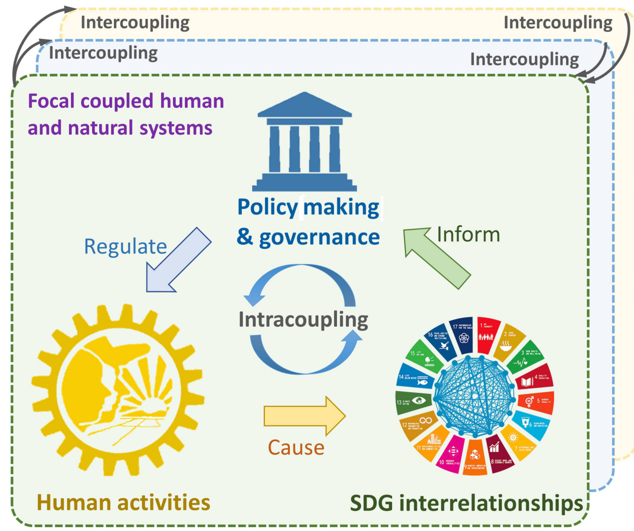
Our approach is an example application of existing frameworks for studying human-nature interactions as coupled human and natural systems (CHANS; Liu et al. 2007) and metacoupling (Liu 2017). We conceptualize a place as a CHANS in which humans interact with nature (Fig. 1). In the CHANS, we focus on three interdependent components that are important for the coherent management of the SDGs: human activities, SDG interrelationships, and policy making and governance (Fig. 1). Human activities are various actions performed by people to meet their needs based on assets available to them: financial, natural, human, physical, and social resources (Scoones 2009, Dietz 2015). Each of the human activities causes a set of impacts across the SDGs, which shape the interrelationships among the goals. Understanding how SDG interrelationships (e.g., synergies and trade-offs) emerge as a result of human activities can inform policy making and governance to regulate human activities so as to achieve progress toward different goals simultaneously (Fig. 1).

The human activities and their impacts on SDG interrelationships that occur in the focal location are not happening in isolation. Different places are increasingly connected by the flow of information, energy, people, organisms, and capital (Liu 2017). As a result, the interactions among human activities, SDGs, and governance within the focal CHANS (intracoupling; Liu 2017) are often affected by the interactions between the focal system and adjacent or distant systems (intercoupling; Liu 2017). Understanding of the intercouplings between the focal system and others helps us to account for the influences of socioeconomic and environmental interactions over distances (e.g., international trade) on the interactions within the system (Sun et al. 2018, Dou et al. 2020, Zhao et al. 2020, Tromboni et al. 2021; Fig. 1).

Quantifying the effects of human activities on SDG interrelationships

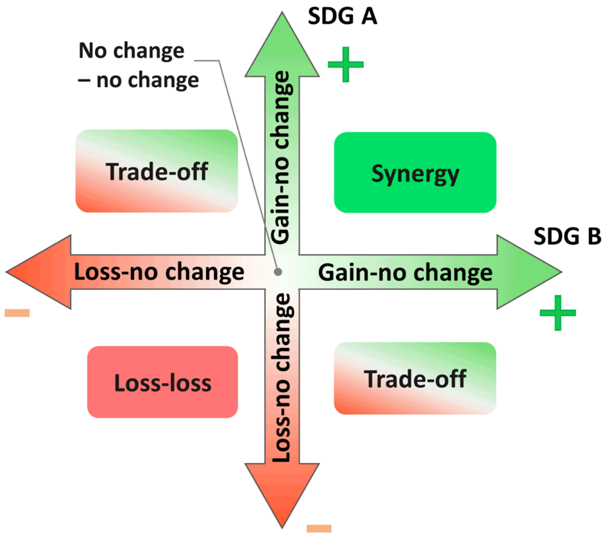
Interrelationships among SDGs can be viewed as an assembly of bilateral linkages among the goals. The bilateral linkages describe the extent to which the progress towards one goal may be

Fig. 1. The conceptual framework for unraveling the human drivers behind interrelationships among SDGs. Different human activities generate varying effects on SDGs and shape the interrelationships among the goals. An improved understanding of the impacts of human activities on SDG interrelationships informs policymaking and governance, which in turn regulate the human activities to minimize conflicts among goals. This interaction process within focal coupled human and natural systems (intracoupling) affects, and is affected by, adjacent or distant human-nature systems through intercouplings.



positively or negatively associated with the progress towards the other. Human activity often impacts more than one goal and shapes the linkages across these goals. For example, transitioning agricultural land for biofuel production could positively impact clean energy provision (SDG 7) while negatively affecting food security (SDG 2) and biodiversity (SDG 15; Renzaho et al. 2017, Pörtner et al. 2021), contributing to a trade-off linkage between SDG 7 and SDG 2 as well as between SDG 7 and SDG 15. We propose a five-point scale to score the effect of a human activity on the bilateral linkage between a pair of goals to reflect the capability of the activity to simultaneously facilitate the goals. Because the impacts of an activity on different goals (e.g., impact on poverty and impact on wildlife conservation) are often not comparable, this scoring is based on the nature of the impacts (positive, negative, or neutral [no significant effect]) of human activity on the goals and does not consider the magnitude of the impacts. The possible combination of the nature of the impacts on a pair of goals can be positive-positive, positive-neutral, positive-negative, neutral-neutral, negative-neutral, and negative-negative. Those six different combinations correspond to six different types of effects of an activity on the bilateral linkage between a pair of goals: synergy (positive effect on both goals), gain-no change (positive effect on one goal, neutral effect on the other), trade-off (positive effect on one goal, negative on the other), no change-no change (neutral effect on both), loss-no change (negative effect on one goal, neutral effect on the other), and loss-loss (negative effects on both goals; Fig. 2). It can be useful to score those six different types of effects on a bilateral

Fig. 2. Illustration (left) and descriptions (right) of the six types of effects of human activity on a bilateral linkage between two Sustainable Development Goals (SDGs): synergy, gain-no change, trade-off, no change-no change, loss-no change, and loss-loss. The type of the effect of a human activity on a linkage between two SDGs is defined by the impacts of human activity on the goals. We ranked and scored different types of effects on bilateral linkage based on their capabilities to facilitate the achievement of the two goals at the ends of the linkage simultaneously.



Impacts on the two SDGs	Effect on the linkage	Score of the effect
Positive on both	Synergy	+2
Positive on one, neutral on the other	Gain-no change	+1
Positive on one, negative on the other	Trade-off	0
Neutral on both	No change -no change	0
Negative on one, neutral on the other	Loss-no change	-1
Negative on both	Loss-loss	-2

linkage ranging from the highest (synergy, scoring +2) to the lowest (loss-loss, scoring -2) to reflect their capacity to facilitate the achievement of the two goals at the ends of the linkage simultaneously (Fig. 2). This scoring system is different from the rating system of SDG interrelation proposed by Nilsson et al (2016). Our system aims to rate the effect of an activity on an interlinkage between two goals while Nilsson's system rates the linkage itself.

The overall impact of human activity on the interrelationships among multiple SDGs is viewed as the sum of its effects on each of the bilateral linkages among the goals. We measured the overall impact by a coherence index, which is calculated by summing the scores of its effects on all the bilateral linkages among the goals. The total number of bilateral linkages among N SDGs equals $N \times (N\text{-}1)/2$. Therefore, the coherence index value of an activity on the interrelationships among N SDGs equals the sum of the scores of its effects on the $N \times (N\text{-}1)/2$ bilateral linkages. For example, if the impacts of a human activity on the three linkages among three SDGs are trade-off (0), synergy (+2), and gain-no change (+1), respectively, its coherence index value would be +3 (0 + 2 +1). A higher coherence index value of a human activity indicates it has a larger capability to facilitate progress toward the goals as a unified whole.

EMPIRICAL ANALYSIS

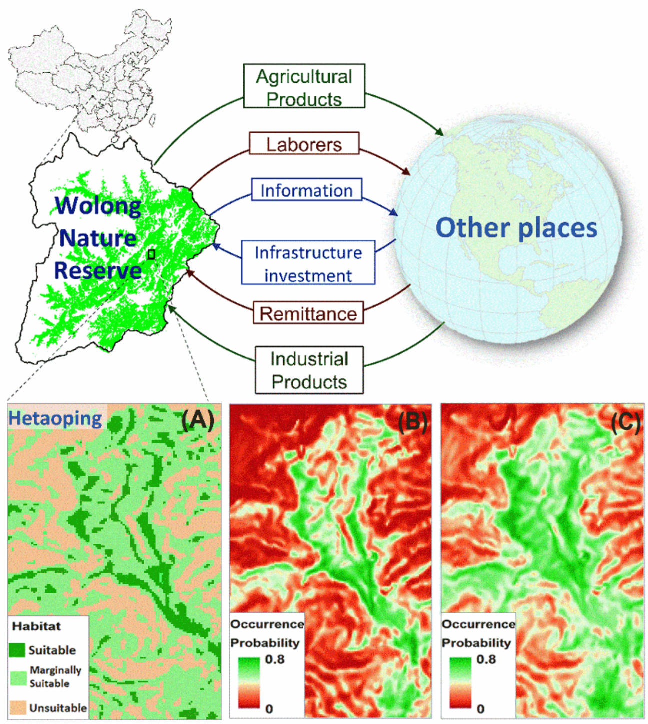
We operationalized our approach in Wolong. In this "proof of concept" analysis, we evaluated the impacts of the four most important human activities that constitute the key local livelihood strategies: cropping, local off-farm labor work, labor migration, and livestock husbandry. We examined the impact of each livelihood on the interrelationships among SDG 1 (no poverty), SDG 3 (enhance human well-being), and SDG 15 (protect life on land) to demonstrate our approach. Those three SDGs represent major economic, social, and ecological sustainability goals in Wolong and are directly or indirectly related to the other 14 SDGs. We note that the four livelihoods evaluated in this demonstration study can have impacts on other SDGs. We did not evaluate those impacts on other goals because of data limitations.

Wolong is an ideal site for demonstrating our approach. The human community, ecosystems, and the interactions between them in Wolong form a prototypical CHANS (Liu et al. 2016, Yang et al. 2018b, 2018c). Wolong is a flagship protected area in Sichuan Province, Southwest China (Fig. 3; Viña et al. 2008). It is designated primarily for the protection of giant pandas, an icon of global conservation, and an umbrella species whose habitats provide sanctuary for many other sympatric species (Linderman et al. 2005b, Li and Pimm 2016). Besides rich biodiversity, Wolong is also home to 4933 human residents (Yang et al. 2018a). Like many other places, Wolong is confronting the sustainability challenge of balancing the needs for socioeconomic development and biodiversity conservation (Yang et al. 2020). Previous research there (e.g., Chen et al. 2012, Yang et al. 2013a, Zhang et al. 2017, Yang et al. 2018a) has explicated some of the human-ecosystem dynamics and thus provides background for our work.

Intercouplings and livelihoods in Wolong

Wolong is connected with other places via intercouplings that shape livelihoods and their impacts on interrelationships among SDGs (Fig. 3). First, households in Wolong have access to outside markets where they sell crops and livestock (e.g., cabbage, radish,

Fig. 3. Wolong Nature Reserve (Wolong) connected with other places via intercouplings and giant panda occurrence probability at Hetaoping region in Wolong before and after livestock encroachment: (A) distribution of panda habitats at Hetaoping in Wolong; (B) the occurrence probability of giant pandas before the encroachment of livestock; and (C) the occurrence probability of giant pandas after the encroachment of livestock. The occurrence probability maps were adapted from (Zhang et al. 2017).



and sheep), a key part of local livelihoods based on cropping and livestock husbandry (Yang et al. 2013b, Liu et al. 2015). Second, as a flagship protected area, Wolong is a famous tourist destination and the site of many infrastructure investments from the central government. The flow of tourists and investments to Wolong provide off-farm labor work opportunities that contribute to the livelihoods of local residents (Liu et al. 2012, Yang et al. 2018a). Third, a growing number of households have members who out-migrate to cities for temporary jobs and send remittance back to Wolong communities, and this also influences our target SDGs (Chen et al. 2012, Yang et al. 2022).

We quantified household livelihood strategies using data from household surveys conducted from 2009 to 2014 (Appendix 1, A1.1–A1.2 and Fig. A1). We measured the local off-farm labor as the number of household members working in local off-farm sectors, cropping as the amount of cropland cultivated by the household, labor migration as the number of labor migrants in each household, and livestock husbandry as the number of livestock raised by each household. To make different types of livestock (sheep, yak, cattle, and horses) comparable, we followed methods from a previous study (Yang et al. 2018a) and measured the livestock number using the equivalent number of sheep based on the ratios of their average selling prices obtained from our survey.

Indicators for SDGs

Although the United Nations has developed 232 indicators for the SDGs (United Nations 2018), these indicators are mostly designed for measuring SDGs at the national level. Many of them can be difficult to operationalize at micro levels (e.g., for households). For example, some of the United Nations indicators measure the progress toward SDGs as an increase in government expenditure to achieve the goals, a logic that cannot be directly applied to our household-level analyses in Wolong. Therefore, we used three measurements appropriate to our analyses as the indicators for the three SDGs: annual household income (SDG 1), human well-being (SDG 3), and giant panda habitat suitability (SDG 15).

For each SDG, there are a couple of specific targets to reflect different dimensions of the SDG. The indicators we chose to measure for SDG 1, SDG 3, and SDG 15 can reflect progress to multiple targets of each goal. We chose annual household income as an indicator for SDG 1 because increasing household income can address or reflect progress in achieving specific targets of SDG 1, such as reducing the number of people living in poverty (Target 1.1, Target 1.2), and improving access to social protection systems and economic resources (Target 1.3, Target 1.4). The median annual household income in the community in 2014 is modest at 53,324 Yuan ($7465 as of 2014), so income increases can have important impacts on these targets. Human well-being is measured by a composite index constructed using a survey-based approach that has been used in several studies in rural communities (Yang et al. 2013a, 2015, 2018a). The instrument (Table A1.1) is based on the human well-being framework proposed in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005). It includes five dimensions: basic material for good life, security, health, good social relations, and freedom of choice and action (Millennium Ecosystem Assessment 2005). These dimensions match key targets of SDG 3, such as combating diseases (Target 3.3), reducing premature mortality (Target 3.4), and enhancing security (Target 3.6). The measure has been calculated for each household using data from our survey. More technical details regarding the construction, validation, and application of the index can be found in previous studies (Yang et al. 2013a, 2015, 2018a).

We chose giant panda habitat suitability as an indicator for SDG 15 because giant panda is an umbrella species for protection of thousands of species sharing the same habitat (Li and Pimm 2016). Changes in giant panda habitat suitability can therefore serve as a barometer for important targets of SDG 15 in this region (Xu et al. 2017), such as the integrity of local ecosystems (Target 15.1, 15.4) and effectiveness of conservation management (Target 15.2, 15.5). We followed previous studies in Wolong (Yang et al. 2013c, Chen et al. 2014) and measured household influence on giant panda habitat suitability using the amount of fuelwood collected by each household because fuelwood collection is a major pathway by which local communities degrade panda habitat (Bearer et al. 2008). Of the four livelihoods considered, livestock husbandry may generate a sizable impact on panda habitat through an extra pathway in addition to affecting household fuelwood collection. Previous studies in Wolong (Hull et al. 2014, Zhang et al. 2017) and other nature reserves (Li et al. 2017, 2019) show that livestock can have a major impact on giant panda habitat suitability by encroaching into core habitats, competing with pandas for space and food sources, and driving pandas from highly suitable habitats to less suitable areas. To capture this impact, we used changes in giant pandas' occurrence probability in their habitats before and after livestock encroachment at Hetaoping area in Wolong as the second indicator of the impact of livestock husbandry on giant panda habitat suitability. A decrease in occurrence probability of pandas in their core habitats after the encroachment of livestock indicates that livestock generated a negative impact on panda habitat suitability.

Quantifying the impacts of livelihoods on SDGs

To evaluate the impacts of different livelihoods on the three SDGs at household level, we compiled a panel dataset using socioeconomic information on households in 2009 and 2014 (Appendix 1, A1.1). In total, there were 186 households surveyed in both years. With the panel data, we constructed linear regression models to relate changes in annual household income, human well-being index, and fuelwood collection between 2009 and 2014 to changes in household livelihoods during the same period. To control for potential confounding effects, our models included some other socioeconomic and demographic factors that may affect changes in the three SDGs (Table A2.1). Similar to livelihood activities, some of these factors (e.g., number of laborers in a household) may change during the study period (2009 to 2014); therefore, we included variables measuring these socioeconomic and demographic conditions in 2009 and their changes between 2009 and 2014 in our models (Table A2.1). The general form of the models can be given as

$$
\begin{cases}
HWB_{\Delta} = \beta_0 + \beta_1 HWB_{2009} + \beta_2 L_{2009} + \beta_3 L_{\Delta} + \beta_4 X_{2009} \\
\qquad + \beta_5 X_{\Delta} + \epsilon \\
INC_{\Delta} = \beta_0 + \beta_1 INC_{2009} + \beta_2 L_{2009} + \beta_3 L_{\Delta} + \beta_4 X_{2009} \\
\qquad + \beta_5 X_{\Delta} + \epsilon \\
FW_{\Delta} = \beta_0 + \beta_1 FW_{2009} + \beta_2 L_{2009} + \beta_3 L_{\Delta} + \beta_4 X_{2009} \\
\qquad + \beta_5 X_{\Delta} + \epsilon
\end{cases}
\tag{1}
$$

where HWB_{Δ}, INC_{Δ}, FW_{Δ} refer to changes in human well-being index, annual household income, and fuelwood collection between 2009 and 2014, respectively; HWB_{2009}, INC_{2009}, FW_{2009} refer to the status of human well-being index, household income, and fuelwood collection in 2009, respectively; L_{2009} and L_{Δ} represent the vectors of livelihood variables in 2009 and their changes between 2009 and 2014, respectively; X_{2009} and X_{Δ} represent the vectors of other socioeconomic and demographic variables in 2009 and their changes between 2009 and 2014, respectively; β_0 and β_1 are intercept and coefficient for the initial status of the SDG indicators, respectively; β_2–β_5 are the vectors of other coefficients to be estimated; ε is the error term. In essence, this is a fixed-effect model where change in an SDG for the household is predicted based on initial SDG level and household characteristics and changes in household characteristics over time (Table A2.1). Standard regression diagnostics of linear regression assumptions revealed no concerns; variance inflation factors were all below 10. The sample size for our regression models is 186. The size of the sample meets the rule of thumb of at least 10 observations per independent variable to detect reasonable-sized effects, but we acknowledge that it may not be large enough to detect small effects. Our study uses existing data to demonstrate the application of the proposed approach. Future research that includes new data collection could usefully deploy procedures, such as power analysis, to ensure the size of the sample is large enough to estimate target effect sizes. We performed the regression analyses in R (R Development Core Team 2020) using the package "rms" (Harrell Jr 2016).

To evaluate the impact of livestock encroachment on giant panda habitat suitability, we analyzed panda occurrence probability change in the Hetaoping area, which is a roughly 30 km² area in Wolong (Fig. 3), with more than 20 pandas living there (Zhang et al. 2017). As a core habitat of giant pandas that has been invaded by livestock, Hetaoping is an ideal site to study the impact of livestock encroachment on habitat suitability. We obtained from a previous study the occurrence probability maps before (year 2012) and after (year 2014) the encroachment of livestock (Zhang et al. 2017). To understand the giant panda occurrence probability change across the landscape, we mapped the distribution of giant panda habitat at Hetaoping using an integrated biophysical model that combines elevation, slope, and forest cover (Liu et al. 2001, Xu et al. 2017). The elevation and slope were derived from a 30 m SRTM digital elevation model. The forest cover was obtained from the digitization of a 0.65 m resolution Google Earth imagery in 2014.

RESULTS

Livelihood impacts on SDGs

Our regression results show that local off-farm labor work had significant positive effects on SDG 1 (no poverty), SDG 3 (enhance human well-being), and SDG 15 (protect life on land). The change in the number of laborers with off-farm jobs inside the reserve was positively related to changes in the human well-being index (Coefficient [Coef.] = 0.031, $p < 0.05$, 95% confidence interval [CI] = [0.006, 0.057]) and in log-transformed annual household income (Coef. = 0.48, $p < 0.01$, CI = [0.337, 0.624]), while having a significant negative effect on fuelwood collection (Coef. = -478.5, $p < 0.05$, CI = [-947.26, -9.79]; Table 1). The expected human well-being index of households with one more laborer participating in local off-farm work between 2009 and 2014 would be 0.031 more than that of their counterparts on a scale of 0 to 1. Holding other variables constant, households with one more laborer participating in local off-farm work would have an additional 61.6% increase in their annual income between 2009 and 2014. On average, having one more laborer who participated in local off-farm work between 2009 and 2014 would decrease fuelwood collection of a household by 478.5 kg.

Cropping had a negative effect on SDG 15, but had little impact on promoting SDG 1 and SDG 3. Increases in cultivated cropland were negatively related to changes in household fuelwood collection (Coef. = 216.9, $p < 0.01$, CI = [69.21, 364.61]; Table 1). On average, an additional mu (1 mu = 0.067 ha) of cropland owned by a households between 2009 and 2014 would increase the household's fuelwood collection by 216.9 kg. Change in cultivated cropland had a positive association with human well-being and annual household income, but these effects were not statistically significant ($p > 0.05$; Table 1).

Table 1. Results of the regression models relate changes in Sustainable Development Goals (SDGs) indicators (human well-being index, annual household income, and fuelwood collection) to livelihood changes and other socioeconomic factors (sample size = 186). The models passed all diagnostics of linear regression assumptions. Variance inflation factors were all tested to be < 10.

Variables	Coefficients		
	Household annual income†	Human well-being‡	Fuelwood collection§
Livelihoods and their changes			
Local off-farm labor work in 2009	0.384***	0.0633**	-311.78
Change in local off-farm labor work from 2009 to 2014	0.481***	0.0313*	-478.53*
Cropping in 2009	0.006	0.0046	313.02***
Change in cropping from 2009 to 2014	0.022	0.0074	216.92**
Labor migration in 2009	0.491***	0.0253	-815.92*
Change in labor migration from 2009 to 2014	0.529***	-0.0180	-445.88
Livestock husbandry in 2009	0.0003	-0.0001	0.43
Change in livestock husbandry from 2009 to 2014	-0.0001	-0.0004**	-0.52
Socioeconomic and demographic characteristics			
Fuelwood collection in 2009	-	-	-0.9959***
Human well-being in 2009	0.297	-0.7142***	2240.08
Household income in 2009	-0.939***	-0.0152	-89.50
Household size in 2009	0.095	-0.0342*	-20.05
Change in household size from 2009 to 2014	0.087	-0.0239*	-283.36
Number of laborers in 2009	-0.009	0.035	297.14
Change in number of laborers from 2009 to 2014	0.017	0.0397**	375.24
Laborers' education level	-0.012	0.001	-77.50
Change in laborers' education level	-0.027	-0.0022	-66.55
Respondent's gender	-0.061	0.0061	64.33
Respondent's education	0.035	0.007*	-80.86
Constant	8.84	0.6019***	2053.37
R^2	0.78	0.51	0.76
Adjusted R^2	0.76	0.45	0.73
Predicted R^2	0.73	0.39	0.69

†The outcome variable here is change in log-transformed annual gross income from 2009 to 2014.
‡The outcome variable here is change in human well-being index from 2009 to 2014; the range of human well-being index is from 0 to 1.
§ The outcome variable here is change in fuelwood use from 2009 to 2014; the unit of fuelwood use is kg. Negative coefficients in predicting fuelwood are viewed as positive impacts on SDG15.
*$p \le 0.05$; **$p \le 0.01$; ***$p \le 0.001$; two-tailed tests.

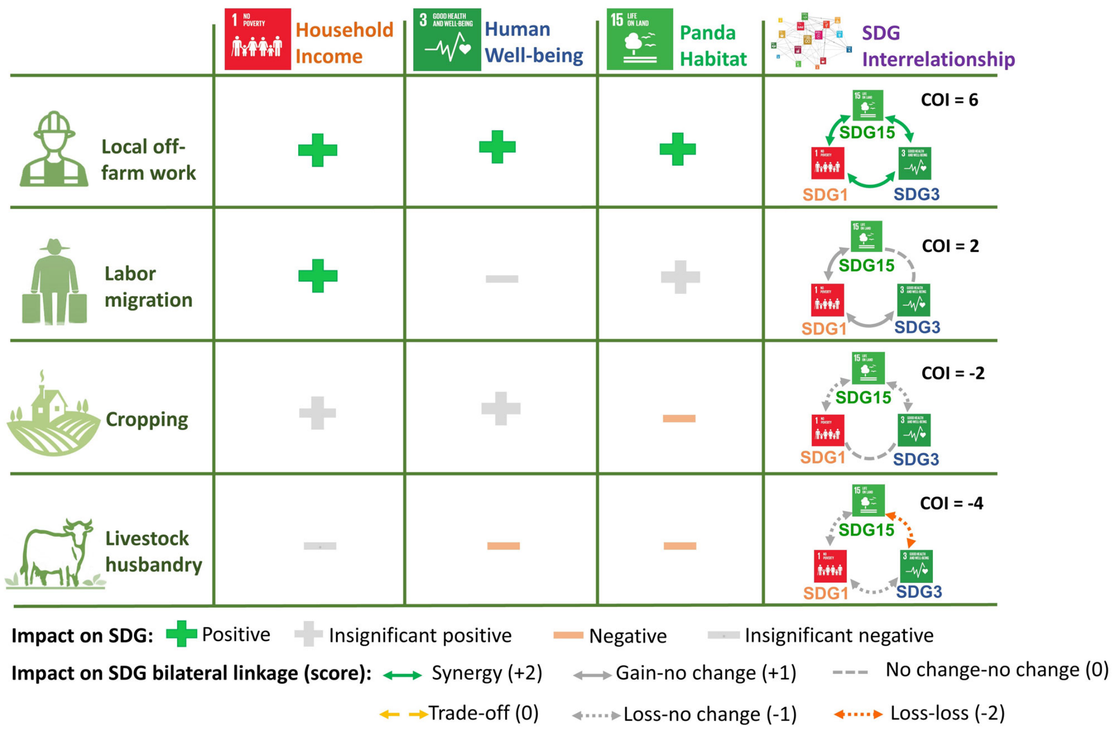
Labor migration positively affected SDG 1, but had little influence on SDG 3 and SDG 15. Change in labor migration was positively related to change in annual household income (Coef. = 0.53, $p < 0.001$, CI = [0.37, 0.69]). For households that had one more laborer who participated in labor migration, the percent increase in household income between 2009 and 2014 was higher than their counterparts by 69.7 percentage points. Change in labor migration was negatively related to change in fuelwood collection and human well-being, but neither of those coefficients were significant ($p > 0.05$).

The livestock husbandry impeded SDG 3, compromised SDG 15, and contributed little to SDG 1. Change in livestock husbandry was negatively associated with change in human well-being (Coef. = -0.0004, $p < 0.05$, CI = [-0.0008, -0.00005]). An additional livestock animal owned by a household would decrease household well-being index value by 0.0004. The association between livestock husbandry and annual household income was not statistically significant ($p > 0.1$; Table 1). Livestock husbandry did not show a significant influence on household fuelwood collection, but we found that the encroachment of livestock degraded the panda habitat (Fig. 3). After the encroachment of livestock into Hetaoping, the average panda occurrence probability decreased in suitable habitat area from 0.55 to 0.49 ($p < 0.001$, paired t-test) and increased in marginally suitable area from 0.26 to 0.32 ($p < 0.001$, paired t-test). This change pattern suggests that livestock encroachment had driven giant pandas from highly suitable habitats to marginally suitable habitats.

Livelihood impacts on SDG interrelationships

Based on the impacts on the three SDGs, we assessed each livelihood's effect on the interrelationships among SDG 1 (no poverty), SDG 3 (enhance human well-being), and SDG 15 (protect life on land; Fig. 4). Local off-farm work generated synergetic effects on all linkages among the three goals, with the highest coherence index value of +6. Labor migration caused two gain-no change effects and one no change-no change effect on the three linkages among the SDGs, with a coherence index value of +2. Cropping contributed little to the coherence among the SDGs. It led to two loss-no change and one no change-no change effect on the three linkages among the SDGs, with a coherence index value of -2. The most negative impact on the SDG interrelationships was found in livestock husbandry. It caused one loss-loss and two loss-no change effects on the linkages among the three SDGs, with a coherence index value of -4.

Fig. 4. Summary of the livelihood impacts on Sustainable Development Goal (SDG) 1, SDG 3, and SDG 15, and on the interrelationships among them. The numbers in the parentheses next to the symbols for impacts on SDG bilateral linkage are the scores for the types of impact (Fig. 2). The total impact of each livelihood on the interrelationships among SDGs was measured by the coherence index (COI), which reflects the livelihood's capability to facilitate progress toward the three goals simultaneously.



These results suggest that local off-farm employment can produce positive synergies among the three SDGs we examined, as can, to a lesser degree, labor migration to cities that send remittances back. In contrast, livestock husbandry seems to cause negative linkages among the goals because it slows progress toward SDG 3 and SDG 15. Of course, these results are specific to the context in which we conducted our study. In other regions, the same livelihood strategies could have different effects on the SDGs and drive different linkages among them.

DISCUSSION

Understanding the effects of human livelihood activities on SDGs and their interrelationships can help policy makers identify obstacles to achieving progress toward the goals. For example, our results show that livestock husbandry in Wolong impeded the achievement of all the three SDGs. An important factor driving the rapid livestock expansion in Wolong is an incentive policy of the local government, that provides interest-free loans to households to raise more livestock (Hull et al. 2014, Zhang et al. 2017). Despite the government's good intentions of boosting household income and well-being, our findings show that livestock expansion actually did the opposite. To make matters worse, free-roaming livestock encroached into giant panda habitat because the pasture land in Wolong was not sufficient to support the rapidly growing number of livestock (Hull et al. 2014, Zhang et al. 2017). To avoid the continuation of the unexpected loss-loss impact on SDG 3 and SDG 15 and enhance the synergies among the goals, we suggest that livestock expansion should be discouraged rather than incentivized in Wolong.

Because different places are increasingly connected by intercouplings (Liu 2017), factors beyond the local system can have important influences on SDG interrelationships. For example, our results show that labor migration positively affected household income but showed no effect on promoting household well-being. A possible reason for this is that labor migrants in cities often confront many hardships (e.g., poor education resources for their children; Qin 2010). Therefore, policies in cities that help to overcome the hardships confronting labor migrants (e.g., investing more to provide quality education to children of labor migrants) can be considered to help turn the effect of labor migration on human well-being to positive and diminish the counterproductive parts of the interrelationships among SDGs.

In different political, geographic, and temporal settings, the interactions among human activities, governance, and SDG interrelationships will likely be different. For example, in many other places, livestock is fed in fenced areas that is not important for wildlife and therefore may not cause much impact on wildlife habitat, generating different effects on SDG interrelationships. Another example is the positive impact of local off-farm jobs on wildlife habitats (SDG 15) in Wolong. Tourism development and infrastructure building, the main sources of off-farm jobs in Wolong, are strictly constrained within a small residential area (< 0.15% of the total area of the reserve) so that possible detrimental impacts on wildlife habitats from tourism development and infrastructure building are limited. However, poorly planned tourism development and associated infrastructure building, noise pollution, and irresponsible behavior of tourists have generated substantial negative impacts on wildlife habitats in some cases (Zhong et al. 2011). Human activities and SDG interrelationships in the same place may also change across time. For example, a new road connecting Wolong to the outside was completed in 2016 (Zhang et al. 2018) and is expected to generate substantial impacts on the intercouplings that link Wolong and other places (e.g., attract more tourist visitations), change local livelihoods (e.g., more people involved in tourism-related businesses), and thus reshape the SDG interrelationships. More research is needed to understand the impact of human activities on SDG interrelationships across space and time, and to assist the design of effective efforts to achieve progress toward different SDGs simultaneously. The evaluation approach and demonstration study presented here lay a good foundation for conducting similar research across different spatial and temporal settings. Many methods and insights from our previous studies conducted in Wolong have been applied to many other countries around the world (e.g., Liu et al. 2007, An et al. 2014) and at different times (e.g., Tuanmu et al. 2011).

Compared to studies evaluating the impacts on a single sustainability goal, it is often more challenging to reveal the effects of human activities on interrelationships between multiple SDGs. As a pioneering effort to tackle the challenges, our study has two limitations. First, we did not reveal the full range of the effects of human activities on SDG interrelationships. With the increased complexity of more goals, more data and analyses are required to assess the effects of human activities on the SDGs, as well as the interrelationships among them. In our demonstration study, for example, labor migration might also affect SDG 11 (sustainable cities and communities) by changing the demographic profile in both rural and urban areas. Our demonstration study did not assess those impacts because of data limitations. Second, weighing the positive impacts of human activities against their negative impacts on SDGs remains a challenge because impacts on different SDGs are often not comparable. The approach we proposed classifies and scores the effects of human activities on SDG interrelationships to measure their potential to achieve multiple goals simultaneously. This scoring approach is based on the nature of the impacts of human activities on SDGs and does not consider the magnitude of the impacts. Results from the approach can assist, but cannot replace, the necessary decision-making process to involve stakeholders and weigh the benefits against costs from certain activities. For example, agricultural expansion often generates a negative impact on wildlife habitats, but is essential for promoting many rural households' income (Socolar et al. 2019). Using our approach may identify this trade-off effect of agriculture expansion on the linkage between the goals of wildlife habitat conservation and poverty reduction, but cannot measure or judge whether it is worthwhile to pursue the economic benefits at the cost of some biodiversity loss. As is often the case, science has to be complemented with consideration of values in making decisions (Dietz 2013). The government, communities, and other stakeholders need to weigh the positive and negative impacts of cropping and jointly plan future cropping strategies to balance the needs of wildlife habitat conservation and human well-being.

CONCLUSION

We presented an approach to understanding how human drivers shape the complex interrelationships among SDGs. Our method moves from the focus of previous research on patterns of SDG interrelationships to interrogating the drivers that shape those patterns. We have focused on the livelihood strategies of households in a local community located in an area of global significance for biodiversity. This bottom-up approach complements top-down (international and national level) analyses tracking changes and patterns of interrelationships among SDGs. We believe this bottom-up approach can help policy makers, resource managers, and other stakeholders to design more effective strategies to unlock the transformational potential of the 2030 Agenda.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13275

Acknowledgments:

We thank Xuejia Li, Dan Li, Yan Chen, and Xuemei Li for their help in collecting some of the data used in this study, and the interviewees for their time and cooperation in participating in our household surveys. We appreciate the logistical support from the staff at Wolong Nature Reserve and Chinese Academy of Sciences during our fieldwork, especially Hemin Zhang and Zhiyun Ouyang. We are grateful for funding from the Smithsonian Institution, U.S. National Science Foundation (grant #1924111), Michigan State University, the Key Laboratory of Southwest China Wildlife Resources Conservation (grant # XNYB19-01), and the National Natural Science Foundation of China (grant #41571517). The contributions of Liu and Dietz were supported in part by Michigan AgBio Research.

Data Availability:

The data and code that support the findings of this study are openly available in Open Science Framework at osf.io/ht6w4/. Ethical approval for this research was granted by the Institutional Review Board of Michigan State University (Approval Number: 10-660).

LITERATURE CITED

An, L., A. Zvoleff, J. Liu, and W. Axinn. 2014. Agent-based modeling in coupled human and natural systems (CHANS): lessons from a comparative analysis. Annals of the Association of American Geographers 104(4):723-745. https://doi.org/10.1080/00045608.2014.910085

Bearer, S., M. Linderman, J. Huang, L. An, G. He, and J. Liu. 2008. Effects of fuelwood collection and timber harvesting on giant panda habitat use. Biological Conservation 141(2):385-393. https://doi.org/10.1016/j.biocon.2007.10.009

Carter, N., M. Jasny, B. Gurung, and J. Liu. 2015. Impacts of people and tigers on leopard spatiotemporal activity patterns in a global diversity hotspot. Global Ecology and Conservation 3:149-162. https://doi.org/10.1016/j.gecco.2014.11.013

Carter, N. H., A. Viña, V. Hull, W. J. McConnell, W. Axinn, D. Ghimire, and J. Liu. 2014. Coupled human and natural systems approach to wildlife research and conservation. Ecology and Society 19(3):43. http://dx.doi.org/10.5751/ES-06881-190343

Chen, X., K. Frank, T. Dietz, and J. Liu. 2012. Weak ties, labor migration, and environmental impacts: toward a sociology of sustainability. Organization and Environment 25(1):3-24. https://doi.org/10.1177/1086026611436216

Chen, X., A. Viña, A. Shortridge, L. An, and J. Liu. 2014. Assessing the effectiveness of payments for ecosystem services: an agent-based modeling approach. Ecology and Society 19(1):7. https://doi.org/10.5751/ES-05578-190107

Chung, M. G., T. Dietz, and J. Liu. 2018. Global relationships between biodiversity and nature-based tourism in protected areas. Ecosystem Services 34:11-23. http://doi.org/10.1016/j.ecoser.2018.09.004

Colglazier, W. 2015. Sustainable development agenda: 2030. Science 349(6252):1048-1050. https://doi.org/https://doi.org/10.1126/science.aad2333

Dietz, T. 2013. Bringing values and deliberation to science communication. Proceedings of the National Academy of Sciences of the United States of America 110(SUPPL. 3):14081-14087. https://doi.org/10.1073/pnas.1212740110

Dietz, T. 2015. Prolegomenon to a structural human ecology of human well-being. Sociology of Development 1(1):123-148. https://doi.org/10.1525/sod.2015.1.1.123

Dou, Y., R. F. B. da Silva, P. McCord, J. G. Zaehringer, H. Yang, P. R. Furumo, J. Zhang, J. C. Pizarro, and J. Liu. 2020. Understanding how smallholders integrated into pericoupled and telecoupled systems. Sustainability 12(4):1452-1462. https://doi.org/10.3390/su12041596

Fader, M., C. Cranmer, R. Lawford, and J. Engel-Cox. 2018. Toward an understanding of synergies and trade-offs between water, energy, and food SDG targets. Frontiers in Environmental Science 6(9):112. https://doi.org/10.3389/fenvs.2018.00112

Fu, B., S. Wang, J. Zhang, Z. Hou, and J. Li. 2019. Unravelling the complexity in achieving the 17 sustainable-development goals. National Science Review 6(3):386-388. https://doi.org/https://doi.org/10.1093/nsr/nwz038

Griggs, D. J., M. Nilsson, A. Stevance, D. McCollum, editors. 2017. A guide to SDG interactions: from science to implementation. International Council for Science, Paris, France.

Guerry, A. D., S. Polasky, J. Lubchenco, R. Chaplin-Kramer, G. C. Daily, R. Griffin, M. Ruckelshaus, I. J. Bateman, A. Duraiappah, T. Elmqvist, M. W. Feldman, C. Folke, J. Hoekstra, P. M. Kareiva, B. L. Keeler, S. Z. Li, E. McKenzie, Z. Y. Ouyang, B. Reyers, T. H. Ricketts, J. Rockström, H. Tallis, and B. Vira. 2015. Natural capital and ecosystem services informing decisions: from promise to practice. Proceedings of the National Academy of Sciences of the United States of America 112(24):7348-7355. https://doi.org/10.1073/pnas.1503751112

Harrell Jr, F. E. 2016. rms: Regression Modeling Strategies. R package version 5.0-0. CRAN.

Hull, V., J. D. Zhang, S. Q. Zhou, J. Y. Huang, A. Viña, W. Liu, M. -N. Tuanmu, R. G. Li, D. Liu, W. H. Xu, Y. Huang, Z. Y. Ouyang, H. M. Zhang, and J. G. Liu. 2014. Impact of livestock on giant pandas and their habitat. Journal for Nature Conservation 22(3):256-264. https://doi.org/10.1016/j.jnc.2014.02.003

Li, B., and S. Pimm. 2016. China's endemic vertebrates sheltering under the protective umbrella of the giant panda. Conservation Biology 30(2):329-339. https://doi.org/10.1111/cobi.12618

Li, B. V., S. L. Pimm, S. Li, L. Zhao, and C. Luo. 2017. Free-ranging livestock threaten the long-term survival of giant pandas. Biological Conservation 216:18-25. https://doi.org/10.1016/j.biocon.2017.09.019

Li, C., T. Connor, W. Bai, H. Yang, J. Zhang, D. Qi, and C. Zhou. 2019. Dynamics of the giant panda habitat suitability in response to changing anthropogenic disturbance in the Liangshan Mountains. Biological Conservation 237:445-455. https://doi.org/10.1016/j.biocon.2019.07.018

Linderman, M. A., L. An, S. Bearer, G. He, Z. Ouyang, and J. Liu. 2005a. Modeling the spatio-temporal dynamics and interactions of households, landscapes, and giant panda habitat. Ecological Modelling 183(1):47-65. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2004.07.026

Linderman, M., S. Bearer, L. An, Y. Tan, Z. Ouyang, and J. Liu. 2005b. The effects of understory bamboo on broad-scale estimates of giant panda habitat. Biological Conservation 121 (3):383-390. https://doi.org/https://doi.org/10.1016/j.biocon.2004.05.011

Liu, J. 2017. Integration across a metacoupled world. Ecology and Society 22(4):29. https://doi.org/10.5751/ES-09830-220429

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider, and W. W. Taylor. 2007. Complexity of coupled human and natural systems. Science 317(5844):1513-1516. https://doi.org/10.1126/science.1144004

Liu, J., V. Hull, H. C. J. Godfray, D. Tilman, P. Gleick, H. Hoff, C. Pahl-Wostl, Z. Xu, M. G. Chung, J. Sun, and S. Li. 2018. Nexus approaches to global sustainable development. Nature Sustainability 1(9):466-476. https://doi.org/10.1038/s41893-018-0135-8

Liu, J., V. Hull, J. Luo, W. W. Yang, W. Liu, A. Viña, C. Vogt, Z. Xu, H. Yang, J. Zhang, L. L. An, X. Chen, S. Li, Z. Ouyang, W. Xu, and H. Zhang. 2015. Multiple telecouplings and their complex interrelationships. Ecology and Society 20(3):44. https://doi.org/10.5751/ES-07868-200344

Liu, J., V. Hull, W. Yang, A. Viña, X. Chen, Z. Ouyang, and H. Zhang. 2016. Pandas and people: coupling human and natural systems for sustainability. Oxford University Press, Oxford, UK. https://doi.org/10.1093/acprof:oso/9780198703549.001.0001

Liu, J., M. Linderman, Z. Ouyang, L. An, J. Yang, and H. Zhang. 2001. Ecological degradation in protected areas: the case of

Wolong nature reserve for giant pandas. Science 292 (5514):98-101. https://doi.org/10.1126/science.1058104

Liu, W., C. A. Vogt, J. Luo, G. He, K. A. Frank, J. Liu. 2012. Drivers and socioeconomic impacts of tourism participation in protected areas. PLoS ONE 7(4):e35420. https://doi.org/10.1371/journal.pone.0035420

McGowan, P. J. K., G. B. Stewart, G. Long, and M. J. Grainger. 2019. An imperfect vision of indivisibility in the sustainable development goals. Nature Sustainability 2(1):43-45. https://doi.org/10.1038/s41893-018-0190-1

Millennium Ecosystem Assessment. 2005. Millennium ecosystem assessment. Ecosystems and human well-being: a framework for assessment. World Resources Institute, Washington, D.C., USA. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

Moallemi, E. A., S. Malekpour, M. Hadjikakou, R. Raven, K. Szetey, D. Ningrum, A. Dhiaulhaq, and B. A. Bryan. 2020. Achieving the sustainable development goals requires transdisciplinary innovation at the local scale. One Earth 3 (3):300-313. https://doi.org/10.1016/j.oneear.2020.08.006

Nilsson, M., E. Chisholm, D. Griggs, P. Howden-Chapman, D. McCollum, P. Messerli, B. Neumann, A.-S. Stevance, M. Visbeck, and M. Stafford-Smith. 2018. Mapping interactions between the sustainable development goals: lessons learned and ways forward. Sustainability Science 13(6):1489-1503. https://doi.org/10.1007/s11625-018-0604-z

Nilsson, M., D. Griggs, and M. Visbeck. 2016. Policy: map the interactions between sustainable development goals. Nature 534 (7607):320-322. https://doi.org/10.1038/534320a Ouyang, Z., J. Liu, H. Xiao, Y. Tan, and H. Zhang. 2001. An assessment of giant panda habitat in Woolong Nature Reserve. Acta Ecologica Sinica 21(11):1869-1874.

Pörtner, H. O., R. J. Scholes, J. Agard, E. Archer, A. Arneth, X. Bai, D. Barnes, M. Burrows, L. Chan, W. L. Cheung, S. Diamond, C. Donatti, C. Duarte, N. Eisenhauer, W. Foden, M. A. Gasalla, C. Handa, T. Hickler, O. Hoegh-Guldberg, K. Ichii, U. Jacob, G. Insarov, W. Kiessling, P. Leadley, R. Leemans, L. Levin, M. Lim, S. Maharaj, S. Managi, P A. Marquet, P. McElwee, G. Midgley, T. Oberdorff, D. Obura, E. Osman, R. Pandit, U. Pascual, A. P. F. Pires, A. Popp, V. Reyes-García, M. Sankaran, J. Settele, Y. J. Shin, D. W. Sintayehu, P. Smith, N. Steiner, B. Strassburg, R. Sukumar, C. Trisos, A. L. Val, J. Wu, E. Aldrian, C. Parmesan, R. Pichs-Madruga, D. C. Roberts, A. D. Rogers, S. Díaz, M. Fischer, S. Hashimoto, S. Lavorel, N. Wu, and H. T. Ngo. 2021. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.5281/zenodo.4782538

Qin, H. 2010. Rural-to-urban labor migration, household livelihoods, and the rural environment in Chongqing Municipality, Southwest China. Human Ecology 38(5):675-690. https://doi.org/10.1007/s10745-010-9353-z

R Development Core Team. 2020. R: A language and environment for statistical computing. https://cran.r-project.org/bin/windows/base/old/3.5.1/.

Renzaho, A., J. Kamara, and M. Toole. 2017. Biofuel production and its impact on food security in low and middle income countries: implications for the post-2015 sustainable development goals. Renewable and Sustainable Energy Reviews 78:503-516. https://doi.org/10.1016/j.rser.2017.04.072

Rulli, M. C., D. Bellomi, A. Cazzoli, G. De Carolis, and P. D'Odorico. 2016. The water-land-food nexus of first-generation biofuels. Scientific Reports 6(1):22521. https://doi.org/10.1038/srep22521

Scoones, I. 2009. Livelihoods perspectives and rural development. Journal of Peasant Studies 36(1):171-196. https://doi.org/10.1080/03066150902820503

Socolar, J. B., E. H. Valderrama Sandoval, and D. S. Wilcove. 2019. Overlooked biodiversity loss in tropical smallholder agriculture. Conservation Biology 33(6):1338-1349. https://doi.org/10.1111/cobi.13344

Sun, J., H. Mooney, W. Wu, H. Tang, Y. Tong, Z. Xu, B. Huang, Y. Cheng, X. Yang, D. Wei, F. Zhang, and J. Liu. 2018. Importing food damages domestic environment: evidence from global soybean trade. Proceedings of the National Academy of Sciences of the United States of America 115(21):5415-5419. https://doi.org/10.1073/pnas.1718153115

Tosun, J., and J. Leininger. 2017. Governing the interlinkages between the sustainable development goals: approaches to attain policy integration. Global Challenges 1(9):1700036. https://doi.org/10.1002/gch2.201700036

Tromboni, F., J. Liu, E. Ziaco, D. D. Breshears, K. L. Thompson, W. K. Dodds, K. M. Dahlin, E. A. LaRue, J. H. Thorp, A. Viña, M. M. Laguë, A. Maasri, H. Yang, S. Chandra, and S. Fei. 2021. Macrosystems as metacoupled human and natural systems. Frontiers in Ecology and the Environment 19(1):20-29. https://doi.org/10.1002/fee.2289

Tuanmu, M. -N., A. Viña, G. J. Roloff, W. Liu, Z. Ouyang, H. Zhang, and J. Liu. 2011. Temporal transferability of wildlife habitat models: implications for habitat monitoring. Journal of Biogeography 38(8):1510-1523. https://doi.org/10.1111/j.1365-2699.2011.02479.x

United Nations. 2015. Transforming our world: the 2030 agenda for sustainable development. UN, New York, New York, USA.

United Nations. 2018. Annex: global indicator framework for the sustainable development goals and targets of the 2030 agenda for sustainable development. UN, New York, New York, USA.

Viña, A., S. Bearer, H. Zhang, Z. Ouyang, and J. Liu. 2008. Evaluating MODIS data for mapping wildlife habitat distribution. Remote Sensing of Environment 112:2160-2169. https://doi.org/10.1016/j.rse.2007.09.012

Wang, Y., H. Yang, D. Qi, M. Songer, W. Bai, C. Zhou, and Q. Huang. 2021. Efficacy and management challenges of the zoning designations of China's national parks. Biological Conservation 254:108962. https://doi.org/10.1016/j.biocon.2021.108962

Wong, R., and J. van der Heijden. 2019. Avoidance of conflicts and trade-offs: a challenge for the policy integration of the united nations sustainable development goals. Sustainable Development 27(5):838-845. https://doi.org/10.1002/sd.1944

Xu, W., A. Viña, L. Kong, S. L. Pimm, J. Zhang, W. Yang, Y. Xiao, L. Zhang, X. Chen, J. Liu, and Z. Ouyang. 2017. Reassessing the conservation status of the giant panda using remote sensing. Nature Ecology and Evolution 1(11):1635-1638. https://doi.org/10.1038/s41559-017-0317-1

Xu, Z., Y. Li, S. N. Chau, T. Dietz, C. Li, L. Wan, J. Zhang, L. Zhang, Y. Li, M. G. Chung, and J. Liu. 2020. Impacts of international trade on global sustainable development. Nature Sustainability 3(11):964-971. https://doi.org/10.1038/s41893-020-0572-z

Yang, H. 2018. Complex effects of telecouplings on a coupled human and natural system. Michigan State University.

Yang, H., T. Dietz, W. Yang, J. Zhang, and J. Liu. 2018a. Changes in human well-being and rural livelihoods under natural disasters. Ecological Economics 151:184-194. https://doi.org/https://doi.org/10.1016/j.ecolecon.2018.05.008

Yang, H., F. Lupi, J. Zhang, X. Chen, and J. Liu. 2018b. Feedback of telecoupling: the case of a payments for ecosystem services program. Ecology and Society 23(2):45. https://doi.org/https://doi.org/10.5751/ES-10140-230245

Yang, H., F. Lupi, J. Zhang, and J. Liu. 2020. Hidden cost of conservation: a demonstration using losses from human-wildlife conflicts under a payments for ecosystem services program. Ecological Economics 169:106462. https://doi.org/10.1016/j.ecolecon.2019.106462

Yang, H., W. Yang, J. Zhang, T. Conner, and J. Liu. 2018c. Revealing pathways from payments for ecosystem services to socioeconomic outcomes. Science Advances 4(3):eaao6652. https://doi.org/https://doi.org/10.1126/sciadv.aao6652

Yang, H., A. Ligmann-Zielinska, Y. Dou, M. G. Chung, J. Zhang, and J. Liu. 2022. Complex effects of telecouplings on forest dynamics: an agent-based modeling approach. Earth Interactions 26(1):15-27. https://doi.org/10.1175/EI-D-20-0029.1

Yang, W., T. Dietz, D. B. Kramer, X. Chen, and J. Liu. 2013a. Going beyond the millennium ecosystem assessment: an index system of human well-being. PLoS ONE 8(5):e64582. https://doi.org/https://doi.org/10.1371/journal.pone.0064582

Yang, W., T. Dietz, D. B. Kramer, Z. Ouyang, and J. Liu. 2015. An integrated approach to understanding the linkages between ecosystem services and human well-being. Ecosystem Health and Sustainability 1(5):1-12. https://doi.org/10.1890/EHS15-0001.1

Yang, W., T. Dietz, W. Liu, J. Luo, and J. Liu. 2013b. Going beyond the millennium ecosystem assessment: an index system of human dependence on ecosystem services. PLoS ONE 8(5). https://doi.org/https://doi.org/10.1371/journal.pone.0064581

Yang, W., W. Liu, A. Viña, J. Luo, G. He, Z. Ouyang, H. Zhang, and J. Liu. 2013c. Performance and prospects of payments for ecosystem services programs: evidence from China. Journal of Environmental Management 127:86-95. https://doi.org/https://doi.org/10.1016/j.jenvman.2013.04.019

Zhang, J., T. Connor, H. Yang, Z. Ouyang, S. Li, and J. Liu. 2018. Complex effects of natural disasters on protected areas through altering telecouplings. Ecology and Society 23(3):17. https://doi.org/10.5751/ES-10238-230317

Zhang, J., V. Hull, Z. Ouyang, R. Li, T. Connor, H. Yang, Z. Zhang, B. Silet, H. Zhang, and J. Liu. 2017. Divergent responses of sympatric species to livestock encroachment at fine spatiotemporal scales. Biological Conservation 209:119-129. https://doi.org/10.1016/j.biocon.2017.02.014

Zhao, Z., M. Cai, T. Connor, M. G. Chung, and J. Liu. 2020. Metacoupled tourism and wildlife translocations affect synergies and trade-offs among sustainable development goals across spillover systems. Sustainability 12(18):7677. https://doi.org/10.3390/su12187677

Zhao, Z., M. Cai, F. Wang, J. A. Winkler, T. Connor, M. G. Chung, J. Zhang, H. Yang, Z. Xu, Y. Tang, Z. Ouyang, H. Zhang, and J. Liu. 2021. Synergies and tradeoffs among sustainable development goals across boundaries in a metacoupled world. Science of the Total Environment 751:141749. https://doi.org/10.1016/j.scitotenv.2020.141749

Zhong, L., J. Deng, Z. Song, and P. Ding. 2011. Research on environmental impacts of tourism in China: progress and prospect. Journal of Environmental Management 92(11):2972-2983. https://doi.org/10.1016/j.jenvman.2011.07.011

Appendix 1 for

Unraveling human drivers behind complex interrelationships among sustainable development goals: a demonstration in a flagship protected area

This document includes:

A1 Household surveys

A2 Changes in livelihoods in Wolong

Fig. A1 Livelihood changes during the study period from 2009 to 2014. (a) The percentage of households with member(s) working in local off-farm sectors in Wolong; (b) The average cropland area each household cultivated in Wolong; (c) The percentage of households with member(s) temporarily working outside Wolong; (d) The average number of livestock (as measured by equivalent number of sheep) raised by pastoral households in Wolong.

Table A1 Survey instrument for constructing the human well-being index based on the Millennium Ecosystem Assessment framework. Reproduced from (Yang et al. 2013).

Table A2 Summary of variables included in the linear regression models that relate changes in SDG indicators (human well-being index, household income, and fuelwood collection) to livelihood changes and other socioeconomic factors (sample size = 186).

A1 Household surveys

The data for evaluating the impacts of the livelihoods on SDG intercorrelations in Wolong at the household level were all derived from survey data. Since household members often make joint or coordinated decisions regarding livelihood affairs, data characterizing livelihoods and SDGs were mainly collected at the household level. We collected household survey data in Wolong in 2010 and 2015. It contains detailed demographic (e.g., household size, members' age, education, and occupation) and socioeconomic (e.g., cropland area, number of livestock, livestock selling prices, and income sources) information of local households in 2009 and 2014 respectively. In the surveys, we included questions (Table A1) to collect information for the construction of human well-being index. We conducted these surveys in the form of face-to-face interviews. During these interviews, we selected household heads or their spouses as interviewees because they usually have the best knowledge about their households' affairs. Before performing the formal surveys, we conducted pretests to assess respondents' comprehension of our survey questions and how difficult they were to answer. Based on interviewees' responses in pretests, we iteratively revised our survey instruments to ensure that interviewees understood and were able to answer our questions correctly. In total, 287 and 245 households completed our formal surveys, with a response rate of 95%, and 96%, respectively. Of the 287 households randomly sampled in 2010, 186 households were revisited in 2015. We asked the survey questions using Mandarin Chinese. 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/).

A2 Changes in livelihoods in Wolong

We observed that cropping in Wolong decreased from 2009 to 2014 (Fig. A1). The average amount of cropland cultivated by each household decreased from 3.4 mu (1 mu = 0.067 ha) in 2009 to 2.9 mu in 2014. About 39% of the cropland loss was caused by the lasting (or post-disaster) impacts of landslides after the 2008 Wenchuan Earthquake and the rest (61%) was caused by land appropriation for infrastructure construction.

The proportion of households having laborer(s) with temporary or permanent off-farm jobs inside Wolong maintained a high level, albeit decreased somewhat after the earthquake: 75.6% in 2009 and 65.2% in 2014 (Fig. A1). Our survey data show that the government-initiated infrastructure construction was the main source of local off-farm jobs in Wolong, with 74% in 2009 and 63% in 2014 of local off-farm jobs were related to infrastructure construction projects. The decline in the local off-farm labor job opportunities might be explained by the completion of some reconstruction projects during the period (Aba Administration 2016).

The other two major types of livelihoods, labor migration and livestock husbandry, increased from 2009 to 2014 (Fig. A1). The proportion of households with member(s) temporarily working in cities increased from 26.8% in 2009 to 48.2% in 2014. The proportion of households that raised livestock during the study period was stable around 30%, but the average number of livestock raised by pastoral households increased from 80.2 in 2009 to 107.8 in 2014.

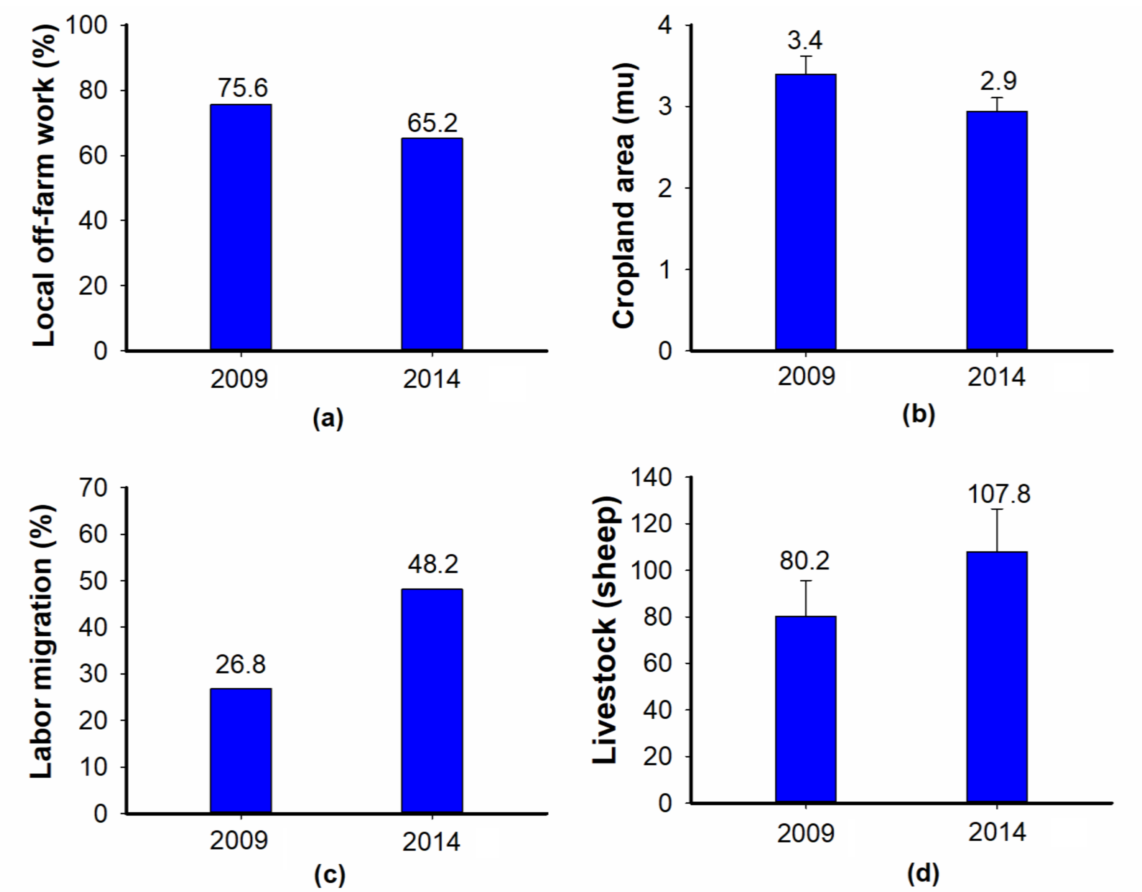


Figure A1 Livelihood changes during the study period from 2009 to 2014. (a) The percentage of households with member(s) working in local off-farm sectors in Wolong; (b) The average cropland area each household cultivated in Wolong; (c) The percentage of households with member(s) temporarily working outside Wolong; (d) The average number of livestock (as measured by equivalent number of sheep) raised by pastoral households in Wolong.

Table A1 Survey instrument for constructing the human well-being index based on the Millennium Ecosystem Assessment framework. Reproduced from (Yang et al. 2013).

Dimensions	**Indicator and description**
Basic material for good life	Q1.1: To what extent it is available to purchase necessities for daily life (Options: 1. Very inconvenient； 2. Inconvenient； 3. Unsure； 4. Convenient； 5. Very convenient)
	Q1.2: Your household can afford enough food with nutrition to keep alive and healthy
	Q1.3: Your household can afford to access basic facilities (e.g., television, washer) and services (e.g., transportation)
	Q1.4: You are satisfied with your housing condition (including size and quality)
	Q1.5: Overall, you are satisfied with your household's basic goods and services (e.g., food, clothe, living conditions, transportation) for life
Security	Q2.1: Your household's life safety in daily life is secure
	Q2.2: Your household's property safety in daily life is secure
	Q2.3*: The local crime incidence (e.g., theft, robbery, murder, other violent incidents) is low
	Q2.4*: The police and judicial system is always ready to help
	Q2.5: The police and judicial system can be trusted
	Q2.6*: It is safe to access basic goods and services such as food, water, and medicine etc. for life
	Q2.7: Overall, you are satisfied with your household security (e.g., life and property)
Health	Q3.1*: You are satisfied with your household's physical health (including illness and injury)?
	Q3.2: You are satisfied with your household's mental health (including stress, depression, and problems with emotions)?
	Q3.3: How often your household members do not get enough rest or sleep? (Options: 1. Always; 2. Often; 3. Sometimes; 4. Seldom; 5. Never)
	Q3.4: How often your household members are not healthy or do not have enough energy for everyday life? (Options: 1. Always; 2. Often; 3. Sometimes; 4. Seldom; 5. Never)
	Q3.5: How often do your household members have negative feelings such as blue mood, despair, anxiety, depression? (Options: 1. Always; 2. Often; 3. Sometimes; 4. Seldom; 5. Never)

	Q3.6*: How often do your household members have the opportunity for leisure activities? (Options: 1. Never; 2. Seldom; 3. Sometimes; 4. Often; 5. Always)
	Q3.7: Overall, you are satisfied with your household's health status
Good social relations	Q4.1: This is a close-knit neighborhood
	Q4.2: Most people in this village are basically honest and can be trusted
	Q4.3*: There are many opportunities to meet neighbors and work on solving community problems
	Q4.4*: How active do you think your household members in your community groups or village or township? (Options: 1. Very inactive; 2. inactive; 3. Neither inactive nor active; 4. Active; 5. Very active)
	Q4.5: Do you agree that people here look out mainly for the welfare of their own families and they are not much concerned with village/neighborhood welfare?
	Q4.6*: Suppose someone in your village/neighborhood had something unfortunate happen to them, such as a family member's sudden death, there are always some others would be ready to help
	Q4.7: Overall, you are satisfied with your household's social relationships with others
Freedom of choices and actions	Q5.1*: Do you think that your household members are always treated equally without regard to gender, race, language, religion, political beliefs, socioeconomic status and more? (Options: 1. Never; 2. Seldom; 3. Sometimes; 4. Often; 5. Always)
	Q5.2: Your household has affordable access to quality and nutritious food for an enjoyable life
	Q5.3: Your household has affordable access to quality medical care
	Q5.4: Your household has affordable access to quality education
	Q5.5: Your household has affordable access to spacious and quality house
	Q5.6*: It is difficult to find a satisfied job
	Q5.7: How often do you feel that you want to help others but limited by your socioeconomic or physical conditions that you cannot help them?
	Q5.8: Overall, you are satisfied with your freedom of choice and actions

Notes: Unless response options are specified after indicator contents, the options are designed in the five-category Likert scale (i.e., strongly disagree, mildly disagree, unsure, mildly agree, and strongly agree). *: Indicators not included in the final confirmatory factor analysis due to low variation or internal consistency with other indicators in the same categories.

Table A2 Summary of variables included in the linear regression models that relate changes in SDG indicators (human well-being index, household income, and fuelwood collection) to livelihood changes and other socioeconomic factors (sample size = 186).

Variables	Description	Mean (SD)
Outcome variables		
Well-being change	Change in the overall human well-being index value from 2009 to 2014.	0.271 (0.182)
Household income change	Change in log-transformed household gross annual income from 2009 to 2014 (Yuan [a])	0.77 (1.53)
Fuelwood collection change	Change in the amount of fuelwood collected by the household from 2009 to 2014 (Kg)	-984.5(4725.4)
Livelihoods and their changes		
Local off-farm labor work in 2009	The number of laborers earned income through working in local off-farm sectors in 2009.	1.102 (0.775)
Change in local off-farm labor work from 2009 to 2014	Change in the number of laborers working in local off-farm sectors from 2009 to 2014.	-0.054 (1.089)
Cropping in 2009	The number of laborers earned income through working outside the reserve in 2009.	0.409 (0.739)
Change in cropping from 2009 to 2014	Change in the number of laborers working outside the reserve from 2009 to 2014.	0.317 (1.081)
Labor migration in 2009	The area of the household's cropland in 2009. (Mu [b])	3.491 (3.228)
Change in labor migration from 2009 to 2014	Change in household's cropland area from 2009 to 2014. (Mu)	-0.481 (3.016)
Livestock husbandry in 2009	The number of livestock (as measured by equivalent number of sheep) raised in 2009.	1.898 (8.624)
Change in livestock husbandry from 2009 to 2014	Change in the number of livestock from 2009 to 2014.	4.056 (18.71)

Socioeconomic and demographic characteristics		
Human well-being in 2009	Overall human well-being index value in 2009.	0.363 (0.15)
Household income in 2009	Log-transformed gross income in 2009. (Yuan)	10.033 (1.391)
Fuelwood collection in 2009	The amount of fuelwood collected by the household in 2009 (Kg)	3117 (4273.9)
Household size in 2009	The number of members in the household in 2009.	4.796 (1.525)
Change in household size from 2009 to 2014	Household house size change from 2009 to 2014.	-0.215 (1.626)
Number of laborers in 2009	The number of members involved in income-earning activities in 2009.	3.387 (1.496)
Change in number of laborers from 2009 to 2014	Change in the number of laborers from 2009 to 2014.	-0.183 (1.718)
Laborers' education in 2009	The average schoolyears of laborers. (Year)	5.979 (3.037)
Change in laborers' education from 2009 to 2014	Change in laborers' average schoolyears from 2009 to 2014.	1.164 (4.21)
Respondent's gender	The gender of the respondent in our survey (0, female; 1, male)	0.602 (0.491)
Respondent's education	The schoolyears of the respondent. (Year)	5.688 (3.560)

[a] 1 Yuan = 0.14 USD as of 2015; [b] 1 mu = 1/15 hectare.

References cited in Appendix 1

Aba Administration. 2016. Wolong Nature Reserve has completed the post-disaster reconstruction. Aba. http://www.abazhou.gov.cn/jrab/zwyw/201611/t20161129_1221576.html.

Yang, W., T. Dietz, D. B. Kramer, X. Chen, and J. Liu. 2013. Going beyond the Millennium Ecosystem Assessment: An index system of human well-being. *PLoS ONE* 8(5):e64582.