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Financial incentives often fail to reconcile agricultural productivity and pro-conservation behavior

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Paying resource users to preserve features of their environment could in theory better align production and conservation goals. We show, however, that across a range of conservation dilemmas, they might not. We conduct a synthesis of dynamic games experiments built around collective action dilemmas in conservation, played across Europe, Africa, and Asia. We find, across this range of dilemmas, that while payments can encourage pro-conservation behavior, they often fail to capitalize on the potential for jointly improving productive and environmental outcomes, highlighting the more nuanced challenge of reconciling livelihoods with conservation goals. We further find production (yield) and the joint production-environment product (i.e., a measure of agricultural production multiplied by a measure of pro-conservation practice) are better preserved in groups that are more educated, more gender diverse and that better represent women. We discuss how the design of incentive programs can better align livelihood and environment goals.

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A common thread across many challenges in environmental management and conservation is excludability (the capacity to enforce boundaries and limit access), with one group of people often struggling to rely on agricultural production from land under competition from nature and other people in the same space[1–4]. In cases where the prevailing solution to such human-environment dilemmas is to push back nature—to spray, to shoot, to fence, or to over-exploit—pro-environment interests will often seek to encourage pro-environment practices with available governance tools, which will differ from place to place[5,6]. Direct payments to individuals or groups—possibly framed as compensation for an action taken or costs incurred—are common choices because they are light-touch, scalable, and applicable to a broad range of barriers to participation—opportunity cost of effort, land, or other input; liquidity constraints; or risk aversion[7]. Importantly, approaches that integrate participation and economic incentive can potentially improve cooperation around the resource[8]. However, evidence for improved cooperation is mixed and limited, and the effectiveness of direct payments in better aligning conservation with local and global development goals depends on the interplay between context, design and implementation[9–11].

In many contexts, requirements for payments are simply to cede production to some pro-environmental goal; in these cases, payments are designed to achieve environmental goals at the expense of production[12]. However, many problems don't fit this simple mold. Many pro-environment challenges are about shifting behaviors to more productively harness ecosystem services. In these contexts, the encouragement may not necessarily reduce production, but rather nudge farmers to expand the supply and use of regulating and supporting ecosystem services while still maximizing production (a provisioning ecosystem service). In the case of conservation agriculture, for example, the encouragement of cover cropping, minimal tillage, and legume intercropping leads to the private benefit of improved soil health over the course of several seasons, aligning production and environment goals[13–15]. We synthesize data from a diverse set of dilemmas encouraging the enhancement and productive use of ecosystem services—spanning more than 1000 participants across 7 countries, for over 14000 decisions—to examine the role of payments in productive and environmental outcomes. Specifically we ask, in contexts where there is potential for the pro-environment practice to lead to private benefits, do payments help encourage this?

Evidence that could inform this question on the function of payments in environmental service contexts is scarce but accumulating, particularly in PES programs[16–19]. However, these trials are expensive to run, with many years elapsing before results are seen, limiting researchers' capacity to pivot and explore alternative designs. Framed field experiments, also called experimental games, are a participatory method that provides insight into resource users' response to intervention where full field trials are expensive or infeasible; they are a valuable tool to accompany full field trials[20–23]. We developed a small family of dynamic games built around collective action dilemmas in conservation—problems in which individuals face some tension or challenge in working together to meet a shared objective—which have generated insight into problem characteristics common to contexts across Europe, Africa, and Asia (Fig. 1). These games are framed around the coordination challenges of (i) replacing pesticides with insect-based ecosystem services (NonCropShare)[24]; (ii) sharing damages in non-lethal control for pest animal species in agriculture (GooseBump)[25]; and (iii) equitably sharing production and allowing for fallowing in open-access agricultural land (SharedSpace)[26]. This dynamic, spatial approach to experimental games allows representation of key features that shape natural resource management decision-making—uncertainty, nonlinearity, temporal variation, and spatial interaction—that are

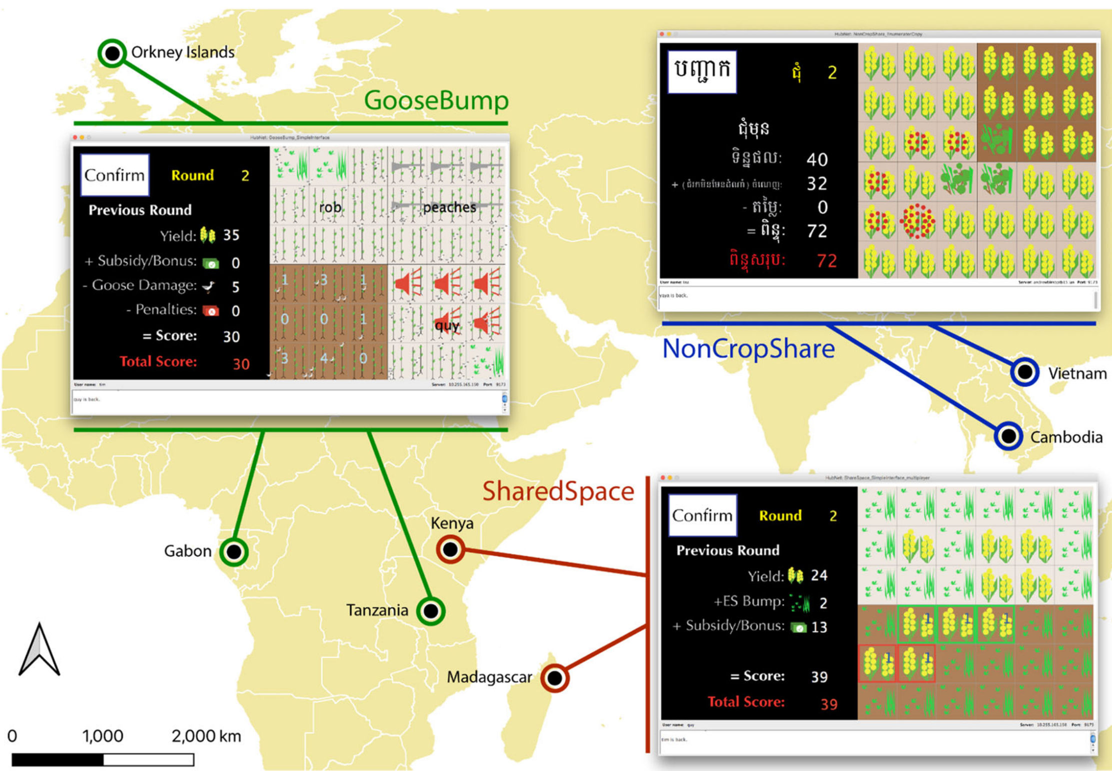

Fig. 1 Study sites for experimental games designed for collective action dilemmas in conservation, with sample client screens. NonCropShare datasets (blue) in Cambodia and Vietnam; GooseBump datasets (green) in Orkney, Gabon, and Tanzania; SharedSpace datasets (red) in Kenya and Madagascar.

challenging to capture, communicate, and make relatable with simpler game structures.

We conduct a synthesis across 7 datasets from this small family of games and find payments targeting conservation actions or outcomes to have varying degrees of alignment with agricultural production and livelihoods across a diverse set of dilemmas. We find that production and the joint production-environment product (i.e., a measure of agricultural production multiplied by a measure of pro-conservation practice) are better preserved in groups that are more educated, more gender diverse and that better represent women. We find stronger relationships (among participants) to be predictors of pro-conservation practice, though at the expense of production. We also find underlying beliefs about the roles of government and community in shaping livelihoods and the environment to be similarly important to observable aspects of identity such as age and gender for predicting conservation and production outcomes.

Results and discussion

Payments do not lead to win-win outcomes for production and conservation. We compare games by three standardized measures observed at each round of play: (i) agricultural production; (ii) pro-conservation practice (differing by game); and iii) the joint product of pro-conservation, agricultural production (see Methods for construction of variables). The games differ in the degree to which production lies in tension with pro-conservation practice (Fig. 2). In SharedSpace, where more land in production means less in fallow, there is a strong trade-off, but with considerable variation in the extent of fallow land held from round to round at high production levels (as ecosystem services from neighboring fallow contribute to production outcomes) (Fig. 2a). GooseBump data show production and pro-conservation practice in tension as well, but differently—production scores are more highly variable (across game rounds) when more animals still persist in the landscape (highlighting the variation in the approaches and success with which different farms co-exist with animals; Fig. 2b)—which holds across landscapes with large numbers of geese (Orkney), lesser numbers of elephants (Gabon), and small numbers of lions (Tanzania). In NonCropShare, where avoiding the heavy use of pesticide is the pro-conservation practice, there are two distinct regimes -- a shallow-sloped, pesticide-dominated regime where land set aside for insect natural enemies is simply land lost (as drift from remaining pesticide use destroys natural enemy services) and environment is improved at the expense of production; and a steeply-sloped, low-pesticide regime where careful coordination allows insect natural enemies to replace pesticides and align production and conservation goals (Fig. 2c).

Across games, it is possible to raise conservation outcomes without loss of production (i.e., moving vertically up in Fig. 2) and possibly with some gain (i.e., moving up vertically and to the right), typically through coordination and collective action across players—sharing ecosystem service benefits from fallow lands, or from dedicated animal or insect habitat, across neighboring properties (i.e., along shared borders). While we do see these solutions emerge across our datasets, we do not see payments as having a significant encouraging effect on this across the dilemmas we examined. In fact, we find that payments for pro-conservation actions do not significantly explain player success in achieving joint environment-production outcomes (with the possible exception of NonCropShare; Table 1), but rather to relax production. Our experimental findings demonstrate that despite differences in game details, direct payments for pro-conservation actions generally (though not universally) encourage pro-conservation practice and consistently reduce production (Table 1). In all game contexts, payments for the pro-conservation practice displaced production, with conservation outcomes usually improved as a result; only in the case of NonCropShare was the joint environment-production outcome improved in response to direct payments. This is a non-trivial finding, as the degree of tension between environment and production outcomes varies across games (Fig. 2), and for any particular conservation outcome there is typically a range of possible production outcomes.

For a subset of 5 of the game datasets (all GooseBump and SharedSpace datasets), game participants responded to a questionnaire that had a large set of harmonizable survey items (i.e., directly comparable items are easily constructed across datasets) measuring participants' beliefs about government, community, and conservation; as well as what we group here as context variables: measures of perceptions about the game, the choices they made in playing, and the strength of existing relationships among players of the game (Table 2). For this subset of our overall data, we observe these groups of belief and context survey items to have comparable explanatory power (in terms of overall explained variance) to the basic observables and presence of payment variables applied in the models in Table 1.

We retain these belief and context variables in further regressions but shift our focus to the explanatory power of observable group characteristics on our environment and production outcomes (Table 3). We observe higher production and joint production-environment outcomes to be associated

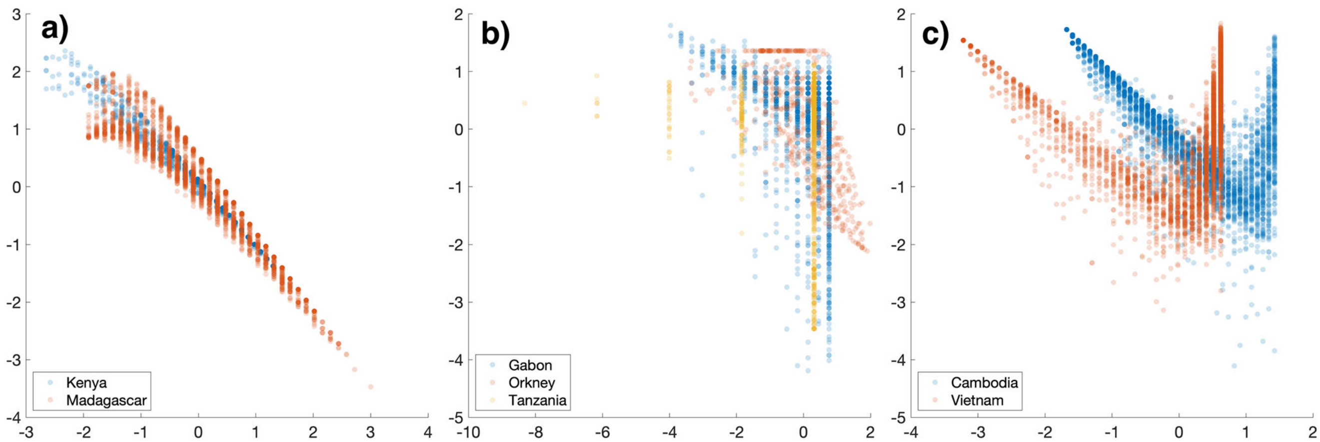

Fig. 2 Environment (x-axis) vs. Production (y-axis) scores across game datasets (as Z-scores, standardized at country-game level—all variables have a mean of 0 at the level of country-game). a SharedSpace; **b** GooseBump (Orkney—Geese; Gabon—Elephants; Tanzania—Lions); **c** NonCropShare.

Table 1 Conservation, production, and conservation-production outcome predictions for all (All), NonCropShare (NCS), GooseBump (GB), and SharedSpace (SS) contexts by observable variables (age, education, gender, and farming as the main income source) and the presence (dummy variable) of payments in the game, across all 7 country datasets.

	Conservation-production				Conservation				Production			
Variables	All	NCS	GB	SS	All	NCS	GB	SS	All	NCS	GB	SS
Payment[a]	0.00860	0.451***	−0.756***	−0.302***	0.317***	0.426***	0.0417	0.356***	−0.360***	−0.184***	−0.845***	−0.322***
Age[b]	0.0888**	0.104*	0.0761*	−0.0440	0.0651*	0.121**	0.0290	0.0539	0.00851	−0.0507	0.0694*	−0.0466
Education[b]	−0.00158	−0.117**	0.0292	0.228***	−0.127***	−0.113*	0.0286	−0.236***	0.0751**	0.0128	0.0306	0.234***
Fraction female[b]	0.0720**	0.0183	0.0647*	0.132	−0.0419	0.0282	−0.0397	−0.140*	0.0659**	0.00196	0.0580*	0.135
Fraction farming as primary income)[b]	−0.00765	−0.00176	0.0188	0.0204	−0.00800	0.0251	−0.0123	−0.0249	−0.0539*	−0.122***	0.00971	0.0212
Constant	−0.00414	−0.191***	0.378***	0.181**	−0.152***	−0.180***	−0.0209	−0.213***	0.173***	0.0779	0.422***	0.193**
Observations	14,351	7840	3208	3303	14,351	7840	3208	3303	14,351	7840	3,208	3303
R-squared	0.013	0.082	0.154	0.110	0.051	0.080	0.003	0.126	0.047	0.025	0.187	0.118
AIC	40556	21587	8581	9000	39989	21605	9106	8939	40043	22061	8451	8972

[a]Dummy variable; [b]Z-score of group mean or fraction.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.
Breakout by country included as Table S1, Supplementary Information.

with greater education, as well as both increased representation by women and gender diversity in the group. We also observe strong relationships—and broader trust in their community to coordinate around conservation—to be associated with lower production and greater pro-conservation practice, consistent with other empirical work on the role of trust in encouraging pro-environment behavior e.g., [27,28]; we do not find that trust in national institutions explains any variation in our three outcomes across our datasets.

Human-environment trade-offs across scale. The degree to which conservation and production goals are in tension (or the degree to which win-win is possible at relevant temporal and spatial scales) is important, as it constrains the possibility space for producers to make improvements and thus also constrains any impact that a nudge or incentive will have in shifting behavior. Depending on the structure of the dilemma, it may be difficult to generate both the private and public social-environmental good, independently of the beliefs, risk tolerance, institutional capacity in a community, or other attributes resource users bring to bear on the problem. Where the environmental good also delivers private benefits -- such as in the coordinated reliance on non-crop habitat in NonCropShare, or more broadly in the widely encouraged practice of conservation agriculture (where improved soil structure delivers both yield benefits and erosion control)[29,30] -- payments (such as in payments for environmental services, or PES programs) can help[16] by enhancing the joint environment-production outcome and potentially even tipping systems into resilient, productive landscapes that don't need any further encouragement[13].

However, the connection from environmental good to private gain may not always be as clear especially during the short term, such as in human-wildlife conflicts of the kind presented in GooseBump, where animal presence will continue to challenge agricultural production goals. While the benefits of wildlife protection (e.g., biodiversity) may be appreciated at a societal scale, such benefits may not be felt at the spatial or temporal scale where management takes place, by those who must bear the costs of protection (reflecting a challenging misalignment of incentives). Furthermore, the effect of spillover deserves attention. Where encouragement of a pro-conservation practice leads to a drop in production, the gap may be made up by expanding production elsewhere (as in cases where consumer states drive deforestation abroad)[31]. Where a locally consumed good is dropped and the gap made up by importing, as Fairet et al.[32] examined in Gabon for example, losses in food quality, local livelihoods, and possibly greener production practices may offset any benefits from the encouraged practice. Further, production cannot be exported ad infinitum, and encouragements must somewhere reconcile people and the environment. This is not to say that payments ought to be ignored as an instrument in cases where synergies between production and environment are not obvious, or appear mismatched in scale. Rather, we only wish to spotlight the need to consider possible unintended consequences occurring at other scales, and put focus on the importance of considering both people and the environment in program design.

Designing interventions with both people and environment in mind. We suggest to those designing interventions or conservation programs to ask critically what encouragements are best poised to harmonize livelihood and environment goals, and to lead to sustained, scalable outcomes. One form of such harmonized design might be incentives programs calibrated jointly to a conservation outcome (e.g., living animal population) as well as a production outcome (e.g., production of a locally important

Table 2 Conservation-production outcomes on observables, beliefs, and context variables for 5-country subset.

	Variables	Payment	Payment + Observables	Payment + Beliefs	Payment + Contexts	All
		Conservation-Production				
	Payment[a]	−0.526***	−0.527***	−0.526***	−0.527***	−0.527***
Observables	Age[b]		0.0315			0.0579
	Education[b]		0.120***			0.138***
	Fraction female[b]		0.0709*			0.0709*
	Fraction farming as primary income[b]		−0.0759*			−0.0410
	Fraction farming as secondary income[b]		−0.192***			−0.127**
	Difference in gender[c]		0.0667*			0.0770**
Beliefs	Trust in community coordination			−0.0943**		−0.0678
	Trust that community is honest			−0.117**		−0.0840*
	Trust that community won't take advantage			0.00493		0.0459
	Belief that conservation outcome harms wellbeing			−0.0485		−0.0510
	Belief that conservation outcome helps wellbeing			−0.0640*		−0.101***
	Belief that conservation is important for future generations			−0.0230		0.0102
	Importance of social disapproval on behavior			−0.0263		0.0166
	Importance of penalty on behavior			0.0740*		0.0356
	Trust in Government[b]			0.00668		−0.00778
	Trust in National Park Authority[b]			0.00479		−0.0462
Contexts	Played game to win				0.0862	0.0620
	Played game to help the group				0.00438	−0.0473
	Played game like I live my real life				−0.00528	−0.0770
	Played game just to have fun				0.0129	−0.0113
	Choices depended on those of others				0.120***	0.0520
	Considered impacts of choices on later generation				−0.0291	0.0258
	Considered impacts of choices on other players				−0.0654	−0.0301
	Relationship strength with other players				−0.130***	−0.0726*
	Constant	0.289***	0.290***	0.289***	0.290***	0.290***
	Observations	6511	6511	6511	6511	6511
	R-squared	0.068	0.134	0.101	0.111	0.179
	AIC	18020	17557	17806	17733	17245

[a]Dummy variable; [b]Z-score of group mean or fraction; [c]Z-score of group variance.
Robust standard errors in parentheses
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

crop). Such a joint incentive could potentially drive producers to innovate or otherwise experiment and take on risks of existing technologies—such as the planting of chilies, installation of bee fences, and switches from maize to less delectable, valuable crops like sunflowers that may provide scalable ecosystems services solutions to herding elephants[33]. Similarly, incentives calibrated both to an action and to coordination (e.g., spatial incentives like agglomeration payments, in which participants earn bonuses through their own actions as well as those of neighboring producers) encourage communities to seek out solutions that are collectively as well as privately beneficial[34,35].

Alternatively, improving access to insurance programs calibrated to the risks posed by the pro-environment outcome (e.g., crop raids by elephants or livestock raids by lions or tigers) may provide the security and income smoothing necessary for producers to experiment with longer-term solutions, or, at the very least, to continue producing. As an example, the recent growth of loss compensation programs from large animals in India builds evidence for the value of innovation in early warning systems[36]. In cases where such supports seem unlikely to lead to self-sustaining outcomes, and may instead require unsustainable funding streams, a further alternative might be to encourage growth in alternative livelihoods that provide comparable well-being unrelated to the state of the conservation outcome. For example, the innovative Bolsa Floresta Program bundled a more conventional PES payment for the forest outcome of interest with additional payments tied to (i) earning income from alternative sources, (ii) contributing to local community associations, and (iii) sending children to school—all encouragements that look past the forest at the alternative livelihoods that are better aligned with it and its sustained presence[37]. Bundling incentives and support programs presents a more holistic approach to seeking solutions, but it also requires system perspective and assessment to anticipate and minimize negative spillover effects. Further, achieving joint production-environment outcomes will also likely require support beyond financial incentives, for example, technical support on shifting from agrochemicals-dependent management to ecologically based and compatible management and support on developing institutional services at the community level.

We do not intend here to be prescriptive in suggesting matching instruments to problem contexts; we only wish to highlight the challenges of aligning encouragements simultaneously with environment and livelihood goals, as other authors

Table 3 Conservation, production, and joint conservation-production outcomes by observables, beliefs, and contexts for 5-game subset.

	Variables	Conservation-production	Conservation	Production
	Payment[a]	−0.527***	0.198***	−0.581***
Observables	Age[b]	0.0579	−0.0212	0.0559
	Education[b]	0.138***	−0.0941**	0.142***
	Fraction female[b]	0.0709*	−0.0716*	0.0706*
	Fraction farming as primary income[b]	−0.0410	0.00290	−0.0220
	Fraction farming as secondary income[b]	−0.127**	0.0394	−0.0836
	Difference in gender[c]	0.0770**	−0.0535	0.0681*
Beliefs	Trust in community coordination	−0.0678	0.0623*	−0.0554
	Trust that community is honest	−0.0840*	0.0738	−0.0860*
	Trust that community won't take advantage	0.0459	−0.0501	0.0702
	Belief that conservation outcome harms wellbeing	−0.0510	−0.0131	−0.0273
	Belief that conservation outcome helps wellbeing	−0.101***	0.0549	−0.106***
	Belief that conservation is important for future generations	0.0102	0.0913**	−0.0407
	Importance of social disapproval on behavior	0.0166	−0.0800*	0.0418
	Importance of penalty on behavior	0.0356	0.0336	0.0131
	Trust in Government[b]	−0.00778	−0.0728	0.0218
	Trust in National Park Authority[b]	−0.0462	0.0193	−0.0248
Contexts	Played game to win	0.0620	−0.135**	0.0782
	Played game to help the group	−0.0473	−0.0172	−0.0531
	Played game like I live my real life	−0.0770	−0.0207	−0.0532
	Played game just to have fun	−0.0113	−0.0441	−0.00138
	Choices depended on those of others	0.0520	−0.102***	0.0636*
	Considered impacts of choices on later generation	0.0258	0.0830	−0.0335
	Considered impacts of choices on other players	−0.0301	0.0117	−0.0121
	Relationship strength with other players	−0.0726*	0.136***	−0.0995**
	Constant	0.290***	−0.109**	0.320***
	Observations	6,511	6,511	6,511
	R-squared	0.179	0.126	0.193
	AIC	17245	17652	17133

[a]Dummy variable; [b]Z-score of group mean or fraction; [c]Z-score of group variance.
Robust standard errors in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Breakout by country included as Tables S2–4, Supplementary Information.

have previously suggested (such as van Eeden et al., in the carnivore-livestock context)[7]. These challenges have perhaps best been taken up by the broad movement of climate smart agriculture (CSA), which encourages practices that mitigate climate change impacts while building resilient, food secure and productive communities[38] (i.e., harmonizing people and environment outcomes), but even in this context, researchers identify problems in aligning financing tools (for some pro-environment practice) with longer-term income and wealth outcomes[39].

Utility of games. Across our datasets we find observable, demographic aspects of player identities to contribute similarly to the less observable belief aspects of their identities, as well as to game and relationship context factors in explaining variance in our environment, production, and joint environment-production outcomes. This insight into the roles of people, their beliefs, and their contexts in shaping conservation decisions deserves more careful attention—into both what it can't and can show. In particular, the significant association between increased representation by women and gender diversity in the group and higher production and joint production-environment outcomes is noteworthy. Although research on gender composition and resources governance generally remains fragmented with mixed empirical results[40–44], this finding is consistent with prior evidence that creating mixed gender groups may lead to better natural resource management[45–47].

On the one hand, Levitt and List[21] highlight the important limitations of games work, including (i) that context is important and imperfectly controlled for in games, (ii) that the stylized world of a game artificially bounds the options available to real people, and (iii) on the issue of incentive compatibility, that the stakes in a game will never match those in reality. Focused closer to the human-environment contexts of this study, Cárdenas and Ostrom[48] separately map out the layers of behavior people bring to the game: their own identities (demography, beliefs, etc.), their group relations, and their response to the rules presented in the game. These two studies carefully bound what we should expect to learn about resource use and conservation governance from game experiments, in contexts where we likely lack the opportunity to validate behaviors through true field experiments or interventions. Qualitative inferences are likely best, even of quantitative analyses, and the linkage from who people are through to their resource decision-making will be masked by layers of play, exploration, and possibly rejection of the frame a game has provided.

However, how people interact with each other and their environment in social-ecological systems has far reaching and potentially irreversible consequences for biodiversity, the health of ecosystems, and ultimately human well-being[49,50]. As such, understanding these interactions and predicting how the collective behavior of people shapes and is shaped by their social-ecological context is vital for long-term sustainable development[51]. In this vein, finding ways to improve game experiments in resource use domains to better engage thinking along longer temporal and broader spatial scales, as well as relationships and non-economic behavior, becomes a critical behavioral research frontier. Collective behavior will be influenced by constraints between environment and agricultural production goals experienced by individual decision-makers, so it is important to investigate these constraints and how they might ultimately be reconciled to encourage win-win outcomes for food security and biodiversity[52]. The results of the seven interrelated experimental games considered here do not support the conclusion that payments (alone) are necessarily effective at promoting joint production-conservation outcomes, suggesting that new and innovative solutions might be necessary to meet urgent sustainability goals.

Methods

We implemented 3 different dynamic spatial games in NetLogo, capturing distinct public goods problems: (1) sharing of insect-based pest control services in agriculture; (2) support of non-lethal control of pest animals in agricultural settings (geese, elephants, and lions); and (3) support for fallowing and vegetation in shared slash-and-burn systems (Table 4). The game system was implemented using Windows OS tablet computers and a mobile router, making it robust to meeting conditions anywhere in the world. We first describe the different games and the problems they were developed to analyze, before outlining our approach to synthesizing games outputs.

NonCropShare. We first developed NonCropShare in 2013 as a coordination game played by passing around a single tablet among players[53], before developing the NetLogo-based approach and recreating NonCropShare with this simultaneous-play platform[24]. NonCropShare stylizes the challenge of sharing insect-based ecosystem services as a symmetric coordination game. Players control a 3×3 quadrant (9 squares) of a 6×6 (36 square) farm landscape, making one of four choices for each square: i) plant without spraying, ii) plant and spray pesticide lightly (with a yield benefit), iii) plant and spray pesticide heavily (with a greater yield benefit), or iv) set aside as non-crop habitat. Non-crop habitat has no productive yield, but offers a spatial ecosystem service to surrounding planted areas—pest management via natural enemy services (such as parasitic wasps)—that is robust to light spraying. However, heavy spraying will cancel any such benefit in all surrounding squares (i.e., pesticide drift). Thus, player farmers face the dilemma in a choice to move from heavy spraying to the use of non-crop habitat, that the continued use (or return to use) of heavy spraying by neighbors can nullify any benefits of the non-crop habitat strategy. As calibrated in the datasets presented here ($Y = 5$, $X = 2$, $Z = 7$, $A = 1$, $B = 2$, $C = 2$, $R = 2$, $S = 1$), NonCropShare has two important equilibria—a Nash equilibrium (where players cannot be made worse off by the choices of other players) of heavy spraying in all squares (in which all players earn 90 points; Fig. 3A), and a weak, cooperative equilibrium (where players can be made worse off should other players change strategies) in which all players spray lightly across most of their farms while sharing the ecosystem services benefits of a small amount of non-crop habitat planted in the center of the farm landscape (again, in which farmers earn 90 points; Fig. 3B). The choice of any one player to defect from the cooperative strategy reduces benefits for all other players (to 72 points for both bordering players, and 84 points for the player diagonally opposite; Fig. 3C). Thus, a central question for this NonCropShare application is, given any unobserved preferences players may have for spraying, ecosystem services or cooperation, what is the premium (i.e., subsidy) that must be offered for the use of non-crop habitat to make the riskier cooperative equilibrium competitive with the heavy spraying Nash equilibrium.

NonCropShare Datasets. Experiments with NonCropShare included in the current analysis examined responses to different levels of subsidy for non-crop habitat, to identify the level of subsidy that maximally encouraged pro-environmental production (i.e., minimal pesticide use) without the subsidy crowding out farming practice. Sampling in this dataset followed a framework established for a paired field experiment designed to capture variation in landscape complexity along a transect leading away from a city (Siem Reap city in Cambodia, and Ha Noi city in Vietnam) of approximately 4 hours in driving time. We first visually classified villages along the transect into low, medium, and high landscape complexity, and then developed a sample of 32 households from each of 16 villages from along the transect (5–6 villages from each of low, medium, and high categories)[24].

Free communication was allowed across all treatment conditions in these experiments, which included a 2×2, within-subject design varying i) subsidy and ii) information. The order in which participants played game treatments 1–4 was randomized to control for possible learning effects. Game treatments 1 and 2 included no subsidy, while game treatments 3 and 4 included a randomly assigned subsidy value of 1 to 10 points introduced at the beginning of the game to players; game treatments 1 and 3 did not reveal the choices of other players until all players had confirmed (i.e., tapped a button labeled Confirm) their choices to end the round, while game treatments 2 and 4 allowed all players to see all decisions as they were being made. Each game was 8–10 rounds in length, with the actual number of rounds randomized and not revealed to participants until the end of the game. Participants received payments equivalent to one day's labor wage at local rates, plus a performance bonus based on their scores in the game. The full framing and training protocol for these experiments is included as Supplementary Methods Protocol 1.

GooseBump. We developed GooseBump using the NetLogo framework and the basic coordination game architecture of NonCropShare to explore a different question of human-wildlife conflict. In GooseBump, crop-damaging animals move around the 6×6 farm landscape, and farmers choose from a different set of four actions for each square of their 3×3 grid: i) plant crops without taking any action, ii) plant crops and take non-lethal crop protection actions (i.e., scaring animals away), iii) plant crops and take lethal crop protection actions (i.e., kill animals in that square), or iv) set aside dedicated land as habitat for the crop-damaging animals. Animals are attracted to habitat and adjacent squares, so these are likely to lead to crop damage in their local area. Because animals move in GooseBump, and a different number of animals may survive in the landscape in each round, equilibria require numerical estimation (please see[54]) and are not as intuitive as those shown above for NonCropShare. However, features of the dilemma faced by farmers are easily described: farmers choose across i) taking lethal control and remove animals from the landscape (addressing problem for all farmers), ii) using non-lethal scare tactics that redistribute animals in landscape (possibly increasing problem for other farmers), or iii) taking some level of crop-damage and crop abstention burden across themselves and their peer farmers, setting aside habitat areas that provide shared benefit across animals and farmers. Experiments with GooseBump included in the current analysis include geese[25], elephants[54], and lions (Sargent et al., In review) as damaging animals, and apply different levels of subsidy for non-lethal control and animal habitat, again to observe the level that maximally encourages a productive landscape without crowding out farming.

Goosebump datasets. Goosebump datasets collected in Gabon, Orkney, and Tanzania drew on snowball and opportunistic sampling approaches to reach households in sparsely populated areas and areas with small communities with varying degrees of social conflicts between conservation and development objectives. Games in Gabon[54] were conducted with members from 140 households across 8 communities in and close to protected areas, as well as 120 households from across 10 communities in areas with active logging; the household member with lead responsibility for farming was invited to participate, who was most commonly female. In Orkney[25] (an area of small islands in Northern Scotland), all farmers willing to participate were invited—through local goose management groups, social media and radio—resulting in a sample of 84 farmers from different households from across 17 Orkney locations. In Tanzania[55], participants were recruited at market days and community events, for a total of 172 household representatives from 8 villages, mainly men from Maasai and Barabaig ethnic groups who had responsibility for livestock management.

Free communication was allowed across all treatment conditions in these experiments, which included a 4-treatment, within-subject design varying subsidies for different control strategies. The order in which participants played game treatments 1–4 was randomized to control for possible learning effects. Game treatment 1 offered no support for any strategy. Game treatment 2 offered support for non-lethal control approaches. Game treatment 3 offered a flat subsidy for each cell committed to animal habitat, while Game treatment 4 offered a variation on this basic subsidy. In the Orkney and Gabon experiments, this was an agglomeration bonus, offering additional bonus for habitat connectivity; in the Tanzania case, the variation in Game treatment 4 was to share a subsidy for the total number of habitat cells, equally across all players. Each game was 6–8 rounds in length, with the actual number of rounds randomized and not revealed to participants until the end of the game. Participants in the Gabon and Tanzania contexts received gifts equivalent to one day's labor wage at local rates, but did not earn a performance bonus based on their scores in the game; participants in the Orkney case were not compensated for their participation. In all cases, these decisions—which deviate from the more common practice of performance based earnings 'incentive compatibility'[21,22]; applied in experimental games broadly and in the other experiments synthesized here—were made based on local and community consultation, and the determination that such payments would be inappropriate. While less common, such decisions also have precedent and place in the experimental games literature with some experimental evidence showing that such payments may have little impact on performance within the game[56,57]. The full framing and training protocol for these experiments is included as Supplementary Methods Protocol 2.

SharedSpace. We developed SharedSpace using the same basic coordination game framework in NetLogo, shifting focus away from animals to examine human-human coordination challenges in conservation. The SharedSpace 6×6 landscape provides a simpler set of two choices for farmers to make in each square—i) plant crops, or ii) conserve forest or fallow land. Land productivity is a function of time

Table 4 Game structures.

Game	Dilemma	Choices	Cost	Yield	Other Effect	Solutions
NonCropShare[24,53]	Insect-based pest control is less harmful to health, but cannot succeed while neighbors apply pesticide	Grow crops	0	Y	-	Productive solutions include i) all farmers heavy spraying and ii) all farmers light spraying with shared non-crop habitat services
		Grow crops with light spraying	A	$Y + X$	-	
		Grow crops with heavy spraying	B	$Y + Z$	Cancels all noncrop habitat bonuses in radius S, across property boundaries	
		Leave land as noncrop habitat	0	0	Bonus of C to all crop cells in radius R, across property boundaries	
GooseBump[25,54,55]	Farmers must trade off among letting wildlife damage crops, scaring wildlife (into other farms), or exercising lethal control	Grow crops/ raise livestock	0	Y—D	Damage D depends on animal count	Productive solutions include i) set aside of secluded land as wildlife habitat and ii) lethal control of crop/livestock-damaging wildlife
		Grow crops/ raise livestock and scare wildlife	A	Y—D	Animals move to other cells in landscape	
		Grow crops/ raise livestock and shoot wildlife	B	Y—D	Animals are removed from landscape	
		Leave land as wildlife habitat	0	0	Animals may be in cropland near habitat	
SharedSpace[26]	Farmers must manage crop and conserve forest/fallow lands to preserve soil productivity, in a shared landscape with non-excludable rights to farm	Grow crops	-	Y_{high} or Y_{low}	Yield drops to low value after being farmed for X rounds, returning to high value after fallowing for Z rounds	Productive solutions optimize the rate at which forests (and their ecosystem services) are preserved and/or cropped land is allowed to recover, with group coordination required when access to land is shared
		Conserve forest/ fallow	-	0	Add value of C to neighboring cropped cells	

All Cost, Yield, and Other Effect values are free parameters set by experimenter.

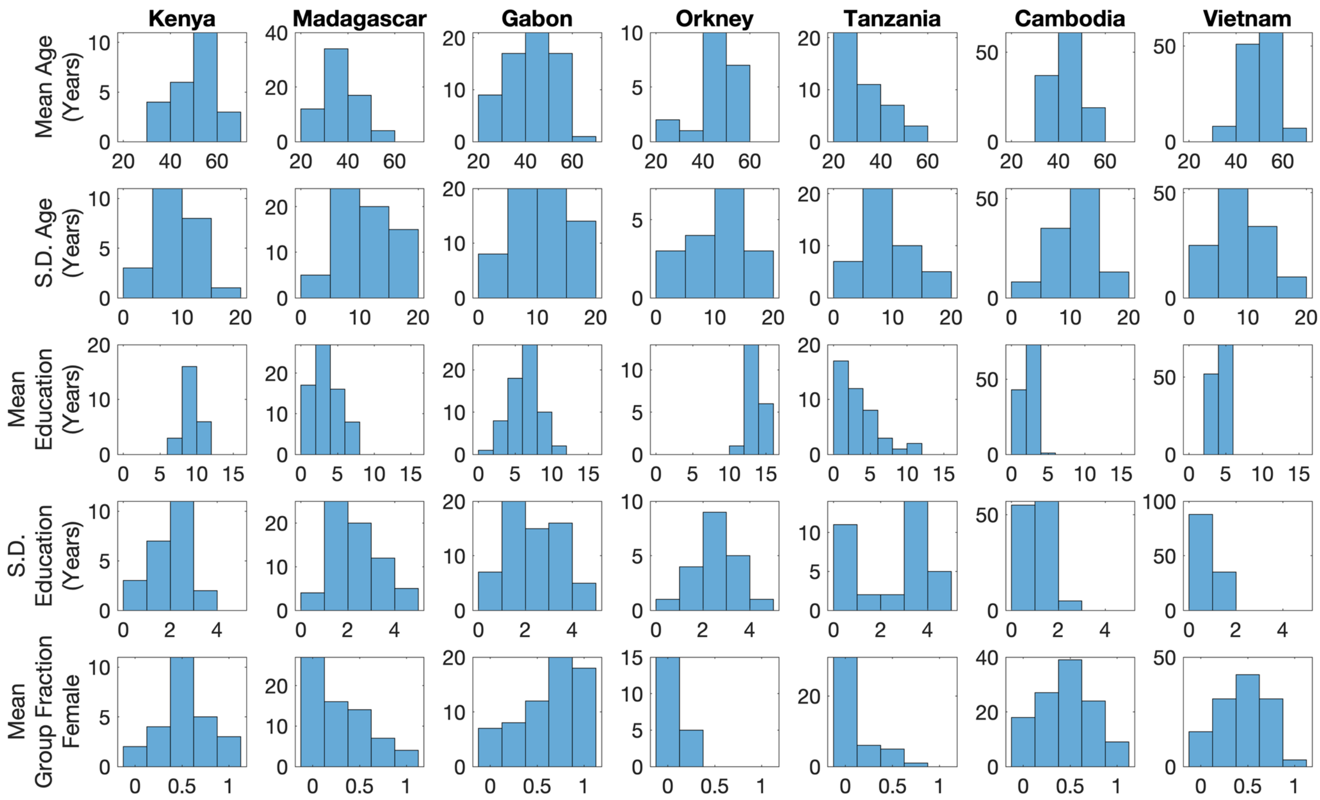

Fig. 3 Distribution of group characteristics across datasets. Row variables are the mean age in game group, standard deviation of age in game group, mean years of education in game group, standard deviation of age in game group, and the fraction of game players that were female in the group; columns separate datasets by countries as Kenya, Madagascar, Gabon, Orkney, Tanzania, Cambodia, and Vietnam. Additional distributions for other explanatory variables included as Figure S1 in Supplementary Information.

and activity—squares will have declining productivity when they are farmed repeatedly in succession, with that productivity improving if forests are conserved nearby or lands are left to fallow. Additionally, the rate at which productivity returns to a square is higher when surrounding squares are also fallow—that is, allowed to have vegetative cover. In this way, SharedSpace stylizes the ecosystem service of soil health enabled in well-managed swidden agricultural systems. The unique feature of SharedSpace is that players are not restricted necessarily to their own, private 3×3 quadrant; instead, which players are entitled to make decisions for a given square may be specified as a game parameter—private space usable only by one player is possible, as is open space that may be used by any player (on a first-come, first-serve basis in each turn). Similarly to GooseBump, the differences in soil productivity over time as well as in the amount of land cultivated by a player under shared property rights complicate the calculation of game theoretic equilibria for players (please see[26]), though the features of the dilemma may still be clearly delineated. Farmers must decide whether they will be better off farming on a particular square or allowing it to stand as vegetation/fallow, knowing that (i) other farmers may choose to use the square if they do not, and (ii) other farmers may choose to use surrounding squares for planting, reducing any possible spatial spillover effects. Experiments with SharedSpace included with the current analysis[26] include those that offer subsidy for fallowing squares, to examine how the level of subsidy shapes the degree of standing forest, agricultural productivity, fallowing rates and coordination among farmers of the same space.

SharedSpace datasets. The SharedSpace datasets in this analysis[26] were collected from four villages near the Mangabe protected area in eastern Madagascar, and two villages adjacent to Mount Kenya National park and forest reserve in Kenya—areas dependent on swidden agriculture yet experienced with conservation restrictions. Households were selected randomly from village lists derived in key-informant interviews, leading to a total of 272 participants in Madagascar and 100 participants in Kenya, with one representative (the main agricultural decision maker) from each household.

Free communication was allowed across all treatment conditions in these experiments, which included a 2×2, within-subject design varying (i) subsidy and (ii) property rights. The order in which participants played game treatments 1–4 was randomized to control for possible learning effects. Game treatments 1 and 2 included no subsidy, while game treatments 3 and 4 included a randomly assigned subsidy value of 4, 8, or 12 points; game treatments 1 and 3 assigned specific parts of the gameboard to specific players, while game treatments 2 and 4 allowed all players to make decisions in any part of the board. Each game was 6–8 rounds in length, with the actual number of rounds randomized and not revealed to participants until the end of the game. Participants received payments equivalent to one day's labor wage at local rates, plus a performance bonus based on their scores in the game. The full framing and training protocol for these experiments is included as Supplementary Methods Protocol 3.

Developing common games metrics. Games experiments were carried out by different researchers, as components of different projects, but all included a household survey capturing basic demographic information, and in some cases, additional harmonizable (i.e., easily made comparable) variables for participant beliefs and attitudes. Comparisons across game treatments within each experimental context are made in the publications highlighted for each game in Table 4. In the current study, our objective is to identify shared variation across these studies in key outcomes of production, environment, and environment-production; as well as to assemble as rich a set as possible of harmonized explanatory variables from across these datasets to explain variation in outcomes in ways that may not have emerged from the individual studies. Direction as to what variables are meaningfully explanatory comes from Cardenás and Ostrom (2004), who highlight individual beliefs, group context, and the game context (rules, etc.) as distinct layers of behavioral drivers brought into gameplay.

For all datasets, the outcome variable environment-production was defined as the product of environment and production outcomes. Production outcomes for all datasets were defined as the agricultural yields for the round of game play summed across all players, net of any subsidies offered. While the games described above presented different dilemmas, which players may take different approaches to solve (Table 4), all included a payment treatment with some level of bonus awarded to players for undertaking pro-conservation practices (e.g., setting aside land as habitat, or fallowing).

Individual games differed in what was estimated for the environment outcome variable. For Orkney, Gabon and Tanzania datasets (Goosebump), the environment outcome was equal to the count of animals still persisting in the game landscape at the end of a round of play. For the Madagascar and Kenya datasets (SharedSpace), the environment outcome was the sum of fallows for all 4 players during the round. For the Vietnam and Cambodia datasets (NonCropShare), the environment outcome was the number of landscape cells not heavily sprayed during the round. Defined thusly, the three outcome variables (environment, production, and environment-production) shared qualitative

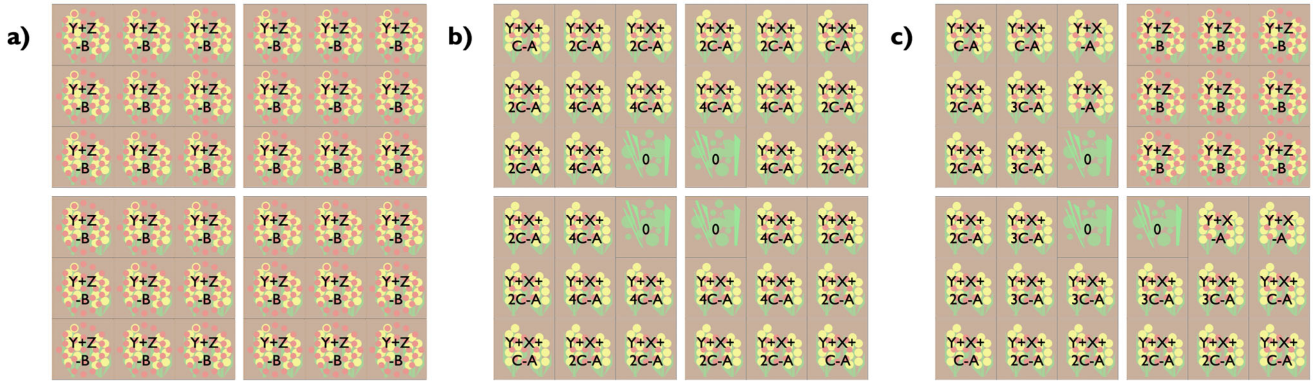

Fig. 4 Examples of spatial equilibria in NetLogo games from NonCropShare. a Heavy spray Nash equilibrium; **b** Light spray and non-crop habitat cooperative equilibrium; and **c** Disrupted cooperative equilibrium. Adapted from Bell and Zhang, 2016.

similarities across datasets, but different ranges and distributions. To best enable intercomparison across datasets, all three outcome variables were standardized to z-scores at the dataset level, and then pooled (with the environment-production outcome constructed from the environment and production outcomes first and then standardized, rather than being constructed from the already-standardized environment and production outcomes). This approach discards differences in the average and variance of success across game datasets, focusing our analyses on who does relatively better or worse in the games, and why. While sampling designs differ across datasets as noted above, they all reflect best practices at reaching agricultural decision-makers in rural areas. Similarly, while all games differ in their structure and rules, they are all best efforts at representing dominant resource dilemmas faced by participants. In the analyses that follow, we thus consider this pooled dataset as informing us about factors shaping decisions for rural agricultural decision-makers in environment-production dilemmas, drawing on our analysis for qualitative inferences about which factors explain variation in the datasets and refraining from making point or parameter estimates.

In addition to the three outcome variables, all game experiments collected data on an extensive list of semantically common questions which are used to construct explanatory variables, including demographic information (age, years of education, gender, if primary occupation is farming; available for all 7 datasets) (Fig. 4); general beliefs (trust in community, trust in government, trust in environmental organisations or national parks authorities, effect of conservation on next generation, effect of conservation on others, dependability of others, government responsibility, risk of social or criminal consequences; for a subset of 5 datasets); and context variables including in-game beliefs (effect of strategy in game on next generation, effect of strategy in game on others, dependability of others; for a subset of 5 datasets), the relationship scores of all players and subsidy. Variables across different datasets were harmonized, with ordinal or binary encodings recoded to common values across all datasets, and all scale questions (i.e., Likert scales) were rescaled to span values from 0 to 1. Means and variations for all 4 players were calculated for every record, and the datasets were normalized column-wise to z scores (i.e., at the dataset level, in the same manner as the outcome variables). These transformed datasets for outcome and explanatory variables were then concatenated. In all statistical analyses, the unit of analysis is the game round; i.e., every record contains all the moves from all 4 players, the treatment applied to the round and their demographic and survey data. While demographics are diverse across datasets (Fig. 4), they were representative within the relevant contexts. All regression analyses cluster standard errors at the level of the game session—all rounds of each of the games were played by the same set of participants.

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All datasets are archived at https://doi.org/10.5281/zenodo.5516710, and viewable as Jupyter notebooks via https://mybinder.org/v2/zenodo/10.5281/zenodo.5516710/.

Code availability

All analysis scripts are archived at https://doi.org/10.5281/zenodo.5516710, and viewable as Jupyter notebooks via https://mybinder.org/v2/zenodo/10.5281/zenodo.5516710/.

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Author contributions

A.R.B. designed NonCropShare to use in work jointly conducted with W.Z. A.R.L. reached out to A.R.B. about NonCropShare and ended up running her own NonCropShare campaign as part of her dissertation work. Cool! O.S.R. and A.R.L. knew each other, and O.S.R. began working with A.R.B. to adapt NonCropShare into two new games, GooseBump and SharedSpace; O.S.R. then designed and oversaw data collection campaigns for these games across four countries during her post-doc. Wow! A.B.D. undertook numerical work to calibrate GooseBump and SharedSpace experiments. Phenomenal! Among the staff who assisted O.S.R. in data collection, A.K. was a key contributor, acting as field coordinator in the Kenya SharedSpace data collection. Super! R.S. knew O.S.R and worked with A.R.B. and O.S.R. to adapt GooseBump to the conditions of her dissertation, running her own GooseBump campaign. Awesome! A.R.B. joined this group at the synthesis stage, undertaking all of the data harmonization work, as well as publishing data and scripts as a Jupyter notebook. Wonderful! A.R.B. led the writing of this synthesis manuscript, with all authors—O.S.R., A.B., A.B.D., W.Z., R.S., A.R.L., A.K.—contributing significantly to the final written product. High fives all around.

Ethics approvals

The current manuscript synthesizes publicly available data published as part of earlier primary studies. All NonCropShare datasets were collected in projects approved by the IRB of the International Food Policy Research Institute (IFPRI) (FWA #00005121). The GooseBump Tanzania dataset was approved by the Newcastle University Faculty of Science, Agriculture and Engineering Ethics Committee (19-SAR-010) and the Tanzania Commission for Science and Technology (2019-95-NA-2018-348). All other datasets were approved by the research ethics committee of the University of Stirling (GUEP286). Research permission in Gabon was granted by the Government of Gabon (AR0010/18/MESRS/CENAREST/CG/CST/CSAR) and the National Agency for National Parks (AE18008/PR/ANN/SE/CS/AFKP). Informed consent was obtained from all participants in all studies.

Competing interests

The authors declare no competing interests.

Additional information

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