An integrated approach to understanding the linkages between ecosystem services and human well-being

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Abstract. In order to use science to manage human–nature interactions, we need much more nuanced, and when possible, quantitative, analyses of the interplay among ecosystem services (ES), human well-being (HWB), and drivers of both ecosystem structure and function, as well as HWB. Despite a growing interest and extensive efforts in ES research in the past decade, systematic and quantitative work on the linkages between ES and HWB is rare in existing literature, largely due to the lack of use of quantitative indicators and integrated models. Here, we integrated indicators of human dependence on ES, of HWB, and of direct and indirect drivers of both using data from household surveys carried out at Wolong Nature Reserve, China. We examined how human dependence on ES and HWB might be affected by direct drivers, such as a natural disaster, and how human dependence on ES and direct and indirect drivers might affect HWB. Our results show that the direct driver (i.e., Wenchuan Earthquake) significantly affected both households' dependence on ES and their well-being. Such impacts differed across various dimensions of ES and well-being as indicated by subindices. Those disadvantaged households with lower access to multiple forms of capital, more property damages, or larger revenue reductions also experienced greater losses in HWB. Diversifying human dependence on ES helps to mitigate disaster impacts on HWB. Our findings offer strong empirical evidence that the construction of quantitative indicators for ES and HWB, especially integrated models using them, is a viable approach for advancing the understanding of linkages between ES and HWB.

Key words: *biodiversity conservation; China; conservation planning; Millennium Ecosystem Assessment; natural disaster; vulnerability; Wenchuan Earthquake; Wolong Nature Reserve*.

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Introduction

Understanding and managing human–nature interactions is a fundamental challenge for sustainability (Liu et al. 2007*a*, 2015, Carpenter et al. 2009, Ostrom 2009). The scope and intensity of human–nature interactions have been increasing in an unprecedented way since the Industrial Revolution (Liu et al. 2007*b*, 2013*a*). The phenomenon of humans interacting with nature was recognized long ago, but our understanding of underlying patterns and processes in these interactions has been evolving much more slowly than the changes in the interactions themselves. In order to use science to manage human–nature interactions, we need much more nuanced, and when possible, quantitative, analyses of the interplay among ecosystem services (ES), human well-being (HWB), and drivers of ecosystem structure and function, as well as of HWB (MA 2005, Carpenter et al. 2009).

The use of the term "ecosystem services" can be traced back to the early 1980s, referring to the benefits from nature (Ehrlich and Ehrlich 1981, Ehrlich and Mooney 1983). It started to gain more attention with the

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publication of the influential book *Nature's Services* (Daily 1997) and the preliminary valuation of world's natural capital (Costanza et al. 1997), as well as the implementation of payments for ecosystem/environmental services programs in Costa Rica (Sanchez-Azofeifa et al. 2007). Research on ES has been booming after the monumental Millennium Ecosystem Assessment (MA; MA 2005) and the inception of several large projects, such as the Natural Capital Project (Kareiva et al. 2011), the Economics of Ecosystems and Biodiversity (TEEB) project (TEEB 2010), and the Reducing Emissions from Deforestation and forest Degradation (REDD) and REDD+ projects (Miles and Kapos 2008, Angelsen and Brockhaus 2009). So far, there have been extensive efforts to assess biophysical and monetary values of ES (Yang et al. 2008, Nelson et al. 2009, Chang et al. 2011), map trade-offs and synergies (Power 2010, Kareiva et al. 2011, Millington et al. 2013), identify ES bundles (Raudsepp-Hearne et al. 2010*a*, Martín-López et al. 2012, Yang et al. 2015*a*), and use ES information for policy making such as landscape and conservation planning and environmental impact assessments (Naidoo and Ricketts 2006, Chang et al. 2011, Li et al. 2013, 2013*b*, Viña et al. 2013, Wong et al. 2015).

The concept of HWB itself is evolving and complex with no universally acceptable definition, but a growing consensus on the feasibility and utility of measuring HWB, understanding what influences it, and using it in policy analysis (MA 2005, Diener 2009, Stiglitz et al. 2010, Summers et al. 2012, OECD 2013, King et al. 2014). There is a half-century-long tradition of research on HWB, including important efforts to link it to human use of the environment (Cantril 1965, Bauer 1966, Wilson 1967, Mazur and Rosa 1974, Campbell 1976, Diener et al. 1999, Easterlin 2001, Abdallah et al. 2008, Dietz 2015). Nevertheless, the literature linking ES to HWB is relatively limited compared to the substantial literature addressing either ES or HWB per se (MA 2005, Carpenter et al. 2009, Summers et al. 2012, Yang et al. 2013*a*, 2015*b*, Villamagna and Giesecke 2014). Contemporary thinking suggests that HWB is multidimensional and includes both objective and subjective components, with ES making substantial contributions to HWB (Summers et al. 2012, Yang et al. 2013*a*, King et al. 2014). Based on Maslow's theory of human needs (Maslow 1943), we defined HWB as "the satisfaction of human needs to achieve a state of being well (i.e., healthy, happy, and prosperous), both physically and mentally" (Yang et al. 2013*a*). Recently, there have been some conceptual discussions or qualitative examinations of the linkages between ES and HWB (Summers et al. 2012, Smith et al. 2013, Milner-Gulland et al. 2014), and an emerging literature examining the efficiency of nations in using natural resources to generate HWB (Dietz et al. 2009, Jorgenson 2014, Lamb et al. 2014, Dietz 2015). However, systematic and quantitative work on the relationship between the multiple dimensions of HWB and of ES at the household level is largely absent in existing literature. This may be largely due to the lack of use of quantitative indicators and integrated models in ES and HWB research (Carpenter et al. 2006, 2009, Yang et al. 2013*a*).

To fill some of these crucial knowledge gaps, we took a two-step approach. In the first step, we developed two index systems based on the MA framework to quantify human dependence on ES and HWB at the household level, respectively. We published these two methodological papers separately (Yang et al. 2013*a*, *b*). We confirmed the validity of the two index systems at Wolong Nature Reserve, southwestern China. In this paper we pursue the second step. We followed the MA framework (Fig. 1) that differentiates indirect drivers (factors altering one or more direct drivers), direct drivers (factors that influence ecosystem processes), ES, and HWB to examine the linkages between ES and HWB (MA 2005). Our goal is to provide insights for effective ecosystem management. Specifically, our objectives were to (1) evaluate the simultaneous effects of direct drivers (e.g., natural disasters) on human dependence on ES and HWB; and (2) examine how ES and indirect and direct drivers influence HWB.

Materials and Methods

Study area

We selected Wolong Nature Reserve (Fig. 2) as our study area for three reasons. First, it is part of the top 25 global biodiversity hotspots (Myers et al. 2000, Liu et al. 2003), supporting provision of many types of ES that are important to the local human population (Yang et al. 2013*b*). It is also home to the largest wild giant panda (*Ailuropoda melanoleuca*) population (~10%) in the world. There are ~4900 local human residents distributed in ~1200 households (Yang et al. 2013*c*). Local households' well-being substantially depends on such ES as agricultural and forest products (e.g., maize, cabbage, yaks, pigs, cattle, fuelwood, mushrooms, and traditional Chinese medicinal plants), water retention, erosion control, air purification, and ecotourism, as well as other socioeconomic activities, such as local and migrant labor work (Yang et al. 2013*b*, *c*). Second, since 1996 our research team has been conducting interdisciplinary research on the coupled human and natural systems (An et al. 2006, Liu et al. 2007*a*, *b*, Hull et al. 2011) of this area. Based on the accumulated extensive local knowledge and data sets, we have developed methods for quantifying human dependence on ES and HWB and have empirically validated our index systems there (Yang et al. 2013*a*, *b*).

Finally, the Wenchuan Earthquake (surface wave magnitude [M_s] 8.0 or moment magnitude [M_w] 7.9) of 12 May 2008 had its epicenter adjacent to the reserve (Viña et al. 2011, Zhang et al. 2014). The earthquake can

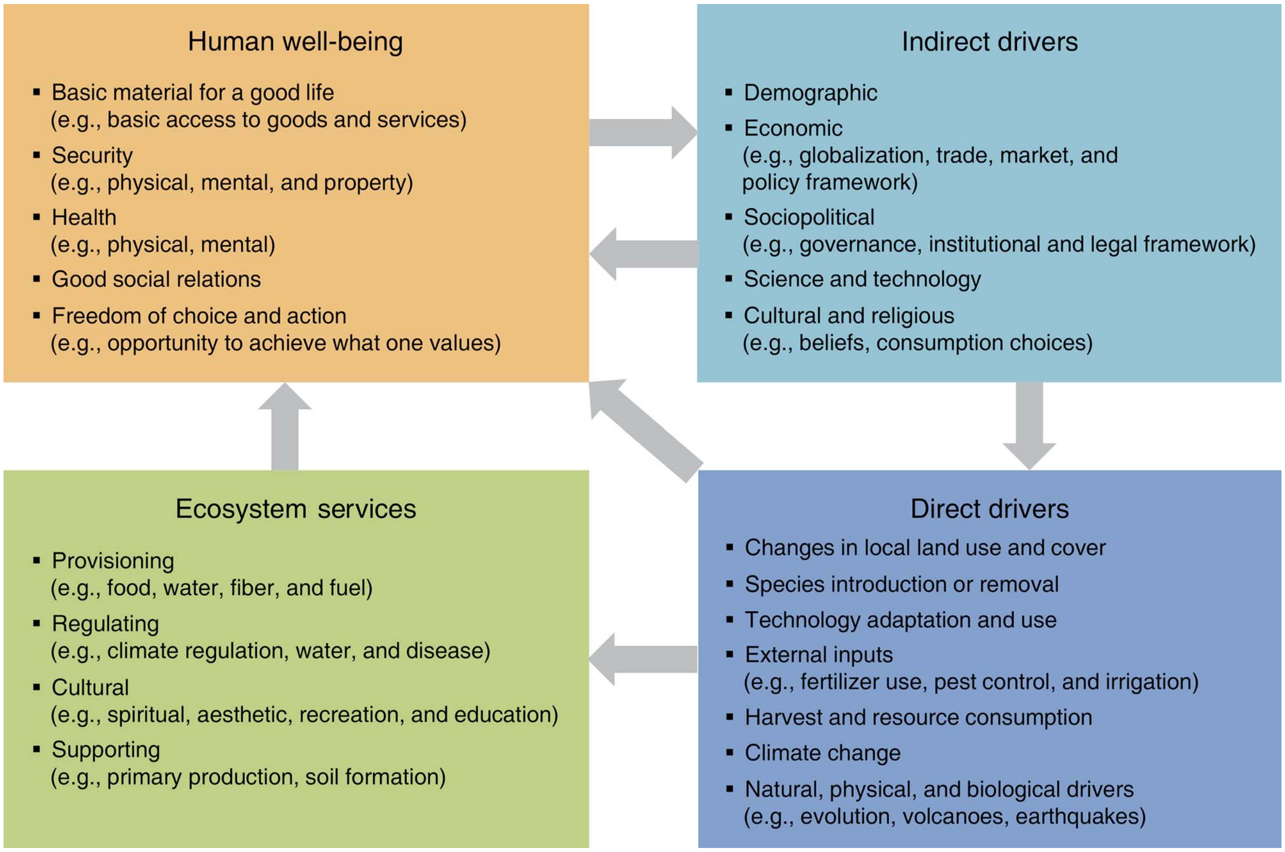

Fig. 1. Millennium Ecosystem Assessment conceptual framework that differentiates indirect drivers (factors altering one or more direct drivers), direct drivers (factors that influence ecosystem processes), ecosystem services (ES), and human well-being (HWB) to examine the linkages between ES and HWB. Arrows indicate the direction of influence. Modified from MA (2005).

be viewed as a tragic direct driver that caused tremendous environmental and socioeconomic impacts (Yang et al. 2013*a*). For instance, the earthquake destroyed ~5200 ha of forest, accounting for 6.5% of total forest area in 2007 (Fig. 2). The earthquake and associated disasters (e.g., landslides, mud–rock flows, and mountain torrents) irreversibly destroyed 12% of the cropland at Wolong Nature Reserve (Yang 2013). The earthquake also killed 48 local residents and several hundreds of workers and visitors who were then within the reserve. It also caused severe destruction to infrastructure, such as the main road, tourism facilities, residential houses, schools, and hospitals (Yang et al. 2013*a*). Thus, it provides a useful case to examine how local households' well-being and dependence on ES may be affected by a direct driver and how indirect (e.g., demographic and social conditions) and direct drivers (e.g., earthquake damage, economic conditions of households) may influence local households' well-being in a short time period.

Data

We collected data using a basic household survey and a HWB survey. We chose household heads or their spouses as interviewees to represent each household since our previous experience in this area suggests that they are the decision makers who are most familiar with household affairs (An et al. 2001). For this study, we used the data collected from 101 households included both in the basic household survey and HWB survey. The basic household survey collected data for measuring household's dependence on ES and indicators of indirect and direct drivers. The HWB survey collected data for constructing HWB indices.

In the basic household survey, we randomly sampled and tracked the same households with repeated surveys. For this paper, we chose to use data from two of the multiple waves of data collection. The first wave was at the end of 2007 (measuring conditions in 2007), before the earthquake. The second wave was in 2010 (measuring conditions in 2009), after the earthquake. Information elicited includes household size, demographic information on each household member (e.g., age, gender, and education), housing conditions (e.g., type and area), house damage severity due to the earthquake, household income and expenditure, and social ties to local leaders (people who are regarded as local elites working for the local government or enterprises [Yang et al. 2013*d*]). For indirect and direct

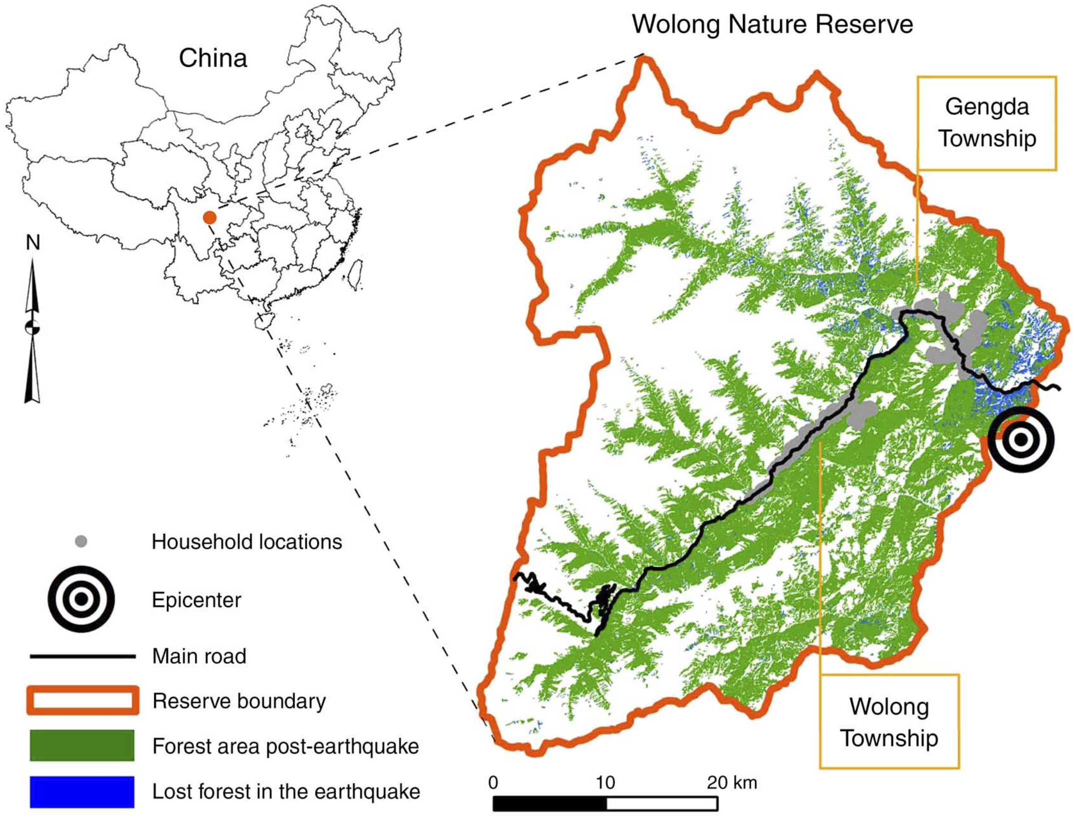

Fig. 2. Wolong Nature Reserve in Wenchuan County, Sichuan Province, southwestern China. Forest cover data are from Viña et al. (2011).

drivers, we considered economic, demographic, and social conditions of households, as well as the level of earthquake damages using an indicator of the damage to the house of each surveyed household.

The HWB survey was conducted during the same field campaign as the basic household survey in 2010. We randomly sampled and measured HWB variables both for 2007 and 2009. To ensure respondents' recall accuracy of such retrospective data collection, we followed the standard practices of life history calendars (Freeman et al. 1988, Axinn et al. 1999). The instrument for the HWB survey was conceptualized based on the MA framework. It includes a set of 34 indicators (see Appendix A) covering all the five MA components of HWB (i.e., basic material for good life, security, health, good social relations, and freedom of choice and action).

Methods for constructing the index system of human dependence on ecosystem services

We constructed the index system of human dependence on ES (IDES) based on data from the basic household survey. We provide an overview of the method, since more technical details were reported in a previous study (Yang et al. 2013*b*). IDES includes an overall index and three subindices, one each for provisioning, regulating, and cultural services. The overall index is defined as the ratio of net benefits from ecosystems (e.g., agricultural products, fuelwood, other non-timber forest products, subsidized electricity fees due to watershed conservation for hydropower, ecotourism, and payments for soil erosion control and carbon sequestration) to the absolute value of total net benefits from both ecosystems and other socioeconomic activities (e.g., wages and small businesses that are irrelevant to ES). Each subindex is calculated in the same manner as the overall index, but with the numerator using only the corresponding ES categories of provisioning, regulating, and cultural services, respectively. Thus, the sum of the three subindices is equivalent to the overall index. Given that supporting services are the bases of the three other services, we did not include supporting services and otherwise followed general guidelines to avoid double accounting (De Rus 2010). We used net benefits rather than gross benefits to allow the indices to capture both ES and disservices, account for costs associated with provision of ES, consider trade-offs and synergies between different ES, and facilitate cross-context comparisons (Yang et al. 2013*b*). While the net benefits show absolute values of benefits from nature, the IDES measures the relative importance of ES to a household. The general form of equations (Yang et al. 2013*b*) is shown as

$$\mathrm{IDES}_i = \mathrm{ENB}_i / \left|\sum_{i=1}^{3} \mathrm{ENB}_i + \mathrm{SNB}\right| \quad (1)$$

$$\mathrm{IDES} = \sum_{i=1}^{3} \mathrm{IDES}_i \quad (2)$$

where i represents each category of ES, that is, provisioning, regulating, or cultural services; IDES_i is the subindex for category i; ENB_i is the total net benefit acquired from ES in category i; SNB is the total net benefit acquired from other socioeconomic activities; and IDES is the overall index.

The IDES measures the relative importance of ES to humans in comparison to other socioeconomic benefits. A higher value of the overall index or subindex indicates a higher dependence of a household on the corresponding ES and thus higher vulnerability to the damages or losses of the corresponding ES (Yang et al. 2013*b*). We adopted the definition of vulnerability as "the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor" (Turner et al. 2003). The absolute importance of ES and socioeconomic benefits is reflected in the net benefits of monetary values. In previous analyses, both the overall index and subindices of IDES were found to have high validity and reliability. The indices reveal the general pattern of households' dependences on ES and the variations across time, space, and different levels of access to other forms of capital, such as human, manufactured, and social capital (Yang et al. 2013*b*).

Methods for constructing the index system of human well-being

We used confirmatory factor analysis to construct the index system of HWB based on the HWB survey data. We also provide a brief overview of the method, while more detailed methods are available in a previous paper (Yang et al. 2013*a*). The human well-being index (HWBI) system includes an overall index and, following the MA, five subindices, one each for basic material for good life, security, health, good social relations, and freedom of choice and action. The final structural equation model for the confirmatory factor analysis included 28 of the originally designed 34 indicators from the HWB instrument (Appendix A). The other six indicators were excluded due to low variation or internal consistency with other indicators in the same categories. All included indicators were those we see as theoretically meaningful and were statistically significant (Yang et al. 2013*a*).

The overall index and subindices of HWBI also had high reliability and validity. The item–total correlations ranged from 0.30 to 0.75, and the Cronbach's alpha values were 0.92 and 0.91 for 2007 and 2009, respectively (Yang et al. 2013*a*), both suggesting very high internal consistency of the indicators. The model fit statistics for the confirmatory factor analysis also showed high goodness of fit, with overall fit statistics all above 0.97 and significant coefficients ($P < 0.05$) for all paths (Yang et al. 2013*a*).

To allow cross-year and cross-site comparisons, each of the overall HWB index and subindices was separately normalized to the range from 0 to 1 using the maximum–minimum normalization method with the same maximum and minimum values applied to both time periods (UNDP 2013). A higher value of the overall index or subindices of HWB suggests higher satisfaction of corresponding human needs (Yang et al. 2013*a*).

Methods for estimating how human dependence on ecosystem services and other drivers affect human well-being

One of the major goals of our analysis was to determine how the earthquake influenced HWB directly and through changes in ES and direct and indirect drivers. We propose that HWB after the earthquake is determined by HWB before the earthquake, human dependence on ES before the earthquake and its change, other time-variant drivers, time-invariant drivers, and the level of earthquake damage experienced. Therefore, the general model can be given as

$$\begin{aligned} Y(t_1) = {} & \beta_0 + \beta_1 Y(t_0) + \beta_2 \mathrm{IDES}(t_0) + \beta_3 \mathrm{IDES}(t_1 - t_0) \\ & + \beta_4 X(t_0) + \beta_5 X(t_1) + \beta_6 C + \beta_7 E + \varepsilon \end{aligned} \quad (3)$$

where $Y(t_0)$ and $Y(t_1)$ refer to HWBI before and after the earthquake, respectively; $\mathrm{IDES}(t_0)$ and $\mathrm{IDES}(t_{1\_}t_0)$ denote IDES before the earthquake and its change; $X(t_0)$ and $X(t_1)$ represent the vectors of time-variant variables before and after the earthquake, respectively. In some cases, it may be more convenient to use the change variables $X(t_{1\_}t_0)$ rather than the post-earthquake variables $X(t_1)$. Obviously all three variables (i.e., $X(t_0)$, $X(t_1)$, and $X(t_{1\_}t_0)$) cannot be included in a single model, but we note the three possible configurations so that any particular specification can be seen as a subset of the three possibilities. Depending on theoretic interests or meanings of variables for interpretation, the collinearity between variables, and model fit, researchers may decide which of the three forms of variables to be included in the model. C is the vector of time-invariant variables; E is the level of earthquake damage; β_0 is the intercept; β_1–β_6 are vectors of coefficients to be estimated; ε is the error term and is assumed to have a normal distribution with a mean of zero.

Statistical analyses

We constructed the structural equation model for the index system of HWB using the software Mplus, version 6 (Muthén and Muthén 1998–2010). We

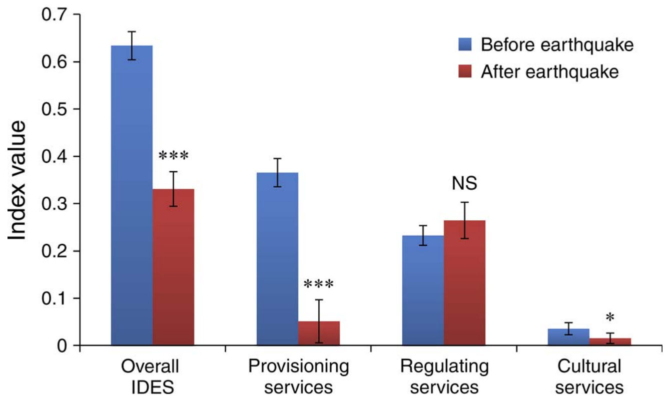

Fig. 3. Impacts of the earthquake on human dependence on ecosystem services. A higher value of the overall index or subindex (IDES, index of dependence on ecosystem services) represents a higher dependence on the corresponding ecosystem services and thus more vulnerable to their damages or losses. Unit of analysis is the household; $N = 101$. * $P < 0.05$, *** $P < 0.001$; NS, not significant.

computed the index system of IDES and performed all other statistical analyses and diagnostics using the software Stata 13.1 (StataCorp, College Station, Texas, USA). We constructed regression models to examine how dependence on ES affects HWB while controlling for indirect and direct drivers. We also controlled for the age, gender, and education of respondents. The structure of the model and standard diagnostics suggest the ordinary least squares estimator is appropriate to estimate the model parameters, but robust standard errors were also estimated. We adjusted the inflation of all monetary values using the consumer price index with 2007 as the base year. The descriptive statistics of variables used in regression analyses are summarized in Appendix B.

Results

Simultaneous impacts of the earthquake on dependence on ecosystem services and human well-being

The earthquake changed both local households' dependence on ES and their well-being (Figs. 3 and 4). The average overall IDES (in raw values) decreased by 48% from 0.634 in 2007 to 0.331 in 2009 ($t = 7.190$, $P < 0.001$). Subindices of provisioning and cultural services decreased by 86% (from 0.366 to 0.051) and by 57% (from 0.035 to 0.015), respectively (Fig. 3). However, there was no significant change in the subindex for regulating services (Fig. 3). Additional analyses (Appendix C) explain the differences in changes across subindices of IDES. On average, the earthquake reduced by 70% and 43% of local households' net benefits (in monetary values) from provisioning and cultural services, respectively, but did not significantly affect net benefits from regulating services. These results suggest that there were absolute declines in use of provisioning and cultural services. Meanwhile, between 2007 and 2009, net socioeconomic benefits (those not derived from ES measured in monetary values) increased, on average, by a factor of three, largely due to the increase of temporary work for local labor after the earthquake. This suggests that there were also relative declines in use of ES due to a dramatic increase of socioeconomic benefits.

The earthquake significantly reduced both overall HWBI and its subindices (in normalized values; Fig. 4). The magnitude of impacts differed across subindices. The earthquake significantly reduced basic material for good life by 5.3% (from 0.436 to 0.413), security by 13.1% (from 0.700 to 0.608), health by 12.9% (from 0.668 to 0.582), good social relations by 7.1% (from 0.689 to 0.640), and freedom of choice and action by 7.4% (from 0.353 to 0.327). The overall reduction in HWBI was

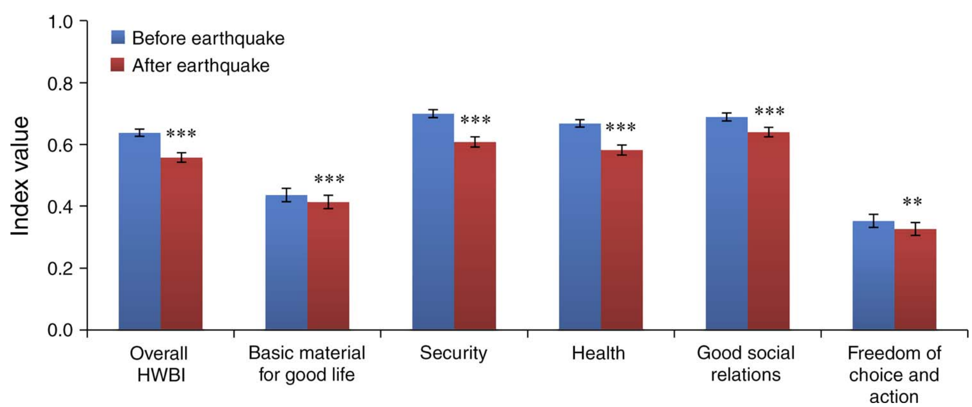

Fig. 4. Impacts of the earthquake on human well-being. A higher value of the overall index or subindex (HWBI, human well-being index) represents a higher state of well-being. Unit of analysis is the household; $N = 101$. Data from Yang et al. (2013*a*). ** $P < 0.01$, *** $P < 0.001$.

Table 1. Effects of human dependence on ecosystem services and other factors on human well-being.

Characteristics and independent variables	Coefficient	Robust SE
Initial HWBI		
HWBI in 2007	0.889***	0.076
Human dependence on ES		
IDES in 2007	0.094*	0.045
Change of IDES	−0.021	0.026
Household economic conditions		
Agricultural income share in 2007	−0.116*	0.051
Household income in 2009 (thousand yuan)	0.406×10^{-3}**	0.122×10^{-3}
Change of per capita income (thousand yuan)	-1.010×10^{-3}*	0.397×10^{-3}
Household demographic conditions		
Household size in 2007	0.015*	0.006
Number of seniors (aged ≥60 years)	−0.029*	0.015
Average education of adults in 2007 (year)	0.009†	0.005
Female adult share in 2007	−0.110	0.072
Household social conditions		
Social ties to local leaders (0, weak; 1, strong)	0.053*	0.023
Earthquake damage		
Indicated by the level of damage to residential houses (0, low as repairable; 1, high as destructive and needs to be reconstructed)	−0.048**	0.017
Respondents' characteristics		
Gender of interviewee (0, female; 1, male)	0.036*	0.017
Education of interviewee (year)	0.105×10^{-4}	0.001
Constant	−0.049	0.057

Notes: Dependent variable is in 2009. R^2 of the ordinary least square regression is 0.693. There were 101 observations. Our results are consistent even using different combinations of independent variables as shown in Appendix E. Our models passed all diagnostics of regression assumptions. Variance inflation factors were tested to be <5. We estimated P values based on robust standard errors as a check of ordinary least square assumptions. Abbreviations are HWBI, human well-being index; ES, ecosystems services; and IDES, index of dependence on ecosystems services.
† $P < 0.1$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

12.5% (from 0.638 to 0.558). Additional analyses (Appendix D) also suggest that the overall HWBI values of affluent households were significantly higher than those of poor households both before and after the earthquake.

Human dependence on ecosystem services affects human well-being

Our results show that IDES in 2007 is positively associated with the HWBI in 2009 (Table 1) and suggest that households more dependent on agriculture before the earthquake had larger decreases in HWBI. Meanwhile, because the dependence on ES varied substantially across households in 2007 and because by 2007 many households no longer depended heavily on ES from agriculture (Yang et al. 2013*b*), the positive coefficient of IDES in 2007 indicates that households more dependent on multiple ES (i.e., provisioning services from agriculture and other nonmarket forest resources, regulating services, and cultural services) suffered less from the earthquake in terms of HWBI. However, our results show that change of IDES is not significantly associated with HWBI in 2009 (Table 1). This may be because the effect of IDES in 2007 overwhelms the effect of its change or because there is a time lag before changes of IDES affect HWBI. The time lag in impacts after a natural disaster is a point made by many other scholars (Liu et al. 2007*a*, Raudsepp-Hearne et al. 2010*b*, Yang et al. 2013*a*). The observed significant effect of IDES on HWBI holds even when we used different combinations of other independent variables (see supplementary regression examples in Appendix E).

Our results also confirm that the observed significant effect of IDES in 2007 on HWBI in 2009 cannot be detected by using the disaggregated indicators constituting it (Appendix F). Controlling for the same independent variables in the model (Table 1), we replaced IDES in 2007 with indicators constituting it (i.e., the corresponding net benefits obtained from provisioning, regulating, or cultural services for households in 2007). However, none of the coefficients of the alternative indicators were significant ($P > 0.05$; Appendix F). These results suggest that IDES as a composite index captures change in HWB that is not evident from the effects of separate indicators constituting it; strong additional evidence of the validity and utility of the IDES.

Effects of indirect and direct drivers on human well-being

Our results also show that disadvantaged households with poorer economic, demographic, or social conditions or those who suffered from a higher level of earthquake damages had significantly larger decreases in HWBI (Table 1). Specifically, households with fewer household members, less income after the earthquake, and weaker social ties to local leaders reported lower HWBI in 2009. Households suffering from higher levels of house damage and more reduction of per capita income also reported lower HWBI in 2009, which are logical and serve as evidence of the validity of the model.

Discussion

We have integrated indicators of indirect drivers, direct drivers, ES, and HWB quantitatively to assess how dependence on ES and other factors affect HWB after a natural disaster. Our results suggest that households dependent on multiple ES had smaller decreases in HWB, while those dependent primarily on provisioning services saw larger decreases in HWB. Our results also demonstrate that disadvantaged households with lower access to multiple forms of capital, more property damages, or larger revenue reductions experienced greater losses in HWB.

In the long run, diversifying the types of ES on which households are dependent will also help to reduce vulnerability to disasters. For instance, provisioning services (e.g., agricultural products, fuelwood, non-timber forest products) often contribute substantially to rural people's basic livelihoods but have relatively low potential to generate extra income due to many limiting factors (e.g., limited land, fluctuating market). Cultural services may be able to generate extra cash income but are also quite vulnerable to disaster impacts (e.g., rapid decline of tourists post-disaster). Therefore, maintaining a balance by dependence on multiple provisioning and cultural services may reduce the vulnerability to disasters. Diversity in use of ES may prove beneficial in the face of stressful events.

Our results show that the earthquake significantly affected both households' dependence on ES and their well-being. Such impacts differed across various dimensions captured by our subindices. There were significant impacts of the earthquake on the overall index and all subindices of households' dependence on ES, except that for regulating services (Fig. 3). We offer two explanations for this. First, due to the massive associated disasters that occurred after the earthquake (e.g., landslides, mud–rock flows), the main road connecting the reserve with the outside world was substantially damaged and blocked in many areas repeatedly. Poor transportation prevented local households from selling their agricultural products outside the reserve and dramatically reduced tourists to the reserve. Thus, the net benefits obtained from provisioning and cultural services to local households dramatically decreased after the earthquake (Appendix C). However, the benefits from regulating services were realized through payments for ecosystem services programs and so did not decline because of the earthquake. But while payments from the programs continued, regulation services themselves, such as soil erosion control and carbon sequestration, were reduced by the earthquake.

Second, our results suggest that the dramatic and rapid decrease of dependence on ES was largely due to huge increase of socioeconomic benefits that were not obtained from ES. This finding has at least two broad implications for managing ES for sustainability. First, it indicates that households strategically use and enhance other resources to improve their HWB when the contribution of natural resources is reduced. In our case, households were good at utilizing special opportunities that came with disaster relief and reconstruction and their monetary income from those sources more than quadrupled with comparison to that before the earthquake (Appendix C). But such dramatic increase of socioeconomic benefits could not be realized without government interventions. It is the post-disaster reconstruction efforts that were implemented by the central government and that provided many governmental subsidies (e.g., subsidies for housing damages and to low-income households) and temporary local employment opportunities (e.g., labor work for road and housing construction). Nevertheless, despite of the large increase in income, the HWBI still showed an overall deterioration, indicating that HWB is multidimensional and is much more than income. Although urgent sociopsychological relief efforts were conducted immediately after the earthquake (Li et al. 2009), in the long-term reconstruction process, government interventions should go beyond basic material well-being. In the future it would be prudent for such efforts to pay more attention to other dimensions of HWB (e.g., health, social relations). Second, this finding provides some insights for the debate about weak vs. strong sustainability (Neumayer 2010). It indicates that there are local limits on the amount of HWB that can be derived from ES. Such limits may stem from biophysical factors, such as the actual depletion of natural resources after a disaster. They can also result from barriers (e.g., transportation difficulty, natural disasters such as the earthquake) to deliver ES or from human interventions, such as the establishment of protected areas that limit resource extraction. Such local limits may also change over time and vary across space. For example, as delivery barriers diminish due to post-disaster reconstruction or technical innovations over time, the limits on ES' contribution to HWB can also be eased.

In addition, we would like to highlight the implications for conservation of declines in social relations observed post-earthquake. The significant decline in social relations may not only reduce local households' life satisfaction but also increase transaction costs and limit the beneficial outcomes of both conservation and development programs, a result suggested in many other studies (Pretty 2003, Bouma et al. 2008, Anthony and Campbell 2011, Liu et al. 2012, Yang et al. 2013*d*). For example, in our study area, our previous analyses

Table 2. Example hypotheses and questions for future research on human–nature interactions.

Theme	Hypotheses/questions
Heterogeneity	Human dependence on ecosystem services and human well-being vary across time and space in all coupled human and natural systems.
Contextual effects and path dependence	Agents (e.g., individual, household, enterprise) that have high dependence on ecosystem services pre-disaster are also more likely to do so post-disaster.
Nonlinear effects and thresholds	The effects of disasters on human dependence on ecosystem services and human well-being are nonlinear. When the magnitude of impacts cross certain thresholds, irreversible shifts may occur (e.g., relocation of human settlements).
Time lags and legacy effects	There is a time lag or legacy effect of changes in human dependence on ecosystem services on human well-being.
Spillover effects	Changes in human dependence on ecosystem services or human well-being (e.g., social relations) of one agent may also affect human dependence on ecosystem services and/or human well-being of its surrounding agents (e.g., neighbors, relatives, friends).
Reciprocal effects and feedback loops	Changes in indirect and direct drivers may affect human dependence on ecosystem services and human well-being. In turn, changes in human dependence on ecosystem services and human well-being may alter people's behaviors (e.g., energy use, land-use practices), affect indirect and direct drivers (e.g., changes in climate, land use, and land cover), and thus form feedback loops.
Policy	How do institutional or technology innovations affect human dependence on ecosystem services and human well-being?
	How does the implementation of policies (e.g., integrated conservation and development projects) affect human dependence on ecosystem services and then human well-being?
	There are interaction effects among different policies in changing human dependence on ecosystem services and human well-being. One policy may enhance (i.e., synergistic effect) or offset (i.e., antagonistic effect) the effect of another policy. When the underpinning mechanisms of such effects are not well-understood, we may regard them as unanticipated outcomes or surprises.

(Yang et al. 2013*d*) suggest that good social relations among household group members enhanced collective action (e.g., forest monitoring) and beneficial resource outcomes (e.g., forest cover preservation). In this study, social ties to local leaders helped to reduce the earthquake impact on households' well-being. Our previous study (Yang et al. 2013*d*) also suggests that strong social ties in the community discourage illegal logging and reduce the amount of formal forest monitoring efforts needed. Strong social ties also increase the probability of households' participation in ecotourism businesses (Liu et al. 2012), enhance the probability of finding jobs (Chen et al. 2012), mitigate their dependence on provisioning ES (Yang et al. 2013*b*), and reduce their environmental impacts (Yang et al. 2013*b*). Such evidence suggests that changes in HWB (e.g., social relations) may lead to changes in both social and environmental behaviors of households, forming feedback loops and, in turn, affecting indirect and direct drivers, as well as human dependence on ES. This further explains why it is critically important to adopt an integrated approach to understand the linkages between ES and HWB through the construction of quantitative indicators of ES and HWB, especially the integration of these indicators with direct and indirect drivers.

Finally, our study indicates that we need both disaggregated and aggregated indicators to understand and manage the linkages between ES and HWB. It should be noted that aggregated and disaggregated are relative, since each disaggregated indicator may be viewed as an aggregated indicator if it is further disaggregated into indicators at a lower spatial or classification level. Some researchers argue that disaggregating beneficiaries and HWB are needed because of the uneven distribution of ES, trade-offs, varied local contexts for mechanisms of access, and cash-based livelihoods (Daw et al. 2011). We agree with those points, as they are also consistent with our findings and previous studies (Liu et al. 2013*b*, Yang et al. 2013*a*, *b*, *c*, *d*). However, aggregated indicators are important in describing overall temporal trends and large-scale spatial patterns, synthesizing common mechanisms, and identifying knowledge gaps for further disaggregated research. In our case, we found that the effect of IDES on HWB cannot be observed from disaggregated indicators constituting IDES (Table 1; Appendix F). This is strong evidence to support the unique value of aggregated indicators. Our findings also show the different impacts on various categories of ES and dimensions of HWB and generate questions and hypotheses for further investigation (Table 2). Therefore, we believe that both disaggregated and aggregated indicators are indispensable, and often analyses need to be conducted at multiple levels to display both the big picture and necessary details.

Conclusions

We offer empirical evidence that the construction of quantitative indicators for ES and HWB and especially integrated models using them is a viable approach for advancing the understanding of linkages between ES and HWB, as well as the ways in which indirect and direct drivers change both ES and HWB. Of course, a single study cannot disentangle all the important questions about the complex and evolving linkages between ES and HWB. For example, part of the responses to the earthquake we observe is a function of the particular set of policies in place, the new policies that were implemented in responses to the earthquake, and the remote location of our study area that made damage to transportation infrastructure particularly important. In a different policy and geographic setting, the effects of the earthquake might have been different, but we believe our study offers a proof of concept regarding the use of systematic quantitative indicators of ES and HWB, and in particular, those based on the MA framework. Further research will certainly refine and expand on the MA approach. But at the moment, it is by far the most commonly used framework with the advantage that it can be applied to multiple scales and units of analysis. Moreover, our methodologies for constructing indices of dependence on ES and HWB can easily be transferred to other frameworks by making modifications to the exact categories of ES and HWB included. Thus, we believe that our integrated approach can also be adapted to other areas and issues to test fundamental hypotheses, answer important questions, and address pressing problems for sustainability (Table 2). In particular, we believe this approach can help establish causal mechanisms regarding how conservation efforts alter ES and thus affect HWB. Further elaborations and applications of this integrated approach could potentially improve the understanding of and help to build coherent theories on human–nature interactions and the vulnerability of coupled human and natural systems (Liu et al. 2007*a*, McConnell et al. 2011) or socioecological systems (Ostrom 2009, Collins et al. 2011) to guide the management of human–nature interactions.

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Supplemental Material

Ecological Archives

Appendices A–F are available online: http://dx.doi.org/10.1890/15-0001.1.sm