Nonlinear effects of group size on collective action and resource outcomes

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For decades, scholars have been trying to determine whether small or large groups are more likely to cooperate for collective action and successfully manage common-pool resources. Using data gathered from the Wolong Nature Reserve since 1995, we examined the effects of group size (i.e., number of households monitoring a single forest parcel) on both collective action (forest monitoring) and resource outcomes (changes in forest cover) while controlling for potential confounding factors. Our results demonstrate that group size has nonlinear effects on both collective action and resource outcomes, with intermediate group size contributing the most monitoring effort and leading to the biggest forest cover gain. We also show how opposing effects of group size directly and indirectly affect collective action and resource outcomes, leading to the overall nonlinear relationship. Our findings suggest why previous studies have observed differing and even contradictory group-size effects, and thus help guide further research and governance of the commons. The findings also suggest that it should be possible to improve collective action and resource outcomes by altering factors that lead to the nonlinear group-size effect, including punishing free riding, enhancing overall and within-group enforcement, improving social capital across groups and among group members, and allowing self-selection during the group formation process so members with good social relationships can form groups autonomously.

casual inference | commons governance | ecosystem services | biodiversity conservation | sustainability

Groups are basic units for collective action and may achieve outcomes that individual efforts cannot (1). However, the threat of free riding implies that the optimal amount of collective action does not always occur, and has led to a substantial literature trying to understand what factors facilitate or block the emergence of collective action. Because collective action is needed to manage many common-pool resources, understanding the mechanisms that shape collective action and resource outcomes is a critical challenge for sustainability (2, 3).

From Pareto in 1906 (4) and especially since the influential work by Olson in 1965 (5), group size has been hypothesized as a crucial factor affecting collective action and resource outcomes. (We note that Olson used an unusual definition of "group size": the potential number of group members. Here we follow conventional practice and consider the actual number of participants.) However, the debate on group-size effect continues with some researchers arguing that it is linear and negative (5–7), others arguing for linear and positive (8–11), and still others insisting it is curvilinear (12–14), ambiguous (1, 15–17), or nonsignificant (18–20). Even in the most recent work (8, 15, 19, 21–24), a consensus on the nature of the effect or even its existence still remains elusive.

Previous literature indicates that there are two hypothetical opposing forces through which group size affects collective action and resource outcomes (Fig. 1). Group members play different roles in collective action, ranging from free riders (i.e., members who enjoy group benefits without paying for the costs) and conditional cooperators (i.e., members who will contribute more when others contribute more) to altruists (i.e., members who contribute regardless of others' behaviors), as well as various roles mixing these strategies (25). Group size can have diverse effects. On the one hand, members tend to free ride as the group becomes larger (5, 26). As group size increases, transaction costs (e.g., communication costs, costs of monitoring to maintain a necessary level of excludability) may rise sharply (1, 7, 13–15); thus, the larger the group, the more difficult to detect and reduce free riding. If the common good has any degree of rivalry, average individual payoff will shrink as group size increases, which further aggravates free riding (15–17). On the other hand, small groups often lack the resources (e.g., labor, time, funds) that large groups can deploy (7, 13, 14, 27). When available resources are limited, it is difficult to devote additional resources to collective action (1, 15). Taking advantage of more resources, large groups may enhance enforcement through monitoring and punishment to reduce free riders and thus improve collective action and resource outcomes (13, 14, 20, 21, 24, 28). Ostrom scrutinized previous evidence and pointed out the problem of focusing on group size itself without considering factors that influence or are influenced by group size (7). Ostrom then suggested further research to focus on the hypothesized curvilinear effects of group size (7).

A few previous studies qualitatively described the curvilinear or nonlinear effects of group size (12, 26, 29), and some claimed a nonlinear relationship by simply plotting collective action against group size without controlling other factors (13, 14). However, none has provided a quantitative analysis of field evidence while controlling potential confounding factors, as suggested by Ostrom (7). Furthermore, there is little empirical examination of the mechanisms of nonlinear group-size effects, which is essential to guide commons governance.

To fill these knowledge gaps, we used empirical data from our long-term studies (30–44) in Wolong Nature Reserve, Sichuan Province, China (N 30°45′ – 31°25′, E 102°52′ – 103°24′) (Fig. 2). Wolong Nature Reserve is home to ~10% of the total wild giant panda (*Ailuropoda melanoleuca*) population, and home to ~4,900 local human residents distributed in ~1,200 households. In response to degradation of forest and panda habitat because of human activities since the 1970s (31), the Reserve implemented the Natural Forest Conservation Program (NFCP) in 2001. NFCP is a nationwide conservation program that aims to conserve and restore natural forests through logging bans, afforestation, and monitoring, using a payments-for-ecosystem-services scheme to motivate conservation behavior (45). Of the total ~120,500 ha in the NFCP monitoring area in Wolong, ~40,100 ha were assigned to ~1,100 rural households and the remaining areas were monitored by the staff of the reserve's administrative bureau. Meanwhile, the bureau

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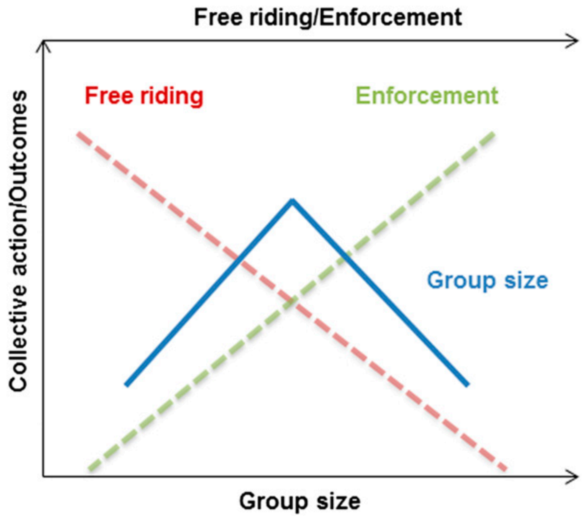

Fig. 1. Hypothetical effects of free riding, within-group enforcement, and group size on collective action and resource outcomes. Both free riding and within-group enforcement are hypothesized to be positively related to group size. However, free riding is hypothesized to be negatively related to within-group enforcement. The combined effects of free riding and within-group enforcement on collective action and resource outcomes are not expected to be additive because of interactions between within-group enforcement and free riding. The net effect of group size is determined by the dynamics (e.g., strength and variation with group size) of free riding and within-group enforcement, which may form a nonlinear pattern.

set two timber checkpoints at the two ends of the only main road crossing the reserve (Fig. 2). The common-pool resource in question in the Reserve is the forest (an essential component of the panda habitat) assigned to households. Because logging is largely the action of local residents (*SI Appendix*, Section 2.4.1), collective action (i.e., forest monitoring) has the potential to reduce illegal logging and improve resource outcomes (i.e., changes in forest cover).

The bureau administering the NFCP has assigned the forest parcels to household groups of various sizes ranging from 1 to 16 (*SI Appendix*, Table S2). Parcels distant from households were assigned to large groups with slightly higher payments (*SI Appendix*, Table S2). Households could not choose which parcel to monitor or in which household groups to participate. Our analyses indicate that the distance from a household to its monitored parcel and NFCP payment do not affect the group-size effects (*SI Appendix*, Section 2.4.3). Thus, the current distribution of group size is suitable for examining the group-size effects and mechanisms. Each assigned household group decides autonomously on its monitoring strategies (e.g., monitoring frequency, duration, and whether to subdivide to monitor in turns). The bureau evaluates the monitoring performance based on field assessments of illegal activities (e.g., logging) and rewards people who report illegal activities (in cash). All households within a group share the same monitoring responsibility and suffer the same payment deduction when any illegal activities are detected by the bureau in their comonitored parcel. However, the households are exempt from penalties if they report lawbreakers, in which case the corresponding lawbreakers are punished instead.

To understand the group-size effects and the underpinning mechanisms, we combined data on characteristics of households, household groups, and monitored parcels (*SI Appendix*, Section 1). We acknowledge that conflicts with regard to monitoring might occur within a household, but because the policy is designed to treat households—not individuals—as monitoring units, the common practice of treating households as the unit of analysis is appropriate here. We measured household monitoring efforts by the total amount of labor input (one unit of labor input is defined as one laborer working for 1 d) (*SI Appendix*, Section 2.1) through surveys. We measured resource outcomes as changes in forest cover derived from previously published forest-cover maps (*SI Appendix*, Section 1.1.1). We also measured factors that might explain the mechanisms, including free riders (i.e., households that did not participate in monitoring), the level of within-group enforcement (i.e., strong enforcement if there are punishment measures for free-riding members within the group; otherwise, weak enforcement), and within-group division (i.e., whether groups divide into subgroups to conduct monitoring in turns) (*SI Appendix*, Section 2). Some other contextual factors shown in previous studies to affect group size, collective action, or resource outcomes were used as control variables (*SI Appendix*, Section 2.3).

Results

Our results show that group size has a nonlinear effect on the monitoring efforts per household, with an intermediate group size contributing the most (Fig. 3*A* and Table 1). These results are consistent whether or not we include the households who monitored parcels individually (i.e., group size of one) and when using different combinations of control variables (*SI Appendix*, Table S13). The effect peaks at a size of eight or nine households, where a household spends 9.2 labor units per year monitoring its forest parcel. Our results also indicate that some other factors besides group size matter substantially. The level of social ties to local leaders has a significantly negative effect on per household monitoring efforts (Table 1). When all other variables are at their mean values, households with strong social ties to local leaders on average input 54% less labor units than households with weak social ties to local leaders. Our experience in the Reserve helps explain this effect. The staff members in the administrative bureau who are in charge of combatting illegal logging activities are hired from outside the Reserve, and anyone can report illegal logging and receive a cash reward from the administrative bureau. We are also not aware of a single case in which staff members turned a “blind eye” to illegal logging so households with strong ties could avoid monitoring or sanctions. Rather, additional analyses (*SI Appendix*, Section 2.4.2) reveal that, compared with households with weak social ties to local leaders, households with strong social ties often have more social relationships, power, knowledge, and experience. Our extensive fieldwork experience at the site indicates that these social ties provide social capital and reputation that discourages others from conducting illegal activities in their monitoring parcels, and thus reduce the need for them to spend efforts on formal monitoring. The distance between each household and the main road has a positive effect on a household’s monitoring efforts, with

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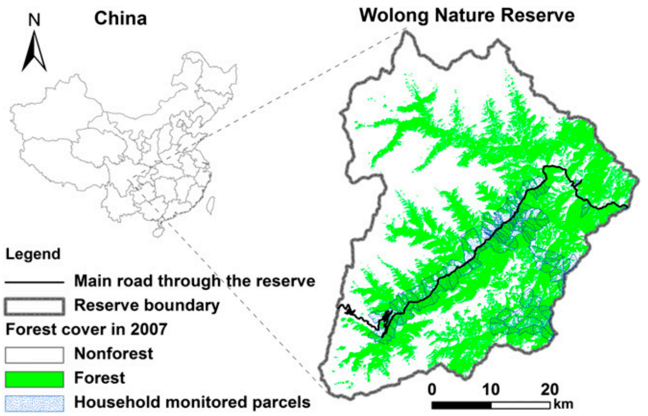

Fig. 2. Map of the location, main road, forest cover in 2007, and household monitoring parcels of Wolong Nature Reserve in Sichuan Province, China.

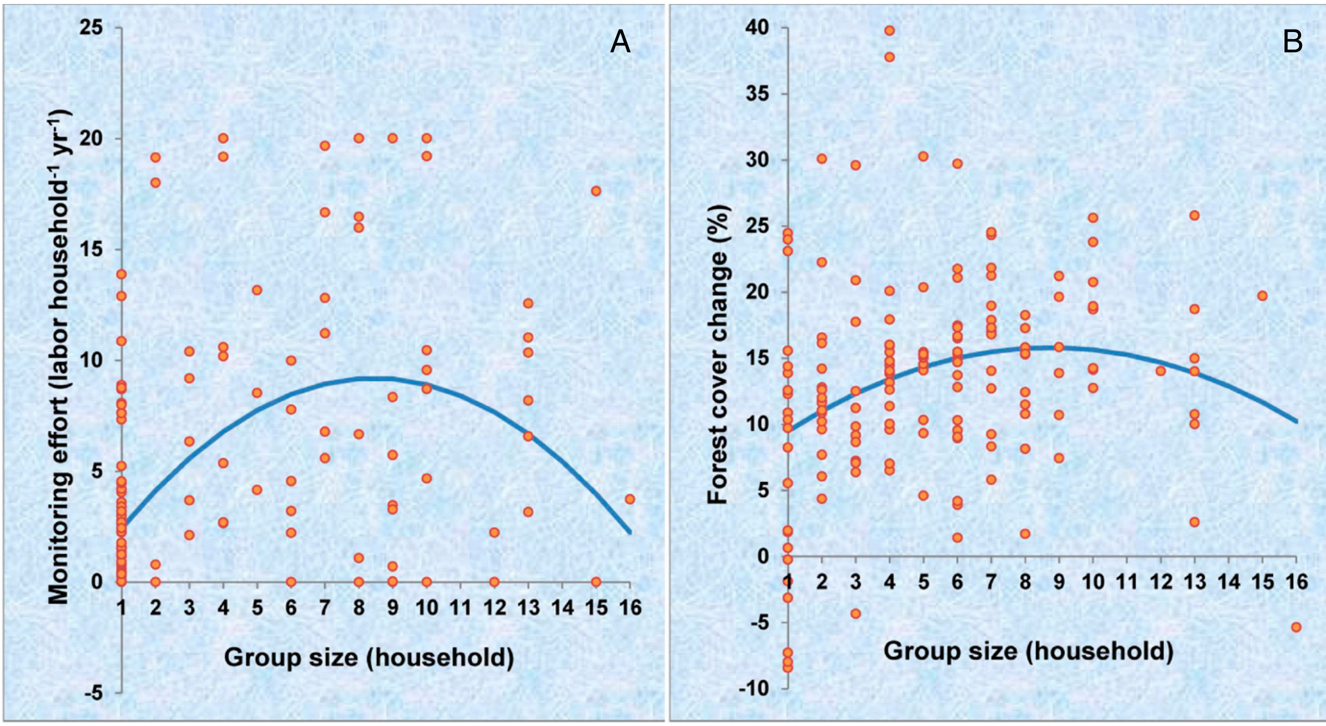

Fig. 3. The nonlinear group-size effects on collective action and forest outcomes. This figure shows the predicted monitoring effort (*A*) and forest-cover change (*B*) from 2001 to 2007 under different group sizes (i.e., number of households monitoring a single forest parcel). The graphs show the net effects of group size on per household monitoring effort and on change in forest cover, while controlling the other variables in Tables 1 and 2. The blue line is the predicted fit based on group size, and the orange dots are the actual observations. One dot may represent several overlapping observations. Except for linear and quadratic terms of group size, all other independent variables were controlled as their mean values (*SI Appendix*, Tables S1 and S3). In *B* our conclusion still holds as the nonlinear effect is still significant even when excluding the parcels with group size of one, or the two parcels with group sizes of 15 and 16 (see details in *SI Appendix*, Section 2.5.2). However, for *A* and *B*, the observations do not visually fit the predicted lines in the same way as the observations in ordinary least-squares regressions (54) because these models are not ordinary least-squares regressions (see details in *SI Appendix*, Section 2.5).

distant households doing more monitoring (Table 1). The average household that lives 1 km further from the main road on average spends 33% more labor units in forest monitoring. Additional analyses (*SI Appendix*, Section 2.3) suggest that households far from the main road are closer to the parcels they monitor (Spearman's $\rho = -0.201$, $P < 0.05$).

Our results demonstrate that group size also has a nonlinear effect on changes in forest cover, with an intermediate group size leading to the biggest gain (Fig. 3*B* and Table 2). These results are consistent whether we include the parcels monitored by single households (i.e., group size of one) or not (*SI Appendix*, Section 2.5.2). The effect peaks at a size of nine households where the forest cover increases 15.8% in comparison with the reference level in 2001. The effects of slope, wetness, initial forest cover in 2001, and spatial error correlation are also significant (Table 2).

We accounted for as many as possible alternative explanations of the observed nonlinear group-size effects based on systematic quantitative and qualitative analyses. No factor other than group size seems to account for the observed nonlinear effects. First, correlation tests (*SI Appendix*, Table S2) show that except for the two criteria used for household group assignment (see details in *SI Appendix*, Section 1.2) by the administrative bureau (i.e., distance between each household and its assigned parcel and received NFCP payment), no other factors were significantly associated with group size and thus are implausible as possible alternative explanations for the group-size effects. We used two additional approaches to ensure that the observed nonlinear effects were not caused by the two criteria used for household group assignments (*SI Appendix*, Section 2.4.3). We examined the associations between the two criteria used for household group assignment and household monitoring efforts, and we

Table 1. Coefficients of the Tobit model for the nonlinear effect of group size on collective action

Variable	Coefficients (robust SE)	Marginal effects
Intercept	8.921*** (2.360)	—
Quadratic term of group size	−0.128** (0.041)	—
Group size	1.331** (0.408)	0.767
Social ties to local leaders (binary: 0 for weak social ties; 1 for strong social ties)	−5.377** (1.920)	−3.012
Distance between each household and the main road	2.787* (1.216)	1.749
Additional controls	Not significant (*SI Appendix, Table S9*)	—

Unit of analysis is the household. Dependent variable is total labor input for monitoring per year. Additional controls include household size, number of household laborers, education of adults, household income, and percentage of agricultural income (*SI Appendix*, Table S9). Log pseudolikelihood is −390.962. Total number of observations is 156. Independent variables were mean centered before entering the model. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Table 2. Coefficients of the spatial autoregressive error model for the nonlinear effect of group size on resource outcomes

Variable	Coefficients (SE)
Intercept	0.146*** (0.015)
Quadratic term of group size	−1.056E-03* (4.800E-04)
Group size	7.205E-03* (3.643E-03)
Slope	0.339** (0.121)
Wetness	0.048*** (0.012)
Initial forest cover in 2001	−0.269*** (0.030)
Additional controls	Not significant (*SI Appendix*, Table S16)
λ (Coefficient of spatial error correlation)	0.561***
Moran's I	0.021

Unit of analysis is the forest parcel. Dependent variable is the percent of forest-cover change from 2001 to 2007. Additional controls include parcel size, parcel size per household, elevation, distance between each parcel and the nearest household, and distance between each parcel and the main road (*SI Appendix*, Table S16). Total number of observations is 151. Log likelihood is 170.281. Independent variables were mean centered before entering the model. Detailed discussion of the spatial autoregressive models are in *SI Appendix*, Section 2.5.2. $*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

estimated two-step Tobit models of monitoring effort. Using either approach, all hypothesized alternatives to group size were linearly associated with household monitoring efforts, and thus could not lead to the observed nonlinear effects.

Our path analysis (Table 3) confirms that group size has effects through the two opposing forces (Fig. 1). If the balance between positive and negative effects shifts with group size, it can yield the observed nonlinear pattern. On the one hand, group size has a significantly positive effect on the probability of a household free riding ($P < 0.01$) (Table 3). With all other relevant factors controlled at their mean values, an increase of group size by one household increases the free-riding probability by 15%. On the other hand, group size has a significantly positive effect on within-group enforcement ($P < 0.01$), which significantly reduces free riding ($P < 0.01$) (Table 3). Again, controlling all other relevant variables at their mean values, an increase in group size by one household strengthens within-group enforcement by 10%, whereas a shift from weak to strong within-group enforcement reduces free riding by 52%. Additional analyses (*SI Appendix*, Section 2.4.4) suggest that as groups become larger, a group member would face higher pressure of deteriorating social relationships with the other members in each group, which enhances within-group enforcement and thus reduces free riding. This result is consistent with the significant effect of social ties on household monitoring efforts (Table 1), indicating that social capital plays an important role in affecting conservation behaviors of households. It follows that collective action might be easier to maintain when social relationships among group members are improved or members with good social relationships can form their groups autonomously.

Discussion

The coexistence of two opposing forces may also explain why previous studies found different group-size effects. If, as we argue, the net effect of group size is determined by the dynamics (e.g., strength and variation with group size) of the two opposing forces, the optimum point of the net effect (or the necessary range of group size to observe a nonlinear effect) would be dependent on the context (14). The range of group size in our study area may appear to be small. However, the nonlinear pattern we observed means that such a range is large enough to exhibit the nonlinear effect in our context. One of the reasons we find such effects with only moderate variation in group size may be because our study area is a flagship nature reserve for giant pandas. As a result, the local administrative bureau has relatively abundant resources to allocate payments for household groups to monitor parcels and evaluate their performance biannually

Table 3. Path analysis of the two opposing forces through which group size affects collective action

Path analysis	Unstandardized coefficient (SE)
Dependent variable: Free rider (binary: 0 for a household that does not free ride; 1 for a household that free rides)	
Group size	0.146** (0.051)
Within-group enforcement (binary: 0 for weak enforcement; 1 for strong enforcement)	−0.522** (0.184)
Dependent variable: Within-group enforcement	
Group size	0.103** (0.038)
Within-group division (binary: 0 for no within-group division; 1 for within-group division)	0.376 (0.266)
Group size × Within-group division	−0.050 (0.061)
Dependent variable: Group size	
Social ties to local leaders (binary: 0 for weak social ties; 1 for strong social ties)	0.052 (0.651)
Distance to main road (log)	−0.067 (0.136)
Number of laborers	−0.051 (0.350)
Household size	0.027 (0.243)
Education of adults	0.016 (0.117)
Household income (log)	−0.093 (0.311)
Percentage of agricultural income	1.839 (0.946)

Unit of analysis is the household, but both characteristics of households and their assigned groups are considered. Continuous independent variables are mean centered. All goodness-of-fit indices show that the model fit is respectably high (*SI Appendix*, Table S5). Total number of observations is 113 households. $**P < 0.01$.

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(*SI Appendix*, Section 1.2). Furthermore, many household activities are substantially affected by kinship and leadership, so it is not surprising that social capital matters substantially in household monitoring efforts and resource outcomes. Neither of these conditions might hold in other contexts where official engagement is less pronounced and social capital is of less importance. In our context, the optimum point can be detected even though no group is larger than 16. In other contexts, a larger range of group size might be necessary to detect nonlinear effects, which raises an important issue for future investigation: What elements of context influence the optimum point in the relationships between group size and either provision of collective action or resource outcomes?

Our study uses intensive analyses based on quantitative and qualitative data, buttressed by years of fieldwork at the site, to examine the effect of group size on per household effort and resource outcome. We acknowledge that the optimal group size may vary across contexts. In some commons management regimes, the variation in group size may not be great enough to demonstrate the nonlinear effect. The approach we have used could readily be applied to other contexts. When a literature based on analyses like ours at other sites emerges, comparison across studies would allow the identification of what aspects of context influence optimal group size, something that cannot be done in a single study.

Randomized experiments are sometimes seen as the "gold standard" for research on causal mechanisms. However, there have been no randomized experiments at our site, nor are there likely to be because of its status as a showcase for conservation efforts. In addition, in the real world, there is no randomized or even quasirandomized field experiment in this field of study. The best that can be done in many real-world resource management situations is to be careful with regard to inference. Our analyses show that significant advances in understanding can be made through careful analyses of nonexperimental data by drawing on historical data. Such efforts of ongoing programs provide a useful complement to field experiments in building a cumulative literature and forwarding the important work on collective action and resource management.

Our findings also suggest that by regulating factors interacting with group size, it should be possible to improve collective action and resource outcomes. For example, all groups of various sizes can stimulate group members to contribute and protect common-pool resources by punishing free riding and enhancing overall and within-group enforcement. Overall enforcement can be enhanced not only through intensifying costly monitoring efforts but also via improving social capital across groups. The within-group enforcement and outcomes may also be enhanced by improving social capital among group members or allowing self-selection during the group formation process so members with good social relationships can form groups autonomously.

Unprecedented deterioration of global commons requires better understandings of the mechanisms shaping collective action and resource outcomes. Because of the complexity of coupled human and natural systems (46), improving such understandings is challenging and requires efforts to integrate data and methods from multiple disciplines. The struggle to understand the group-size effects is one example showing the importance of such efforts. Our findings help disentangle the puzzle of group-size effects and guide solutions to pressing problems of coupled human and natural systems (47), as well as the design of commons governance policies.

Materials and Methods

We acquired the map of household monitoring parcels and associated documentation (e.g., the number of households that monitor each forest parcel) from the administrative bureau of Wolong Nature Reserve. To estimate forest-cover change, we used previously published forest-cover maps derived from Landsat imagery in 2001 and 2007 (48, 49). These maps included two main land-cover classes (i.e., forest and nonforest) with overall accuracies between 80% and 88% using independent ground-truth data. Topographic data, such as elevation, slope, and the Compound Topographic Index, a relative measure of wetness (50), were obtained from a digital elevation model at a spatial resolution of 90 m/pixel (51). We measured all household locations (~2,200 households) inside and surrounding the Reserve using Global Positioning System receivers. We calculated geographic metrics of forest parcels and households using the software of ArcGIS 10.1 (ESRI). These metrics include parcel size, parcel size per household, average elevation, average slope, average wetness, distance between each parcel and the nearest household, distance between each parcel and the main road, distance between each household and its monitored parcel, distance between each household and the main road, initial forest cover in 2001, and the percent of forest-cover change from 2001 to 2007.

To understand the NFCP planning, implementation, evaluation, and decision-making processes, and to prepare for the household interview, we invited eight Reserve administrative staff for focus group interviews and five officials who were or are in charge of the NFCP for personal interviews. We used best available household survey data containing NFCP implementation information in 2007 and 2009 from our long-term study in the Reserve, which has been tracking ~220 randomly sampled households across the years since 1998 (52). The panel survey elicited basic information, such as demographic status, socioeconomic conditions, and energy use (53). In the 2007 and 2009 surveys, besides basic information from panel surveys, we also asked questions regarding NFCP implementation [e.g., NFCP payments, monitoring frequency, time spent for each monitoring, monitoring strategy (e.g., within-group division), and within-group enforcement]. A total of 156 randomly sampled NFCP participating households in 2007, covering the full range of group size (i.e., 1 to 16), were used to examine how group size affects collective action (i.e., household forest monitoring). The 113 households who monitored NFCP parcels with group size larger than one (i.e., 2 to 16) in 2009 were used to examine the mechanisms of nonlinear group-size effects.

We first used a Tobit model to examine the effect of group size on monitoring efforts at the household level. We then used a spatial autoregressive model to examine the effect of group size on forest-cover change at the parcel level. Finally, we conducted the path analysis to test the two hypothetical, opposing forces on the mechanisms of nonlinear group-size effects. Detailed descriptions of data collection, processing, and model specification and construction are provided in *SI Appendix*.

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