Causal estimates of wildlife damages from a payment for environmental service (PES) afforestation program

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Abstract

As global efforts to protect ecosystems expand, there is increasing concern about conservation costs borne by rural communities. To date, these costs have largely been estimated from foregone livelihood opportunities directly caused by conservation, while subsequent impacts to livelihoods due to ecological gains from conservation have often been ignored. As a first attempt to quantify this impact, we estimated the effect of afforestation promoted by one of the world's largest conservation programs (Grain-to-Green Program, GTGP) on crop damage by wildlife using data from China's Wolong Nature Reserve for giant pandas. Despite the program's pro-poor pursuit, we found that 64% of crop damage on remaining cropland was attributable to the afforestation from GTGP. Our study highlights that ecological gains from conservation can cause substantial losses to local communities. Scientists, policy makers, and conservation practitioners should consider this negative impact in the design and management of conservation for realizing conservation's pro-poor potential.

Keywords: Environmental conservation; Grain-to-Green Program; Human-Wildlife conflict; Impact evaluation; Matching; Wolong Nature Reserve

Introduction

Since the start of the 21st century, a remarkable international agreement on the urgency of poverty alleviation has made the conservation cost borne by rural communities an important concern (Andam et al. 2010; Colglazier 2015). In this context, there has been a growing search for pro-poor conservation strategies that can deliver both poverty alleviation and ecosystem conservation (Adams et al. 2004; Roe and Elliott 2006). Although the success of pro-poor conservation remains elusive (Muradian et al. 2013; Rasolofoson et al. 2016), previous studies have shown that specific consideration of conservation costs borne by rural communities can substantially improve outcomes of conservation programs (Ansell et al. 2016; Kremen et al. 2000; Naidoo et al. 2006). To date, however, conservation costs borne by local communities have largely been estimated based on foregone livelihood opportunities caused by conservation, while the subsequent impacts to livelihoods of ecological gains from conservation have often been ignored (See *SI Text* for more discussion on this topic).

Of the livelihood impacts from conservation's ecological gains, a striking example involves the intensification of human-wildlife conflicts. The conservation efforts around the world over the past decades have generated many ecological gains, as evidenced by the forest transition in many countries such as China (Viña et al. 2016), the comeback of gray wolves in the USA (USFWS 2013), and the recovery of large carnivores in Europe (Chapron et al. 2014). Besides enhancing the provision of ecosystem services, ecological gains from conservation may cause substantial socioeconomic losses through intensifying human-wildlife conflicts (Bonacic et al. 2016; Linkie et al. 2007). Although human-wildlife conflicts have long been studied (Bonacic et al. 2016), associated losses that are attributable to conservation efforts have rarely been quantified. This information gap may bias conservation cost estimation and thus constrain the effectiveness of conservation management (e.g., targeting cost-effective conservation areas and compensating affected households cost-efficiently).

As a first attempt to quantify the impact of conservation on human-wildlife conflicts, we estimated the effect of afforestation promoted by China's Grain-to-Green Program (GTGP) on crop damage by wildlife in Wolong Nature Reserve (Wolong hereafter) for giant pandas (*Ailuropoda melanoleuca*). GTGP is one of the world's largest payment for ecosystem services (PES) programs, which aims to increase the provision of ecosystem services (e.g., water and soil retention) through offering payments to rural farmers for converting their cropland to forestland or pastureland (Liu et al. 2008). Aside from its primary goal of ecosystem conservation, GTGP also intended to alleviate poverty in China's rural areas (SFA 2002). With massive investment, the GTGP has generated substantial ecological gains (e.g., increase in forest cover) (Li et al. 2013).

However, the ecological gains of GTGP through afforestation on cropland might have negative impacts on agricultural production on remaining cropland, especially in biodiverse rural areas like Wolong. In those regions, cropland close to forests are often susceptible to crop damage by wildlife and thus generate less economic benefit than cropland farther from forests (Linkie et al. 2007). Naturally, less-profitable cropland is more likely to be enrolled into GTGP because it has lower opportunity cost (Fig. 1). However, after former cropland enters GTGP, afforestation may create new habitat for wildlife that damage crops and make remaining cropland more accessible to them (Fig. 1). In addition, crop damage previously borne by cropland enrolled in GTGP (GTGP lands) may be displaced to nearby remaining cropland after the implementation of GTGP. Therefore, afforestation on GTGP lands may intensify crop damage on nearby remaining cropland and cause unanticipated loss to local households.

In this study, we estimated the impact of GTGP on crop damage by addressing a counterfactual question, "Were the cropland enrolled into GTGP not afforested, how much crop damage would there have been on the nearby remaining cropland?" For practical reasons, we cannot observe this counterfactual crop damage directly. Instead, we estimated this counterfactual crop damage using matching methods (Stuart 2010), and then compared that with the observed crop damage on nearby remaining cropland to estimate the increase in crop damage attributable to GTGP.

Methods

Study Area

Wolong is a flagship protected area located within one of the top 25 global biodiversity hotspots in Southwest China (Fig. 2) (Liu et al. 2016). Besides providing sanctuary to hundreds of species of wildlife (including the iconic giant panda), Wolong is home to about 5,300 residents, most of whom are farmers (Liu et al. 2016). To restore and protect wildlife habitat in Wolong, a series of conservation programs have been implemented since early 2000s (Yang 2013).

In Wolong, GTGP enrollment began in 2000, and additional contracts were signed in 2001 and 2003. Under GTGP, the government paid local households about $571 US per ha per year for converting their cropland to forest land and keeping it vegetated (Yang 2013). Totally, about 56% of local cropland was converted to forest. Like many other rural areas, crop damage by wild animals, such as wild boar (*Sus scrofa*), sambar deer (*Rusa unicolor*), and hedgehog (*Erinaceinae*), is common in Wolong (Yang 2013). Thus, the majority of cropland parcels enrolled in GTGP are close to the forest and susceptible to wildlife damage (Chen et al. 2010).

This study benefits from two-decades of research in the reserve (e.g., An et al. 2006; Chen et al. 2009; Liu et al. 1999). Many results and methods developed in the reserve have been applied to studies at regional, national, and global levels (e.g., An et al. 2014; Chen et al. 2011; Liu et al. 2003). The findings of this study will be similarly useful for studies in many other parts of the world, especially in light of calls for more formal causal investigations of the impacts of conservation (Baylis et al. 2015; Ferraro et al. 2015).

Data Collection

We conducted a household survey in Wolong from June to August in 2015. Household heads or their spouses were interviewed because they are familiar with household affairs (e.g., locations of cropland and losses due to wildlife damage). 245 households (about 21% of the total) were randomly sampled and completed the survey. On Google Earth Imagery of Wolong, we digitized boundaries of all cropland parcels owned by each surveyed household with respondents' help. For each cropland parcel, we recorded characteristics of the land plot (e.g., types of crops planted), yield losses due to wildlife damage, and whether preventative measures were taken to avoid wildlife damage (e.g., building fences). We collected information on 423 cropland parcels, of which 176 experienced crop damage by wildlife in 2014.

Using Google Earth Imagery, we obtained boundaries of all former cropland parcels now enrolled in GTGP in Wolong by interviewing local village leaders familiar with the distribution of cropland. In addition, we mapped the distribution of all houses, the main road, and forest areas in Wolong based on visual interpretation of Google Earth Imagery (see sample map in Fig. S1). The average slope of each cropland parcel was derived from elevation information provided by Shuttle Radar Topography Mission.

Study Design

Our unit of analysis is individual remaining cropland parcel after implementation of GTGP, and our outcome measure is crop damage intensity: the reported proportion of crop yield lost in a land parcel due to wildlife damage. Based on distance to nearest GTGP parcel (former cropland parcels that were enrolled into GTGP and were afforested), each analysis unit was placed into one of three ranges: close (< 10 m); medium (10 m - 40 m); and far (> 40 m). Cropland in the close and medium ranges are assumed to be units on which crop damage intensity was highly and moderately affected by afforestation on GTGP parcels, respectively. Cropland parcels in the far range are assumed to be unaffected by GTGP afforestation. We chose 40 m as the threshold to differentiate affected and unaffected lands because the average distance of remaining cropland to forest edge would have been about 40 meters less if cropland enrolled into GTGP were not afforested. Of all the 423 cropland parcels, 169, 97, and 157 fell into the close, medium and far range, respectively.

We were interested in estimating two differences in crop damage intensity: (i) the expected difference between observed crop damage intensities of cropland parcels in the close range (the treated) and the crop damage intensities of these units had they instead been in the far range while holding all else equal (the control); (ii) the expected difference between observed crop damage intensities of cropland parcels in the medium range (the treated) and the crop damage intensities of these units had they instead been in the far range while holding all else equal (the control). The expected differences (i) and (ii) represent the increases in crop damage attributable to GTGP. Our hypothesis that ecological gains from GTGP through afforestation intensified crop damage on nearby remaining cropland would be supported if both (i) and (ii) are positive and a dose-response relationship where (i) > (ii).

Estimating the Impact of GTGP on Crop Damage and the Forgone Crop Revenue

We used cropland units in the far range to construct the control group for each of the above two analyses using matching methods (Stuart 2010). The goal of matching here is to control for observable confounding bias between treated and control cropland parcels (See *SI Text* for more details). Based on our knowledge of Wolong and literature on crop damage, we controlled for a set of variables commonly found to affect crop damage intensity (Table S1). After matching, we performed a test of mean difference of crop damage intensity between treated and control cropland parcels to estimate the crop damages attributable to GTGP. For comparison, we also estimated the increase in crop damage intensity attributable to GTGP using a conventional approach: mean difference between treated and control without matching.

After estimating increases of crop damage intensity attributable to GTGP on cropland in the close and medium ranges, we further estimated the overall proportion of observed crop damages attributable to GTGP using the following equation:

$$Proportion = \frac{In_{close} \times A_{close} + In_{medium} \times A_{medium}}{I_{close} \times A_{close} + I_{medium} \times A_{medium} + I_{far} \times A_{far}} \quad (1)$$

where In_{close} and In_{medium} represent average increases of crop damage intensity caused by GTGP for cropland units in the close and medium range respectively; I_{close}, I_{medium} and I_{far} represent average crop damage intensities for cropland units in the close, medium and far ranges respectively; A_{close}, A_{medium} and A_{far} represent the total areas of sample units in the close, medium and far ranges respectively.

To estimate foregone crop revenue due to crop damage attributable to GTGP, we estimated the impact of GTGP on crop damage intensity with the study design proposed above for each type of the crops susceptible to wildlife damage in Wolong, including corn, potato, and cabbage.

We then assessed the total foregone crop revenue due to crop damage attributable to GTGP in Wolong using the following equation:

$$\text{Forgone Revenue} = \sum_i (In_{close,i} \times A_{close,i} + In_{medium,i} \times A_{medium,i}) \times Productivity_i \times Price_i \qquad (2)$$

where $i \in \{corn, potato, cabbage\}$; $In_{close,i}$ and $In_{medium,i}$ represent average increases in crop damage intensity caused by GTGP for crop type *i* in the close and medium range respectively; $A_{close,i}$ and $A_{medium,i}$ represent total cropland areas of crop type *i* in close and medium ranges in Wolong estimated based on our random sample respectively; $Productivity_i$ represents the average yield of crop type *i* on cropland units that were not affected by crop damage; $Price_i$ represents the average price at which households sold crop type *i* in 2014.

Results

Impact estimates (Table 1) show that afforestation on GTGP lands significantly intensified crop damage on nearby cropland. The first column in Table 1 presents the results of comparing cropland units in the close range with their controls (i.e., cropland units in the far range). The mean difference estimated using the matching method was 0.189 (Row 5) and implies that afforestation promoted by GTGP caused 18.9% more yield was lost in the close range due to wildlife damage. The conventional mean difference estimate (0.240, Row 3) was about 27% higher, suggesting the impact of GTGP on crop damage would be overestimated without controlling for covariate differences.

Results GTGP impact on crop damage on cropland units in the medium range show a similar pattern (Column 2, Table 1). The estimate using the matching method was 0.044 (Row 5) and suggests that afforestation from GTGP caused 4.4% more yield loss due to wildlife damage. The conventional estimate (0.058, Row 3) is also higher than that using matching approach (0.044), again, indicating the matching method helped control potential bias.

GTGP's impact on crop damage on cropland units in the close range (0.189) is about four times as high as in the medium range (0.044). This negative dose-response relationship further supports our hypothesis that afforestation on cropland promoted by GTGP intensified crop damage on nearby remaining cropland. Holding all else equal, cropland closer to GTGP lands experienced more crop damage.

Based on the impact estimates above, we calculated the proportion of crop damage that occurred on remaining cropland attributable to GTGP along with foregone crop revenue of this added damage using Equation (1-2). The result suggests that were there no afforestation, crop damage on remaining cropland would have been 64% less. The total foregone revenue of crop damage attributable to GTGP in Wolong is 364,910 Yuan (58,479 USD as of 2014; Fig. 3), an amount up to 27% of total annual payment of GTGP in Wolong.

Robustness Checks

We conducted a set of analyses to check the sensitivity of our results to potential biases and changes in research design (See *SI Text* for details of each of these analysis). First, we performed Rosenbaum's sensitivity tests (Rosenbaum 2002) to estimate how strong a hidden factor would have to be to overturn the conclusions. Our results, the high Γ values in the sixth and seventh row of Table 1, suggest that our estimates of GTGP's impact on crop damage are robust to potential hidden biases. Second, we compared crop damage intensities of the two halves of cropland units in the far range (i.e., the closer half and farther half in terms of their distance to GTGP lands) to check whether cropland units in the far range can reasonably be used to construct the controls. Our results (Table S5) show that the difference is negligible, indicating the control groups in our analyses are reasonably constructed. Third, we varied the distance threshold used to differentiate cropland units strongly and moderately affected by the afforestation on GTGP lands and re-estimated the impact of GTGP on crop damage. The patterns of the estimated impacts are identical (i.e., cropland closer to GTGP lands experienced more damage by wildlife), indicating our results are insensitive to how this threshold distance was defined. Finally, we checked the validation of using forgone crop revenue (Equation 2) to reflect the losses borne by local households through ruling out the possibilities that local households substantially switched crops or altered crop production inputs in response to wildlife damage. But we note that to the extent that wildlife damages led to increased expenditures to prevent damage, the foregone revenue is a conservative measure of the losses due to GTGP-induced wildlife damage.

Discussion

Ecosystem conservation and poverty eradication are two of the United Nations Sustainable Development Goals (United Nations 2016). To design effective pro-poor conservation projects that can achieve both objectives, conservation community needs a better understanding of conservation costs borne by rural communities (Naidoo et al. 2006). Our analysis illustrates that, besides forgone livelihood opportunities on conservation lands, ecological gains from conservation can also cause significant unanticipated additional losses to rural households.

Consideration of this cost has important implications for conserving ecosystems ethically and sustainably. For instance, payments for ecosystem services (PES) are increasingly implemented for their potential to alleviate poverty (Fischer et al. 2012; Naeem et al. 2015). To date, however, payment levels of PES programs are largely designed based on the foregone productive uses (e.g., farming) of the land being targeted. This would be unfair to service providers (e.g., rural farmers) if PES programs can cause unanticipated additional losses not covered by the payments they offered. In the case of GTGP, the current payments are made solely based on the amount of cropland afforested under the program, while the potential impact of GTGP on crop damage to remaining lands was not considered. Therefore, rural households that bore the cost of crop damage induced by GTGP might have been undercompensated. In addition, as losses due to wildlife damage increases, local people may grow to view conservation projects and wildlife negatively, thereby compromising the sustainability of conservation.

To mitigate these negative impacts, novel and comprehensive management strategies and policies are required to achieve socioeconomic and ecological gains simultaneously. Although direct compensation for wildlife damage can be an effective way to address human-wildlife conflicts, its efficiency might be subject to some common factors in poor rural areas like government corruption and insufficient financial and human resources to handle all cases of wildlife damage (Nyhus et al. 2005; Storie and Bell 2016). Therefore, other complementary measures such as systematic land-use planning (e.g., switching to crop types that are less susceptible to wildlife damage) and preventative strategies (e.g., establishing fence) should also be considered to mitigate wildlife damage attributable to conservation efforts (See *SI Text* for more details).

Although our analysis here is restricted to the afforestation prompted by GTGP in China, similar effects are likely to occur in regions where related conservation efforts have been taking place. For example, in the United States, about 9.52 million hectares of cropland has been enrolled in the Conservation Reserve Program and converted to other vegetative covers (USDA 2016). In Europe, the Common Agricultural Policy has resulted in afforestation of about 8 million hectares of cropland (European Commission 2013). In the Russian Federation, about

2.74 million hectares of cropland has been afforested for conservation purposes (Kulik et al. 2015). Although the specific effects of ecological gains from conservation on costs borne by rural communities may vary in different contexts, the general trends may be similar. To truly understand conservation costs, more interdisciplinary studies are needed to quantify all different sources of costs and understand the underlying processes under various policies in different regions. Armed with such knowledge, conservation practitioners may be able to design more effective pro-poor conservation programs for the dual objectives of ecosystem conservation and poverty alleviation targeted by the United Nations Sustainable Development Goals.

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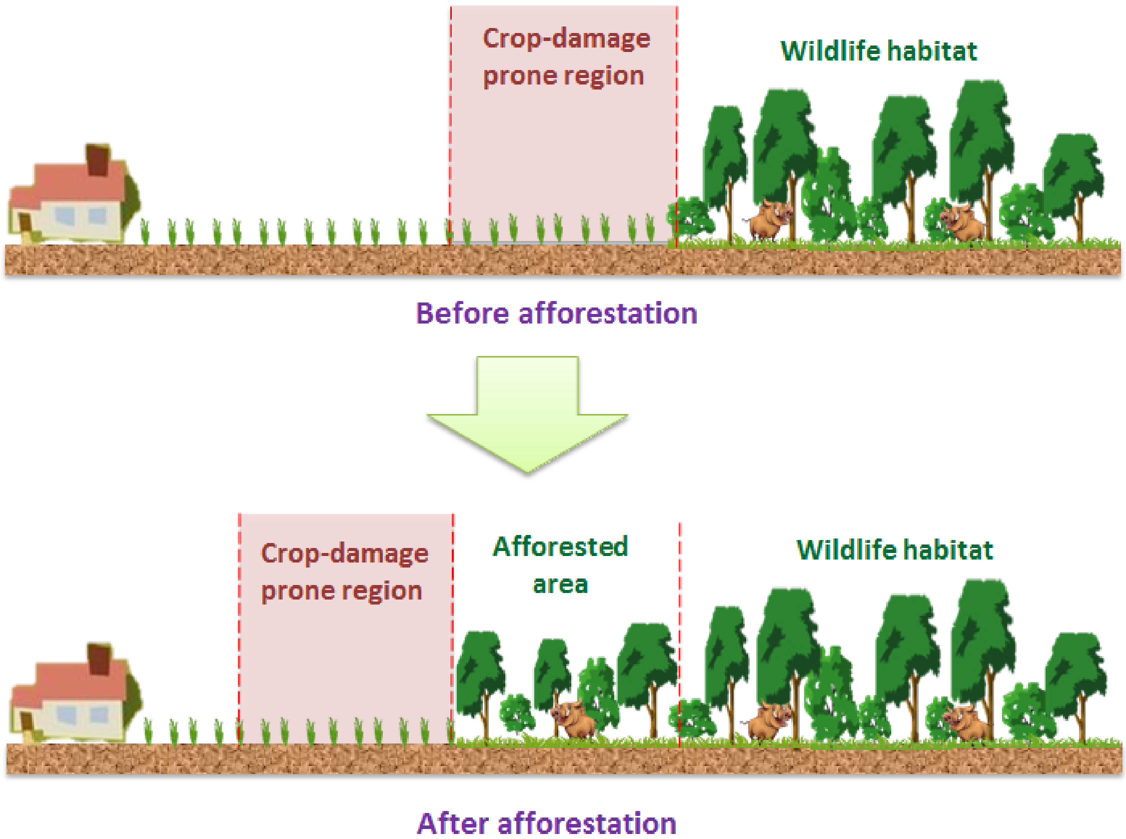

Figure 1 Illustration of the change of crop damage by wildlife before and after afforestation on cropland promoted by conservation program(s). Before afforestation, cropland close to wildlife habitat (e.g., forest) are more likely to be affected by crop damage by wildlife. After afforestation, cropland close to wildlife habitat are afforested and the remaining cropland become more likely to be affected by crop damage by wildlife.

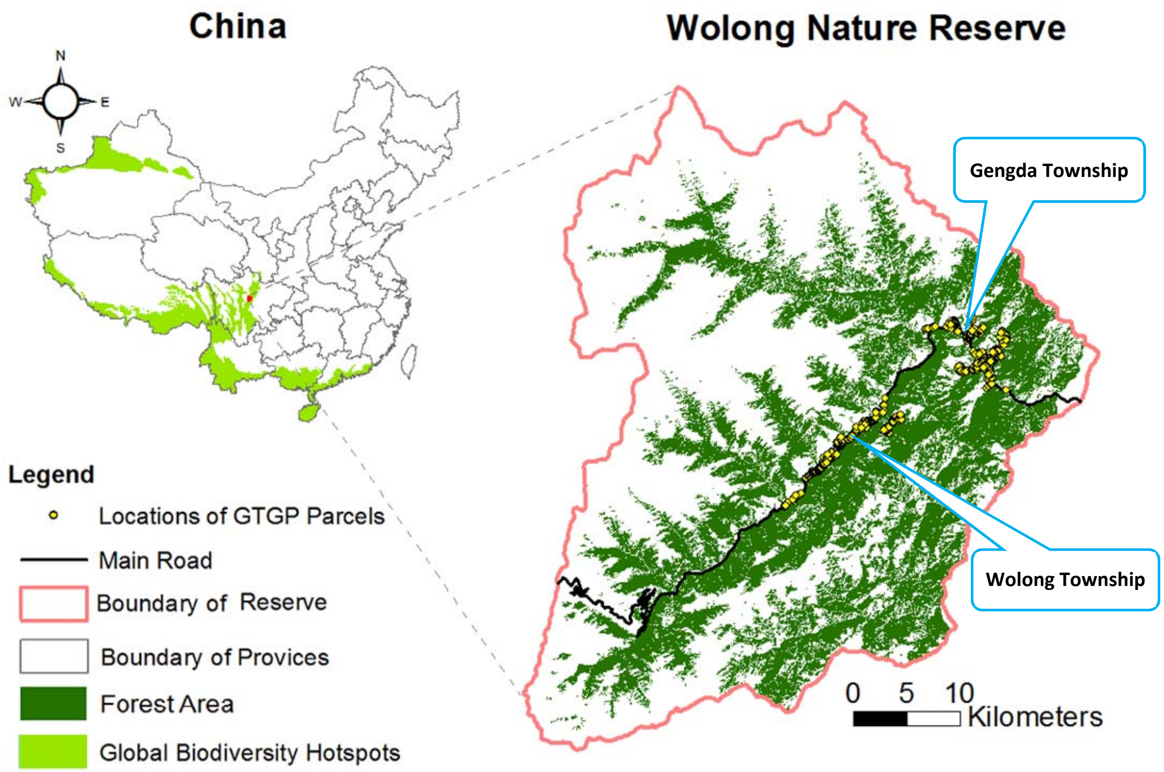

Figure 2 Wolong Nature Reserve in Southwest China. The reserved was established in 1963 and expanded to its current size of 20,000 km^2 in 1975. It is managed by the Wolong Administration Bureau, which is hierarchically structured with two townships under its governance – Wolong Township and Gengda Township, with a total population of about 5,300.

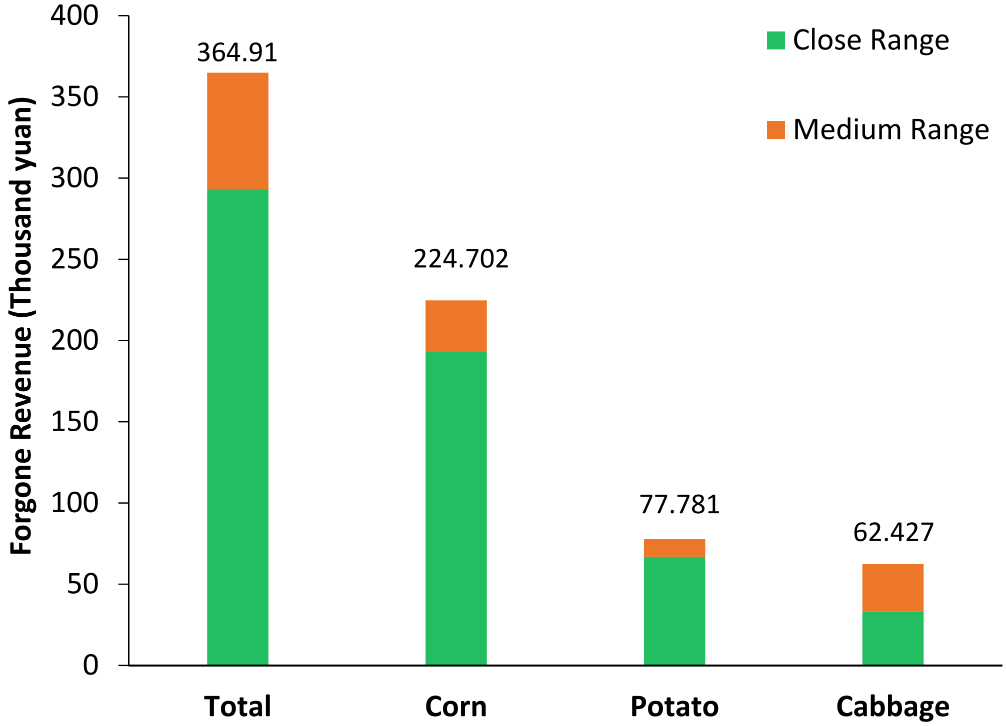

Figure 3 Foregone revenue of crop damage in Wolong attributable to GTGP for each type of crop at the close (< 10 m) and medium (10 m – 40 m) ranges.

Table 1 Average crop damage intensities on cropland units in the close range (< 10 m), medium range (10 m to 40 m) and far range (> 40 m), and the differences among them estimated using different methods.

Approaches	Close vs. Far (i)	Medium vs. Far (ii)
Conventional approach		
Means of the treated and the control	0.255, 0.015	0.073, 0.015
Mean difference without matching †	0.240 ***	0.058 ***
Matching approach		
Mean difference after matching	0.189 (0.024) ***	0.044 (0.010) ***
Γ sensitivity (Wilcoxon) ‡	4.3	3.1
Γ sensitivity (Hodges-Lehmann) §	2.6	1.1
[Number of treated and control]	[169, 157]	[169, 97]

† The significance level is estimated based on the unpaired t-test.

‡ The value of Γ at which the null of zero effect would fail to be rejected at P=0.05 level based on Wilcoxon signed-rank p-value.

§ The value of Γ at which the lower bound of 95% confidence interval for the Hodges-Lehmann point estimate of the effect includes zero.

¶ Significance: *** indicates statistical significance at the 0.001 level.

Appendix: Supporting information

This document includes:

1. Conservation Costs Borne by Rural Communities

During the past half-century, human activities (e.g., agricultural expansion and deforestation) have caused unprecedented degradation of important ecosystems that are essential for human well-being (Barrett et al. 2011; Martínez-Ramos et al. 2016). To address this critical issue, hundreds of conservation programs have been designed and implemented in many rural areas across the world, where most of the world's poorest people reside (Williams 2013). Unfortunately, conservation's economic costs are often not distributed in proportion to their ecological gains. The ecological gains (e.g., enhanced water supply, wildlife habitats and carbon sequestration) are often shared regionally or even globally, but many of the costs are borne by local poor communities (Adams et al. 2004; Cao et al. 2009).

Conservation costs borne by rural communities mainly include two parts: the forgone livelihood opportunities and the negative impacts on existing livelihood activities (Naidoo et al. 2006). For example, forest conservation is often pursued by conservation programs through restricting extractive uses of forests (e.g., timber harvesting). In such cases, the forgone extractive use of the forest would be the opportunity cost to local households. Afforestation on marginal cropland is another type of conservation practice often pursued by conservation policies (e.g., the Grain-to-Green Program in China (Liu et al. 2008) and the Conservation Reserve Program in the United States (USDA 2016)). In these cases, the forgone crop production due to afforestation would be the opportunity costs to participating in rural households. But opportunity costs may not be all of the costs to local households because the ecological gains from the conservation (e.g., improved forest conditions) may boost the populations of crop and livestock predators, exacerbate human-wildlife conflicts, and result in other costs to local households. For example, Chinese governments have been implementing a series of national conservation policies (e.g., the Natural Forest Conservation Program and the Grain-to-Green Program (GTGP)) since late 1990s (Liu et al. 2008; Wang et al. 2007). Evidences from different parts of China (e.g., Jilin (Meng 2016), Jiangxi (Xiao 2011), Ningxia (Zhuang 2009), and Hubei (Li 2011)) showed that these conservation policies have contributed to the increase of crop damage and livestock predation by wild animals such as wild boar (*sus scrofa*), amur tiger (*Panthera tigris altaica*), and amur leopard (*Panthera pardus orientalis*).

Although human-wildlife conflicts have been a common cause of economic losses to many rural communities worldwide (Bonacic et al. 2016; Conover 2001; Treves et al. 2006) and conservation policies (e.g., protected areas) are believed to be an important driving factor behind this issue (Linkie et al. 2007; Naidoo et al. 2006), the resulting losses attributable to conservation programs have rarely been estimated. Therefore, to date, conservation costs to rural households is largely estimated from foregone livelihood opportunities [e.g., cost estimation in ref. (Adams et al. 2010; Kremen et al. 2000; Machado et al. 2016; Uchida et al. 2005)], without incorporating costs imposed by ecological gains from conservation.

2. Supporting Methods and Results

2.1 Matching Method for Impact Estimation

The goal of matching methods is to control for observable differences between treated and control cropland parcels that may affect both the crop damage intensity and proximity to GTGP parcels (Rosenbaum 2002). Matching effectively reweights the sample observations (e.g., cropland parcels that are poor matches receive a weight of zero), and makes the covariate distributions of cropland parcels in control and treatment groups similar (called covariate balancing). In this way, matching seeks to replicate a randomized experiment by reducing bias due to observable confounding factors. After matching, the average crop damage intensities of cropland units in the far range will reasonably approximate the counterfactual crop damage intensities that would have occurred on cropland units in the close and medium range respectively, had GTGP not been implemented.

In this study, we controlled for a set of variables that are commonly found to affect crop damage intensity, including distance to other forests (forests other than GTGP forests), distance to main road, slope, crop species and whether preventative measures were used (Table S1). Without controlling for these covariates via matching, our estimates may be biased. For example, GTGP lands are mostly located in places distant from human settlements and the main roads and close to forests (see unmatched covariate balance in Table S2 and Table S3, Supporting Information) because cropland there is more susceptible to wildlife damage. Thus, remaining cropland parcels that have similar characteristics are more likely to be located close to GTGP lands and experience crop damage by wildlife.

To control for these variables, we used a one-to-one matching approach (i.e., one treated unit is matched with one control unit) that attempts to maximize the covariate balance via a genetic search algorithm (Diamond and Sekhon 2013). The matching is with replacement. A caliper, i.e., a maximum tolerated distance, was also used to improve the matching quality and was set at 0.5 standard deviation of each matching covariate. After matching, the difference between treated cropland units and control cropland units move dramatically toward zero (see matched covariate balance in Table S2 and Table S3, Supporting Information).

2.2 Robustness Checks

To test the robustness of estimated increases in crop damage intensity, we conducted Rosenbaum's sensitivity tests (Rosenbaum 2002) to estimate how strong a hidden factor would have to be to overturn the conclusion of this study. These tests assume that each cropland parcel has a fixed value of an unobserved covariate (hidden factor) that causes cropland parcels in treatment and control groups to systematically differ in their odds of being affected by afforestation on GTGP lands. A sensitivity parameter Γ measures the magnitude of this odds difference. While the actual values of Γ are unknown, one can try different values of Γ to see whether the conclusions of this study change. A Γ value near one indicates a small hidden factor could account for the treatment effect. The larger the Γ value that is required to change the conclusion, the more robust the conclusion is (Rosenbaum 2002).

The Rosenbaum sensitivity test results (i.e., Γ values in the sixth and seventh rows of Table 1 in the *Main Text*) indicate that estimates of crop damage that are attributable to GTGP from the matching method are robust to potential hidden factors. The Γ value of 4.3 (Row 6, Table 1) shows the result of Rosenbaum sensitivity analysis based on Wilcoxon sign rank test (Rosenbaum 2002). An intuitive interpretation of this statistic is that that the crop damage estimate would remain significantly different from zero ($P < 0.05$) even in the presence of a strong hidden bias that could cause the odds of being affected by afforestation on GTGP lands to differ by a factor as high as 4.3. The Γ value of 2.6 (Row 7, Table 1) shows the result of Rosenbaum sensitivity analysis based on Hodges-Lehmann (HL) point estimate (Rosenbaum 2002). The result indicates the 95% confidence interval of the HL estimate would still exclude zero in the presence of an additive fixed hidden bias that could cause the odds of being affected to differ by a factor of 2.6. These high Γ values suggest that our estimates of GTGP's impact on crop damage by wildlife are robust.

We also tested whether we had underestimated the distance within which crop damage on remaining cropland was still affected by afforestation on GTGP lands. If the afforestation has significant influence on crop damage intensity on cropland units farther than 40 m, it would downwardly bias our estimates because the crop damage intensity on control units (cropland parcels unaffected by GTGP) had been overestimated. To test this bias, we divided cropland units in the far range into two halves based on their distance to GTGP lands, and compared their average crop damage intensities using matching method. If there is no significant difference between the crop damage intensities, this bias would be negligible.

Our test results (Table S5) indicate that using cropland parcels in the far range (i.e., distance to GTGP parcels > 40 m) to construct control groups for our analyses is reasonable. Comparison between crop damage intensities of the two halves of cropland units in the far range (i.e., the closer half and farther half in terms of their distance to GTGP lands) shows that the difference is quite small (0.0008) and statistically insignificant ($P > 0.2$). This indicates that afforestation on GTGP lands has little impact on crop damage on cropland units beyond 40 m to GTGP lands.

In addition, we varied the distance threshold used to differentiate cropland units that are strongly and moderately affected by the afforestation on GTGP lands, and checked whether our conclusions still hold. Our results (Table S6 and Table S7) show that the patterns of the estimated impact of the afforestation on crop damage are consistent when different distance thresholds (i.e., 15 m and 20 m) were used to differentiate cropland units strongly and moderately affected by GTGP. Similar to what we observed using the distance threshold of 10 m, holding all else equal, cropland units that are closer to GTGP lands (i.e., more strongly affected by the afforestation on GTGP parcels) experienced more crop damage by wildlife.

Finally, we checked the validity of using foregone crop revenue (Equation (2) in the *Main Text*) to reflect the losses borne by local households due to crop damage attributable to GTGP. Using foregone revenue for losses may be biased if local households systematically switched crops in response to wildlife damage because these crops could have different revenues and production costs. In Wolong, corn, potato and cabbage are the three major crops. Our results (Table S8-10) suggest corn and potato were much more likely to experience damage by wildlife than cabbage. Therefore, planting cabbage on cropland close to forests and corn and potato far from forests could help to reduce crop damage. Interestingly, our analysis (Table S12) indicates corn and potato plots in Wolong were closer, rather than farther, to forest edge than cabbage plots. This result indicates the spatial arrangement of cropland in Wolong is mainly determined by factors other than crop damage. For example, our survey data indicates that the weight of annual yield of cabbage on the same area of land (about 6 kg/mu) is much higher than corn (about 0.5 kg/mu) and potato (about 1 kg/mu). Meanwhile, croplands close to forest are often far from main roads and have steeper slope than croplands far from forest. If cabbage were planted on cropland close to forest edges, the transportation cost would be much higher than that of corn and potato.

Our measure of foregone crop revenue tends to overstate losses if local household defensively lowered their input for crop production (e.g., fertilizer and seeds) on land susceptible to wildlife damage. To test this potential bias, we performed a regression analysis to check whether significant differences in production costs exist among households experienced different levels of crop damage. If local households did change their production costs for cropland susceptible to wildlife damage, the impact of crop damage intensity on production costs would be significant. Our regression result (Table S11) shows that the impact of crop damage intensity on household production costs is insignificant, indicating local households did not significantly change their inputs for cropland susceptible to wildlife damage.

It is worth mentioning that the foregone revenue might be a conservative measure of the losses due to increased wildlife damage because some households may have had increased expenditures to prevent damage by wildlife. Our analysis (Table S13) indicates cropland close to forest edge, and therefore more susceptible to wildlife damage, was more likely to have preventive measures to avoid crop damage. In Wolong, the preventative measures undertaken by households included building iron fences, building simple wooden fences, tying their dogs to stakes on the edge of cropland, and sending a household member to patrol cropland when crop damage was most likely occurring (e.g., when the corn and potato mature). The range and nature of the preventative measures made estimation of their monetized cost difficult, so we note that by omitting these costs we have a conservative measure of the added costs to households of afforestation on GTGP lands.

We ran all the matching and sensitivity tests in R (R development Core Team 2013) using the packages 'Matching' (Sekhon 2007) and 'Rbounds'(Keele 2011). We performed regression analysis and *t*-tests using Stata 12 (software, STATA Corp., College Station, Texas, USA).

3. Policy Recommendations

To mitigate the negative impact of ecological gains from conservation on rural livelihoods, novel and comprehensive management strategies are required. Currently, compensating households that experienced wildlife damages (including crop damage and livestock predation by wildlife) has been the most common mitigation strategy (Nyhus et al. 2005). However, previous studies indicate that the use of compensation schemes have had mixed success due to issues related to inefficient governance (e.g., corruption) and shortage of necessary resources (e.g., financial and human resource to handle all cases) (Nyhus et al. 2005; Storie and Bell 2016). In Wolong, our survey shows that of all the cropland that experienced crop damage by wildlife, only 2% received compensation. Therefore, an integrated strategy that combines compensation together with other complementary measures such as preventative management and land-use planning may be a better option to address the issue of wildlife damage induced by conservation (Bulte and Rondeau 2005; Gross et al. 2016). For example, given the relative small size of the remaining cropland area in Wolong (about 0.15% of the whole reserve), establishing fences around the remaining cropland may be a cost-effective way to reduce crop damage without much influence on the connectivity of panda habitats. In addition, planting alternative crop types less likely to be affected by wildlife damage may also help to address this issue. For example, plum has been introduced to Wolong in recent years and become a promising new type of cash crop. Unlike corn and potato, plum is not susceptible to wildlife damage. Planting plum on cropland close to forest may help to avoid the losses to wildlife damage on remaining cropland that was induced by GTGP.

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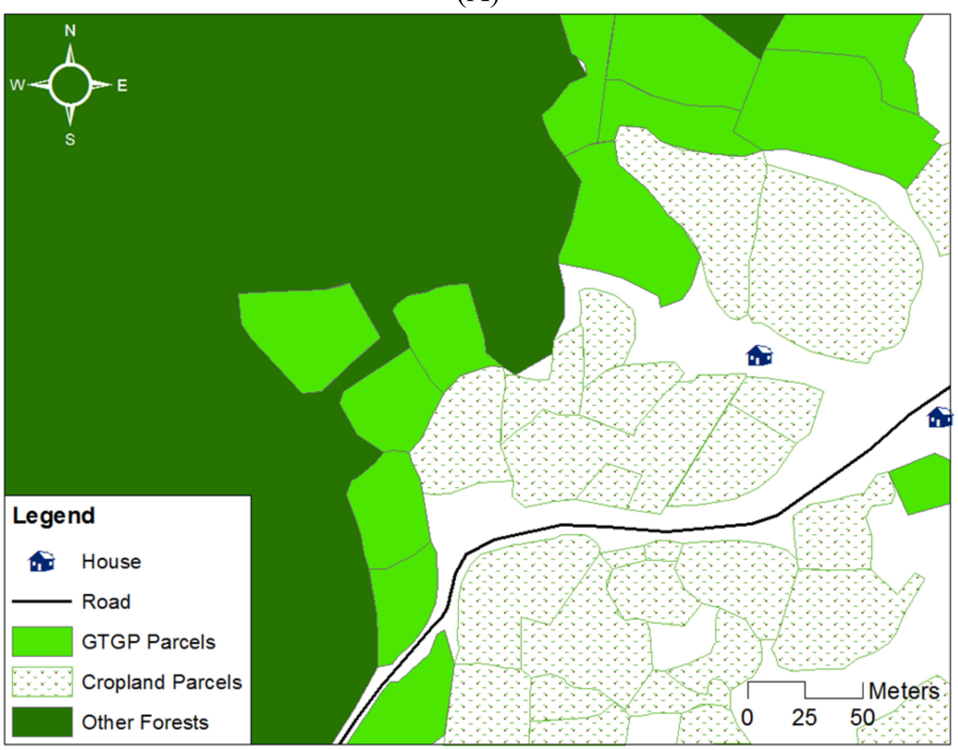
(A)



(B)

Figure S1 Google Earth Image of a sample area in Wolong (A) and the corresponding classification map based on survey results and visual interpretation (B).

Table S1 Descriptive statistics of variables used in estimating the impact of the GTGP on crop damage occurring on nearby remaining croplands (n = 423).

Variables	Description	Mean (SD)
Outcome Variable		
Crop damage intensity	The proportion of crop yield lost in a parcel due to wildlife damage 2014	0.12 (0.22)
Treatment variable		
Distance to GTGP forests	The straight-line distance from the cropland parcel boundary to the edge of GTGP parcel.	46.48 (64.55)
Covariates		
Distance to other forest edge	The straight-line distance from the cropland parcel boundary to the edge of forests other than GTGP forest.	66.82 (52.45)
Slope	The average slope of the cropland parcel	19.98 (10.09)
Distance to the main road	The straight-line distance from the centroid of the cropland parcel to the main road	404.67 (599.46)
Distance to nearest house	The straight-line distance from the centroid of the cropland parcel to the nearest house	57.28 (74.44)
Crop species	Whether the planted crop is corn or potato: 1, Yes; 0, No.	0.68 (0.47)
Preventive measure	Whether preventative measures were taken to avoid crop raiding	0.14 (0.35)

† the basic unit for these measurements is individual remaining cropland parcels.

Table S2 Covariate balance for comparing cropland units in the close range (< 10 m) with units in the far range (> 40 m).

Variable	Status	Mean for units in the close range	Mean for units in the far range	Difference in mean value	Mean eQQ difference†
Distance to other forest edge	Unmatched	51.75	86.97	-35.22	36.46
	Matched	47.69	49.14	-2.45	3.77
Slope	Unmatched	22.60	16.85	5.75	5.62
	Matched	22.01	21.49	0.52	1.30
Distance to the main road	Unmatched	522.07	251.98	270.09	265.95
	Matched	328.13	291.31	36.82	6.94
Distance to nearest house	Unmatched	73.82	42.77	31.05	29.63
	Matched	46.46	44.73	1.73	4.97
Crop species	Unmatched	0.79	0.57	0.22	0.21
	Matched	0.76	0.76	0.00	0.00
Preventive measure	Unmatched	0.21	0.05	0.16	0.15
	Matched	0.065	0.065	0.00	0.00

†The mean difference in the empirical quartile functions for each covariate.

Table S3 Covariate balance for comparing cropland units in the medium range (10 to 40 m) with units in the far range (> 40 m).

Variable	Status	Mean for units in the medium range	Mean for units in the far range	Difference in mean value	Mean eQQ difference[†]
Distance to other forest edge	Unmatched	60.46	86.97	-26.51	26.46
	Matched	63.35	63.41	-0.06	4.00
Slope	Unmatched	20.47	16.85	3.62	3.83
	Matched	19.83	19.45	0.38	0.68
Distance to the main road	Unmatched	447.25	251.98	195.27	203.27
	Matched	311.83	289.97	21.86	32.17
Distance to nearest house	Unmatched	51.97	42.77	9.20	10.16
	Matched	20.79	20.72	0.27	2.67
Crop species	Unmatched	0.65	0.57	0.08	0.08
	Matched	0.64	0.64	0.00	0.00
Preventive measure	Unmatched	0.18	0.05	0.13	0.12
	Matched	0.064	0.064	0.00	0.00

†The mean difference in the empirical quartile functions for each covariate.

Table S4 Covariate balance for comparing the first half and second half of cropland units in the far range (> 40 m). Units in the first half are closer to GTGP parcels (40 m to 95 m) while units in the second half are farther to GTGP parcels (> 95 m).

Variable	Status	Mean for units in the first half	Mean for units in the second half	Difference in mean value	Mean eQQ difference†
Distance to other forest edge	Unmatched	80.33	95.22	-14.89	15.96
	Matched	78.29	79.61	-1.32	7.23
Slope	Unmatched	18.15	15.23	2.92	3.11
	Matched	14.81	14.38	0.43	1.14
Distance to the main road	Unmatched	389.75	80.76	308.99	300.93
	Matched	146.62	131.53	15.09	36.61
Distance to nearest house	Unmatched	47.08	37.41	9.67	11.40
	Matched	29.10	25.85	3.25	0.051
Crop species	Unmatched	0.66	0.47	0.19	0.17
	Matched	0.65	0.65	0.00	0.00
Preventive measure	Unmatched	0.057	0.043	0.014	0.014
	Matched	0.027	0.027	0.00	0.00

† The mean difference in the empirical quartile functions for each covariate.

Table S5 Average crop damage intensities on cropland units in the first half and second half of cropland units in the far range (> 40 m), and the difference between them. Units in the first half are closer to GTGP parcels (40 m to 95 m) while units in the second half are farther to GTGP parcels (> 95 m).

Approaches	First half vs. Second half
Conventional approach	
Means of the treated and the control	0.015, 0.016
Mean difference without matching †	-0.001
Matching approach	
Mean difference after matching	-0.0008 (0.004)
[Number of treated and control]	[78, 79]

† The significance level is estimated based on unpaired *t*-test.

Table S6 Average crop damage intensities for cropland units in the close range (< 15 m), medium range (15 m to 40 m) and far range (> 40 m), and the differences among them estimated using different methods.

Approaches	Close vs. Far (i)	Medium vs. Far (ii)
Conventional approach		
Means of the treated and the control	0.233, 0.015	0.044, 0.015
Mean difference without matching †	0.218	0.029
Matching approach		
Mean difference after matching	0.17 (0.02) ***	0.035 (0.003) ***
Γ sensitivity (Wilcoxon) ‡	4.5	2.3
Γ sensitivity (Hodges-Lehmann) §	2.7	1.1
[Number of treated and control]	[203, 157]	[63, 157]

† The significance level is estimated based on the unpaired t-test.

‡ The value of Γ at which the null of zero effect would fail to be rejected at P=0.05 level based on Wilcoxon signed-rank p-value.

§ The value of Γ at which the lower bound of 95% confidence interval for the Hodges-Lehmann point estimate of the effect includes zero.

¶ Significance: *** indicates statistical significance at the 0.001 level.

Table S7 Average crop damage intensities for cropland units in the close range (< 20 m), medium range (20 m to 40 m) and far range (> 40 m), and the differences among them estimated using different methods.

Approaches	Close vs. Far (i)	Medium vs. Far (ii)
Conventional approach		
Means of the treated and the control	0.215, 0.015	0.027, 0.015
Mean difference without matching †	0.20	0.012
Matching approach		
Mean difference after matching	0.16 (0.02) ***	0.02 (0.005) ***
Γ sensitivity (Wilcoxon) ‡	4.9	1.6
Γ sensitivity (Hodges-Lehmann) §	2.1	1.1
[Number of treated and control]	[228,157]	[38, 157]

† The significance level is estimated based on the unpaired t-test.

‡ The value of Γ at which the null of zero effect would fail to be rejected at P=0.05 level based on Wilcoxon signed-rank p-value.

§ The value of Γ at which the lower bound of 95% confidence interval for the Hodges-Lehmann point estimate of the effect includes zero.

¶ Significance: *** indicates statistical significance at the 0.001 level.

Table S8 Average crop damage intensities for cropland units planted with potato in the close range (< 20 m), medium range (20 m to 40 m) and far range (> 40 m), and the differences among them estimated using different methods.

Approaches	Close vs. Far (i)	Medium vs. Far (ii)
Conventional approach		
Means of the treated and the control	0.289, 0.026	0.089, 0.026
Mean difference without matching †	0.263	0.063
Matching approach		
Mean difference after matching	0.198 (0.028) ***	0.07 (0.016) ***
Γ sensitivity (Wilcoxon) ‡	3.6	3.0
Γ sensitivity (Hodges-Lehmann) §	4.6	1.1
[Number of treated and control]	[113,87]	[38, 157]

† The significance level is estimated based on the unpaired t-test.

‡ The value of Γ at which the null of zero effect would fail to be rejected at P=0.05 level based on Wilcoxon signed-rank p-value.

§ The value of Γ at which the lower bound of 95% confidence interval for the Hodges-Lehmann point estimate of the effect includes zero.

¶ Significance: *** indicates statistical significance at the 0.001 level.

Table S9 Average crop damage intensities for cropland units planted with Corn in the close range (< 10 m), medium range (10 m to 40 m) and far range (> 40 m), and the differences among them estimated using different methods.

Approaches	Close vs. Far (i)	Medium vs. Far (ii)
Conventional approach		
Means of the treated and the control	0.302, 0.026	0.077, 0.026
Mean difference without matching †	0.276	0.049
Matching approach		
Mean difference after matching	0.244 (0.029) ***	0.068 (0.016) ***
Γ sensitivity (Wilcoxon) ‡	4.4	2.9
Γ sensitivity (Hodges-Lehmann) §	3.3	1.1
[Number of treated and control]	[130,90]	[58, 90]

† The significance level is estimated based on the unpaired t-test.

‡ The value of Γ at which the null of zero effect would fail to be rejected at P=0.05 level based on Wilcoxon signed-rank p-value.

§ The value of Γ at which the lower bound of 95% confidence interval for the Hodges-Lehmann point estimate of the effect includes zero.

¶ Significance: *** indicates statistical significance at the 0.001 level.

Table S10 Average crop damage intensities for cropland units planted with cabbage in the close range (< 10 m), medium range (10 m to 40 m) and far range (> 40 m), and the differences among them estimated using different methods.

Approaches	Close vs. Far (i)	Medium vs. Far (ii)
Conventional approach		
Means of the treated and the control	0.086, 0.0	0.022, 0.00
Mean difference without matching †	0.086	0.022
Matching approach		
Mean difference after matching	0.022 (0.02) *	0.026 (0.05)
Γ sensitivity (Wilcoxon) ‡	1.5	1.6
Γ sensitivity (Hodges-Lehmann) §	1.1	1.1
[Number of treated and control]	[36,67]	[34, 67]

† The significance level is estimated based on the unpaired t-test.

‡ The value of Γ at which the null of zero effect would fail to be rejected at P=0.05 level based on Wilcoxon signed-rank p-value.

§ The value of Γ at which the lower bound of 95% confidence interval for the Hodges-Lehmann point estimate of the effect includes zero.

¶ Significance: *** indicates statistical significance at the 0.001 level.

Table S11 Impact of average crop damage intensity on total production costs, which includes expenses for seeds, fertilizer, pesticide, herbicide and plastic film.

Variables	Description	Coefficient (SE)
Crop damage intensity	Weighted average crop damage intensity of household's cropland parcels based on each their areas.	411.22 (421.19)
Flat land area	The total area of household's flat cropland (slope < 5°).	135.40 (32.28) ***
Sloping land area	The total area of households' sloping cropland (slope ⩾ 5°).	184.85 (42.13) ***

†The unit of analysis is individual household.

‡ Significance: *** indicates statistical significance at the 0.001 level.

Table S12 Unpaired *t*-test of distance to forest edge between cropland plots susceptible to wildlife damage (corn and potato plots) and the ones unsusceptible to wildlife damage (cabbage plots).

	Susceptible (Mean ± S.D.)	Unsusceptible (Mean ± S.D.)	Unpaired *t*-test (two-tailed)
Distance to forest edge: Corn plots V.S. cabbage plots	26.37±36.23	46.67 ± 41.85	-20.30***
Distance to forest edge: Potato plots V.S. cabbage plots	27.46 ±36.82	46.67± 41.85	-19.22***

†The unit of analysis is individual cropland plot.

‡ Significance: *** indicates statistical significance at the 0.001 level.

Table S13 Unpaired *t*-test of distance to forest edge between cropland parcels used preventive measure (e.g., building fence) and the ones did not.

	Prevention (Mean ± S.D.)	No prevention (Mean ± S.D.)	Unpaired *t*-test (two-tailed)
Distance to forest edge	15.06 ± 31.06	33.00 ± 41.32	17.94**

† Significance: ** indicates statistical significance at the 0.01 level.