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Using adaptation insurance to incentivize climate-change mitigation

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Running header: Incentivizing cooperation

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Abstract

Effective responses to climate change may demand a radical shift in human lifestyles away from self-interest for material gain, towards self-restraint for the public good. The challenge then lies in sustaining cooperative mitigation against the temptation to free-ride on others' contributions, which can undermine public endeavours. When all possible future scenarios entail costs, however, the rationale for contributing to a public good changes from altruistic sacrifice of personal profit to necessary investment in minimizing personal debt. Here we demonstrate analytically how an economic framework of costly adaptation to climate change can sustain cooperative mitigation to reduce greenhouse gas emissions. We develop game-theoretic scenarios from existing examples of insurance for adaptation to natural hazards exacerbated by climate-change that bring the debt burden from future climate events into the present. We model the as-yet untried potential for leveraging public contributions to mitigation from personal costs of adaptation insurance, by discounting the insurance premium in proportion to progress towards a mitigation target. We show that collective mitigation targets are feasible for individuals as well as nations, provided that the premium for adaptation insurance in the event of no mitigation is at least four times larger than the mitigation target per player. This prediction is robust to players having unequal vulnerabilities, wealth, and abilities to pay. We enumerate the effects of these inequalities on payoffs to players under various sub-optimal conditions. We conclude that progress in mitigation is hindered by its current association with a social dilemma, which disappears upon confronting the bleak consequences of inaction.

Key words: collective risk; game theory; natural disasters; public goods; risk reduction.

1. Introduction

Climate-change mitigation for emissions reduction is widely agreed to require cooperation at all levels of society from individuals to nation states (Stern, 2007; IPCC, 2014b). Cooperative enterprises are always susceptible to being undermined by self-interest, however, unless the priorities of the group match those of its members. The threat of dangerous climate change pits the priority to reduce global greenhouse gas emissions against the priorities of individual consumers of fossil fuels, of businesses that profit from fossil-fuel consumption, and of policy-makers reluctant to pass unpopular environmental legislation. The misalignment of public and private needs presents a social dilemma (Capstick, 2013), which threatens disaster as a result of a global-scale 'tragedy of the commons' (Hardin, 1968; Milinski et al., 2006). Coordinated management of commons is facilitated by polycentric governance systems and the application of social norms (Kinzig et al., 2013), but presents particular challenges for scaling up to the global commons (Ostrom, 1999). In this paper we present a novel mechanism for removing the social dilemma by aligning private with public needs, which we model with game theory.

Game theory has become an influential tool for conceptualizing the difficulty of motivating cooperative action on climate change (Tavoni, 2013). Previous applications have found that successful achievement of a mitigation target requires coordinated responses. These may take the form of altruism (Milinski et al., 2006), or locally interacting groups (Santos and Pacheco, 2011; Shirado et al., 2013), or bottom-up locally operating sanctions (Vasconcelos et al., 2013), or low costs relative to benefits and coordinated pledges where there is uncertainty on impacts (Barrett and Dannenberg, 2012, 2014). Here we demonstrate for the first time that coordination is not a necessary prerequisite for mitigation against dangerous climate change by self-interested individuals, organizations, or nations. We apply game-theoretic principles to a public-goods model of homogeneous interactions amongst cooperators and defectors. We develop a novel mechanism for incentivizing cooperative mitigation that sets its cost against the counterfactual of a large personal cost in adaptation to climate change. The need for adaptation can incentivize mitigation efforts because the costs of adaptation depend on mitigation level (Ingham et al., 2013). We use insurance as a mechanism to bring into the present a future debt burden of natural hazards caused by climate change, in order to incentivize mitigation to reduce climate-change drivers. In the context of public-goods games, an option for players to purchase insurance against the costs of defection can undermine cooperation (Zhang et al., 2013). Our climate-change scenario uses non-optional insurance, however, with the premium itself functioning as the cost of defection, against which players evaluate the utility of cooperation.

Our rationale for homogeneous cooperation builds on national- and global-scale templates of insurance against natural hazards such as New Zealand’s mandatory Earthquake Commission insurance (Glavovic et al., 2010), the French CatNat system for insurance against flood damage (Poussin et al., 2013), and the Caribbean Catastrophe Risk Insurance Facility against a range of climatic uncertainties (Grove, 2012). We introduce a simple model for testing the strategic impact of mandatory adaptation insurance aimed at removing cooperation from the realm of a social dilemma. Such an approach has the potential to catalyse collective action on mitigation without the need of coordinating mechanisms. The Global Agenda Council on Climate Change (2014) recommends developing private-sector insurance as a vehicle to finance climate resilience. It cites an increasingly popular banking model for buildings insurance that leverages capital improvements to energy efficiency from securitized discounts on premiums. Our model applies the same principle to insurance for adaptation to natural hazards exacerbated by climate-change. In this case collective mitigation is leveraged from discounts that are securitized by reducing the premium in proportion to achieved mitigation. This application has not previously been explored in theory or practice, yet its policy implication is that willingness to fund public mitigation for emissions reductions can be traded against private costs of adaptation to climate-change impacts.

We define the conditions by which a mandatory adaptation insurance will incentivize purely self-interested actors to achieve the proposed mitigation target from voluntary contributions, without additional coordinating mechanisms. We start with the simplest model of independent players with equal ability to pay an insurance premium that is the same for all players. Real-world premiums are likely to vary, however, with geographic variation in risk, and abilities to pay the voluntary contribution will vary with wealth inequality (Tavoni et al., 2011; Burton-Chellew et al., 2013). We therefore consider options for accommodating potentially large regional differences in players vulnerabilities to climate change. We further extend the model to include players with unequal abilities to pay for mitigation or adaptation. We apply the model to players at the scale of households in a nation, and to players at the scale of nations in an international consortium. We discuss ways to adapt existing scenarios for multinational aggregation that would lead to the effective management of a global commons. We consider ways to minimize the political difficulty of approving up-front costs for future benefits.

2. Framework

In order to demonstrate the concept of aligning public need with private interest, we illustrate how insurance against natural hazards associated with climate change could leverage the UK government's recently proposed annual target of £1.3bn for funding green-energy solutions to mitigation (Energy Companies Obligation, 2012). This target was introduced in January 2013, and repealed within a year in response to public opposition to it, largely centred around concerns that it would be raised from a mandatory annual supplement of ~£50 to all household energy bills (DECC, 2013).

Consider a scenario in which all households must buy insurance to cover them for adaptation to natural catastrophes caused by climate change. They can choose whether to contribute to a public fund for climate-change mitigation that secures a discount on the insurance premium, or to defect from contribution and still enjoy the discount won by others' contributions. In our scenario, each household makes a personal choice either to pay the contribution or to defect from cooperation, according only to whichever strategy minimizes personal costs. Figure 1 describes the conceptual framework. With the insurance premium discounted for all in direct proportion to the size of collective pot, the decision variable on mitigation changes from a public target in raising funds to a private target in obtaining discounts. The discount cancels the premium altogether in the event of target success, on the premise that successful mitigation cancels the need for adaptation.

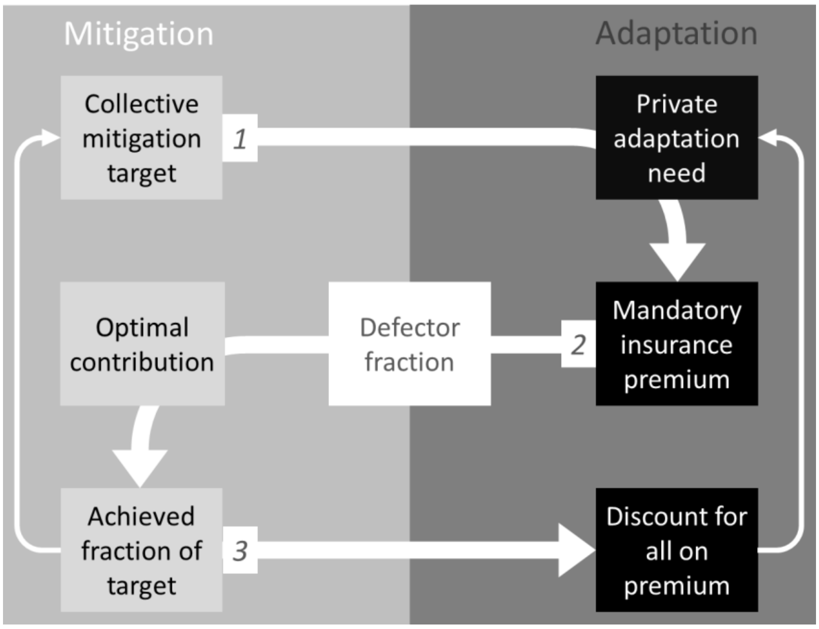

Fig. 1. Mechanism for linking adaptation insurance against climate-related natural hazards to publically-funded mitigation for reducing climate-change drivers. (*1*) A collective mitigation target defines private adaptation need in the absence of mitigation, which determines the insurance premium. (*2*) The premium sets an optimal contribution for the mitigation target and associated defector fraction, which together determine the size of collective pot as a fraction of target. (*3*) This fraction determines the discount for all on the insurance premium, and informs updating of the mitigation target and adaptation need.

The game theoretic framework costs the hazard and likelihood of climate-related natural catastrophes through the mechanism of insurance, rather than modelling catastrophes directly. We assume a state-enforced insurance, with basic premium before any discounts (henceforth 'premium') determined by commercially available catastrophe models of hazard and likelihood in the absence of pre-emptive action (Toumi and Restell, 2014). Whereas a mandatory contribution to mitigation would function to safeguard public interests, mandatory insurance functions to prevent personal ruin. Implementing its legislation is justified on the same principles as for a compulsory health or national insurance scheme which builds entitlement to state benefits such as medical procedures or a pension; in this case it builds entitlement to an environment with an acceptable level of vulnerability to climate driven hazards. In contrast to the conventional aim of improving the opportunity for cooperation, insurance here works by devaluing mutual defection. It differs in this respect from mechanisms for coordinating incentives, such as policing and coercion that control unilateral behaviours.

The framework depends on the insurance industry having adequate tools to build risk and uncertainty into the costs of adaptation, and mitigation effectively reducing this cost by reducing long-term risk. Catastrophe modelling technology is now used extensively by insurers, reinsurers, and governments to calculate fair pricing, and it is considered essential to understanding the natural world (Toumi and Restell, 2014). Here we focus on mitigation to decrease climate-change drivers, such as conversion to renewable energy for emissions reduction, although in principle the framework can apply also to adaptation for building resilience such as flood protection. In the Discussion we consider existing tools for costing adaptation. Prospects of tipping points to bifurcations in the climate-Earth system, leading to raised frequencies and magnitudes of natural catastrophes (Lenton et al., 2008), may render insurance prohibitively expensive without mitigation or other risk-reduction measures (Mills, 2005; Toumi and Restell, 2014). We accommodate this possibility by allowing for fairly-priced premiums up to a putative infinite cost, prior to discounting by the value of any investment in cooperative mitigation.

3. Model

3.1. General model

We wish to identify an optimal voluntary contribution by households for maximizing a collective mitigation target. As a two-strategy public-goods game, the alternative payoffs to a player for cooperating or defecting depend on what others do (Doebeli and Hauert, 2005). Table 1 shows the payoff matrix for a player of each strategy sampled from a finite population of *n* players (*n* households in our example). This is a version of an ecological Lotka-Volterra model of competition between two species or two phenotypes, constructed as a game between of two-strategies (Doncaster et al., 2013a, b). '*Premium*' is the personal cost of mandatory insurance to cover adaptation to a catastrophe in the absence of mitigation. '*Contribution*' is a voluntary contribution per player towards a collective target for mitigation. '*Pot*' is the size of collective pot as a fraction of target, or as a fraction of its maximum size with pure cooperation if this is less than target; it can take any value between zero and unity.

Cooperators pay the voluntary contribution, plus the premium discounted by the achieved fraction of target; defectors pay only the premium discounted by the achieved fraction of target. Self-interested players cooperate with a probability defined by their payoffs for unilateral interactions: Temptation, *T* (free-ride on others' contributions) and Sucker, *S* (contribute when others do not), relative to mutual interactions: Reward, *R* (everyone contributes) and Penalty, *P* (nobody contributes). The Table-1 payoff matrix summarizes the problem at hand: a target for voluntary mitigation, combined with a mandatory insurance cost that declines with achieved fraction of target, creates a two-strategy game for *n* players that either cooperate with, or defect from, contributions to the mitigation target.

Table 1

Matrix of payoffs for a player of the row strategy in the environment of the column strategy.

	$n - 1$ cooperators †	$n - 1$ defectors †
Cooperator	$R = -contribution$	$S = -contribution - (1 - pot)\cdot premium$
Defector	$T = -(1 - pot)\cdot premium$	$P = -premium$

† The payoffs to each player in an environment of $n - 1$, $n - 2$, $n - 3$, …, 0 cooperators decline linearly, from *R* to *S* for a cooperator and from *T* to *P* for a defector.

For purposes of generality, we quantify the values of annual contribution and premium in multiples of the annual collective target as a per capita value: C. Predictions in this non-dimensionalized currency unit then apply to any target and number of players. For example, we will interpret the model against a target pot of £1.3bn in public contributions by householders to fund mitigation, equalling the annual target of the UK government's green-energy levy (Energy Companies Obligation, 2012). Dividing this sum by the UK's population of 26.4 million households (ONS, 2013) sets C = £49.24 per household. For alternative scenarios involving players as nation states, the larger target and smaller number of players may force the value of C larger by orders of magnitude; the type of player will not alter model predictions, however, when reported in units of C.

3.2. Wealth equality

Here we develop the theory of two-strategy games that identifies the optimal contribution to achieve or approach a given target for collective mitigation, at a given premium for personal adaptation insurance. We assume unordered and uncoordinated (homogeneous) interactions amongst independent players. The homogeneity implies equal wealth in the sense of players not differing in their abilities to pay the mandatory premium or voluntary contribution. We will expand the model to address unequal wealth in the next section.

The probability of defection y by a payoff-maximizing player drawn from an infinite population of players has the following strict Nash equilibrium:

$$y^* = \frac{T-R}{S-P+T-R}\,, \tag{1}$$

with a stable mixed strategy, $1 > y^* > 0$, on conditions $S > P$ and $T > R$ (a Snowdrift game: Hofbauer and Sigmund, 1998). Pure defection (stable $y^* = 1$, a Prisoner's Dilemma) results from failing condition $S > P$ only; pure cooperation (stable $y^* = 0$, a Harmony game) results from failing condition $T > R$ only; bi-stability (stable $y^* = 0$ or 1, a Stag-Hunt game) results from failing both conditions (Doncaster et al., 2013a). An infinitely large population would by definition have an infinitely small value of C in the local currency (£ in our national-scale example). Under a widely applicable scenario, which we assume here, y^* is the Pareto optimal (evolutionarily stable) fraction of defectors in a finite random sample of n payoff-maximizing players (Gokhale and Traulsen, 2010). Specifically, the scenario assumes a 2×n payoff matrix in which the payoffs for alternative strategies adopted by a focal player decline linearly with the cooperator fraction in the population, from payoffs R and T in a pure cooperator population to payoffs S and P respectively in a pure defector population. Table 1 thus shows the corners of a 2×n payoff matrix on the assumption of proportionate payoffs in the intervening cells.

The always-negative R and P payoffs, given by the costs of the contribution and premium respectively (Table 1), mean that S expresses alternative types of costly cooperation, depending on its relationship to P. If $S > P$, cooperation can persist amongst homogeneous interactions with S as a sustainable cost of hosting freeloader defectors, who are parasitic in the broad sense that they drive the unilateral interaction (Doncaster et al., 2013a).

Alternatively, If $P \geq S$, then S is a cost of strongly altruistic cooperation that is a stable strategy only if cooperators interact preferentially amongst like types (enumerated in section 0 below). It presents a social dilemma when the payoffs for defection exceed those for cooperation ($P > S$ and/or $T > R$) whilst collective welfare pays better than individual welfare ($2R > T + S$, Macy and Flache, 2002).

Substitution of the Table-1 payoffs into equation (1) gives y^* in terms of *contribution*, *premium* and *pot*:

$$y^* = \frac{contribution - (1 - pot) \cdot premium}{(2\,pot - 1) \cdot premium}, \tag{2}$$

with a stable mixed strategy, $1 > y^* > 0$, if $pot > contribution/premium > 1 - pot$. Pure defection results from failing the left-hand condition only, pure cooperation from failing the right-hand condition only, and bi-stability from failing both conditions. Note that any $contribution \leq premium$ has a bi-stable outcome at $pot = 0$, which means it repels the defector fraction y away from equilibrium y^* towards a pure strategy. Thus in the particular case of such a game starting at $y = 1$, its initial state of pure defection resists invasion by cooperation and the pot stays empty. If it starts at $y < 1$, however, the presence of cooperation ensures $pot > 0$, potentially allowing escape from pure defection. The following analyses assume a start at $y = 0$ in order to prevent initial strategies from dictating the game outcome. Section 3.4 below simulates an example of a mechanism for ensuring it.

The predicted pot amassed by the equilibrium fraction of cooperators equals the contribution valued as a multiple of C (the per capita collective target), weighted by equilibrium cooperation:

$$pot^* = (1 - y^*) \cdot contribution. \tag{3}$$

The contribution that maximizes pot^* is obtained by substitution of equation (2) into (3) to set pot^* as a function of premium and contribution, and solving for the contribution at maximal *pot** (henceforth '*pot*$^*_{\max}$'), when the differential d *pot** / d *contribution* = 0. Target success is only achievable in principle if *contribution* ≥ 1C, since pure cooperation requires at least this size of contribution to achieve it. The target is then achieved if also *pot*$^*_{\max} \geq 1$. We are now equipped with the necessary tools to assess whether the proposed insurance scheme is feasible.

Proposition 1. Payoff-maximizing players with equal ability to pay the premium and contribute to mitigation may achieve the mitigation target without coordinating mechanisms.

We use equations (2) and (3) to assess under which conditions Proposition 1 holds. The optimal contribution for achieving closest to target (including target success itself) is the contribution at *pot*$^*_{\max}$, for values of *pot*$^*_{\max} < 1$, and otherwise at *pot*$^* = 1$. Solutions to simultaneous equations (2) and (3) at *pot*$^*_{\max}$ yield the optimal contribution and y^* as functions of premium (Table 2, derivations in Appendix A). The functions depend on whether stable equilibrium defection is pure ($y^* = 0$ or 1) or mixed ($0 < y^* < 1$), and whether this equilibrium achieves target success (*pot*$^*_{\max} \geq 1$ at *contribution* ≥ 1C). For example, only *premiums* ≥ 4C satisfy the conditions for target success (equation A7); the optimal contribution is then obtained by substituting equation (2) into (3) and solving for contribution at *pot*$^* = 1$. This function expresses minor and major contributions ≥ 1C that both achieve the target, associated with minor and major mixed-equilibrium defection (bottom rows of Table 2).

Table 2

Optimal contribution for achieving closest to target, and associated stable defector probability y*, for a given premium.

Premium (C)	Optimal *contribution* (C)	y^*
0 to 1	0	1
1 to 2	$premium/(1+premium)$	0
2 to 4	$2 \cdot premium/(8-premium)$	$1-2/premium$
≥ 4	$premium \cdot \left(1 \pm \sqrt{1-4/premium}\right)/2$	$\left(1 \pm \sqrt{1-4/premium}\right)/2$

Currency unit C = target/*n* for a population of size *n*.

Having determined the optimal contribution and defector fraction in terms of premium size (Table 2), we predict the achieved fraction of target and the consequent payoff to players also as functions of premium size. We summarize these insights in the following proposition.

Proposition 2: The size of premium determines the fraction of players that cooperate, their optimal contribution for maximizing the collective mitigation target, the achieved fraction of target, and the average outlay per player.

The average payoff per player is an outlay that is summed from the contribution weighted by equilibrium cooperation, plus the premium discounted in proportion to the size of collective pot:

$$\text{average } payoff = -[pot^* + (1 - pot^*) \cdot premium]. \tag{4}$$

3.3. Wealth inequality

The personal payoff from helping another with shared characteristics has both direct and indirect components, which are aggregated by ‘inclusive fitness’ (Hamilton, 1964). In terms of collective mitigation, a player gains indirect benefit when some of the benefit to others from its own contribution to emissions reduction feeds back to itself. Such feedbacks arise wherever players have a vested interest in each other's wealth, for example within a population of individuals that funds public services through taxes, or within a set of nation states that share trade agreements or subsidies. In the case of a population with unequally distributed wealth, indirect benefits are obtained in emissions reduction for players that subsidise those with lower ability to pay premiums. Here we enumerate wealth inequality amongst players as the assortment of interactions in the form of interests in each other's wealth that resolves differences in their capacity for cooperation.

In the two-strategy game, direct payoffs with $P \geq S$ have a Prisoner's Dilemma outcome that resists invasion by the cooperative strategy under homogeneous interactions. They may yet have inclusive payoffs $S^i > P^i$, however, that allow equilibrium cooperation. The threshold at which inclusive payoffs escape the Prisoner's Dilemma is set by Hamilton's rule (Hamilton, 1964): $-cost + r \cdot benefit > 0$, where *cost* is the net direct costs to the donor of cooperation, *benefit* is the direct benefit to the recipient of the donor's cooperation, and r is a 'relatedness' coefficient that enumerates assortment of interactions with a value between 0 and 1. In effect, cooperation persists if the cost of benefitting another is outweighed by the benefit returned through shared interests. Expressed in terms of the negative Table-1 payoffs for interactions between strategies, a cooperator obtains net payoff $S - P$ from benefitting another, and the beneficiary receives payoff $T = S - R$ from the interaction. This means that $P - S$ defines *cost*, and $-T$ defines the cost-cancelling *benefit* of which fraction r returns to the cooperator through interactions with like types. Hamilton's rule is then:

$$-(P - S) - r \cdot T > 0. \tag{5}$$

For the population of n players, the assortment of interactions is defined by $r = E[f \mid \text{cooperator}] - E[f \mid \text{defector}]$, in which f is the expected relative frequency of cooperators amongst interactions with the focal player (Doncaster et al., 2013b).

Application of Hamilton's rule to a two-strategy game allows enumeration of the effect of coordinated interactions on equilibrium defection. A value of $r > 0$, indicating positive assortment, gives inclusive payoffs: $R^i = R - (1 + r) \cdot T$, $S^i = S - r \cdot T$, $T^i = 0$, $P^i = P$ (derived in Doncaster et al., 2013b). By elaboration of equation (1), equilibrium defection in the presence of assortment:

$$y^* = \frac{T^i - R^i}{S^i - P^i + T^i - R^i} = \frac{(1+r) \cdot T - R}{S - P + T - R}. \tag{6}$$

with a stable mixed strategy, $1 > y^* > 0$, on conditions $S^i > P^i$ and $T^i > R^i$. Substitution of the Table-1 payoffs into equation (6) sets y^* in terms of *pot*, *premium* and *contribution*:

$$y^* = \frac{contribution - (1+r) \cdot (1 - pot) \cdot premium}{(2\,pot - 1) \cdot premium}. \tag{7}$$

with a stable mixed strategy, $1 > y^* > 0$, if $1 - (1 - r) \cdot (1 - pot) > contribution/premium > (1 + r) \cdot (1 - pot)$. Pure defection results from failing the left-hand condition only, pure cooperation from failing the right-hand condition only, and bi-stability from failing both conditions. Equation (7) shows larger values of r decreasing defection at given values of *premium*, *contribution*, and $pot < 1$, but r ceasing to have an effect upon achieving the target ($pot = 1$). The optimal contribution for achieving closest to target, and the associated y^*, are derived in Appendix A as the general case of Table 2 extended to $r \geq 0$.

The final proposition summarizes the effect of wealth inequality on the outcome of the game.

Proposition 3: Wealth redistribution amongst players that resolves inequalities, including trade agreements and subsidies, influences the achieved fraction of target, and hence the average outlay per player.

We illustrate the properties of r by considering an application of the two-strategy game to nation states as players, starting with a simplified scenario of a group of nation-players that are equally wealthy in terms of their ability to pay a premium. Suppose they owe 20% of this wealth on average to trade agreements between them. They might each owe 20%, or one nothing and another 40%, and so on. The nations take relatedness coefficient $r = 0.2$. Its value has quantifiable impacts on the optimal contribution for the collective mitigation target and equilibrium defection, and consequently on the achieved fraction of target and average payoff per player. These impacts are enumerated by equations (3) and (4), given (7) (Appendix A).

In an alternative scenario, the group of nations may have no trade agreements but unequal wealth in terms of ability to pay the premium. For the purposes of the Table-1 framework, the value of r is the average proportionate redistribution of wealth amongst them that resolves this discrepancy. For example, $r = 0.2$ when the discrepancy is resolved by a 20% redistribution of wealth available for paying the premium. Thus, $r = 0.2$ when all nations have equal ability to pay after one has subsidised four others each to the value of 25% of the premium; equally $r = 0.2$ when equality is obtained by four nations each subsidizing a fifth nation to the value of 25% of the premium. We assume that subsidies are paid through an intermediary such as the World Bank, to prevent donors from taking ownership of recipients' choices in paying the contribution. A fully subsidized recipient stands to benefit from paying the contribution just as any other player, by holding on to all of the unspent premium in the event of target success, or otherwise fraction pot^* of it.

Combining the trade-agreement and subsidy scenarios, a group of nations may be connected by trade agreements, and by subsidies that resolve outstanding wealth inequalities. In the Table-1 framework of collective mitigation leveraged from discounts on premiums, their average relatedness is aggregated from the two sources of co-dependence. For example, $r = 0.4$ if nations owe 20% of their wealth on average to others, in terms of ability to pay the premium, and additionally one nation subsidises four others to the value of 25% of the premium.

3.4. Agent-based simulation

We developed a simulation to represent a playable scheme. It requires all players to submit an annual deposit at the start of the year for an amount equal to a recommended *contribution*. At any time during the year, players may tag their deposit for retraction. At all times they can view the projection of their year-end invoice, payable as a pre-set insurance *premium* discounted by the fraction of collective target currently achieved in untagged contributions, minus any part of their contribution tagged for retraction. The simulation assumed that each player acts to maximize its individual payoff. The choice of cooperation or defection was simulated for homogeneous interactions (wealth equality) amongst players at the optimal contribution for a given premium set by Table-2 formulae. It was repeated at ±20% of optimum to gauge the sensitivity of the outcomes to the size of contribution. The simulation was repeated again for coordinated interactions (wealth inequality) quantified by $r > 0$ at the optimal contribution for a given premium set by Appendix-A formulae.

Each simulation trial had n players, each set the same size of *premium* and voluntary *contribution*. The trial started with a population of pure cooperators and incrementally switched players to defectors for as long as it paid players to make the switch. As the observed defector fraction, y_{obs}, rose in the population, it lowered the fractional size of collective pot, $pot_{\text{obs}} = (1 - y_{\text{obs}})\cdot contribution$, which in turn devalued unilateral payoffs T and S. Cooperators defected at an average rate of 1.0 defection per increment (s.d. = 0.29), until cooperation obtained a positive benefit per capita of not switching to defection, $(S^i - P^i)/(1 - y)$, as large or larger than the benefit per capita of defection not switching back to cooperation, $(T^i - R^i)/y$. The resulting y^*_{obs} set the year-end fraction of target, pot^*_{obs}, which determined the final invoice, measured as an average *payoff* per capita: $-[pot^*_{\text{obs}} + (1 - pot^*_{\text{obs}})\cdot premium]$. Appendix B shows examples of within-year trajectories towards y^*_{obs} and pot^*_{obs}.

The simulation reported values of y^*_{obs}, pot^*_{obs} and *payoff* averaged over 50 replicated trials, at values of *premium* from 0 to 6C in 0.1 steps. Simulations were run for small populations (n = 5), indicative of players at the global scale of nation states, and for large populations (n = 500), indicative of players at the regional or national scale of individuals, households, or corporations. Appendix C contains the R script for the simulation.

4. Results

4.1. Well-mixed populations of independent players

The principal finding is that successful achievement of the collective target for mitigation requires a premium for adaptation insurance worth at least four times the value of the target per capita (i.e., ≥ 4C, Fig. 2*a*-*d*). This validates Proposition 1. Premiums < 4C result in an average payoff as much as 42% worse than the payoff for achieving the target (Fig. 2*d* line). For premiums up to 1C (worth £49.24 in the example application), everyone defects (Fig. 2*b*) because the achievable fraction of target is too small for any resulting discount on the premium to compensate for paying a contribution even if everyone contributed to the collective pot. Premiums ≥ 1C initiate cooperation because the average payoff is then better than the –*premium* that obtains with pure defection. For premiums between 1C and 2C (£49.24-£98.48), the payoff for everyone cooperating with an optimal contribution cannot be bettered by defection (shifting the game from Prisoner's Dilemma to Harmony). Full cooperation fails to achieve the target at these low premiums, and average payoff falls below –1C (Fig. 2*c*-*d* lines). Higher premiums up to 4C (£196.97) sustain increasing amounts of defection from paying the optimal contribution (shifting the game from Harmony to Snowdrift). Defection rises from zero to half the population of players (Fig. 2*b* line), as pot^* rises to achieve the target at a premium of 4C (Fig. 2*c* line) and an average payoff of –1C (Fig. 2*d* line). This lowest target-achieving premium is also predicted directly from substitution of equation (2) into (3) at $pot^* = 1$, to obtain: $premium_{x^*=1} = 1\big/\left[y^*\left(1-y^*\right)\right]$ with a single minimum of 4C, at $y^* = 0.5$.

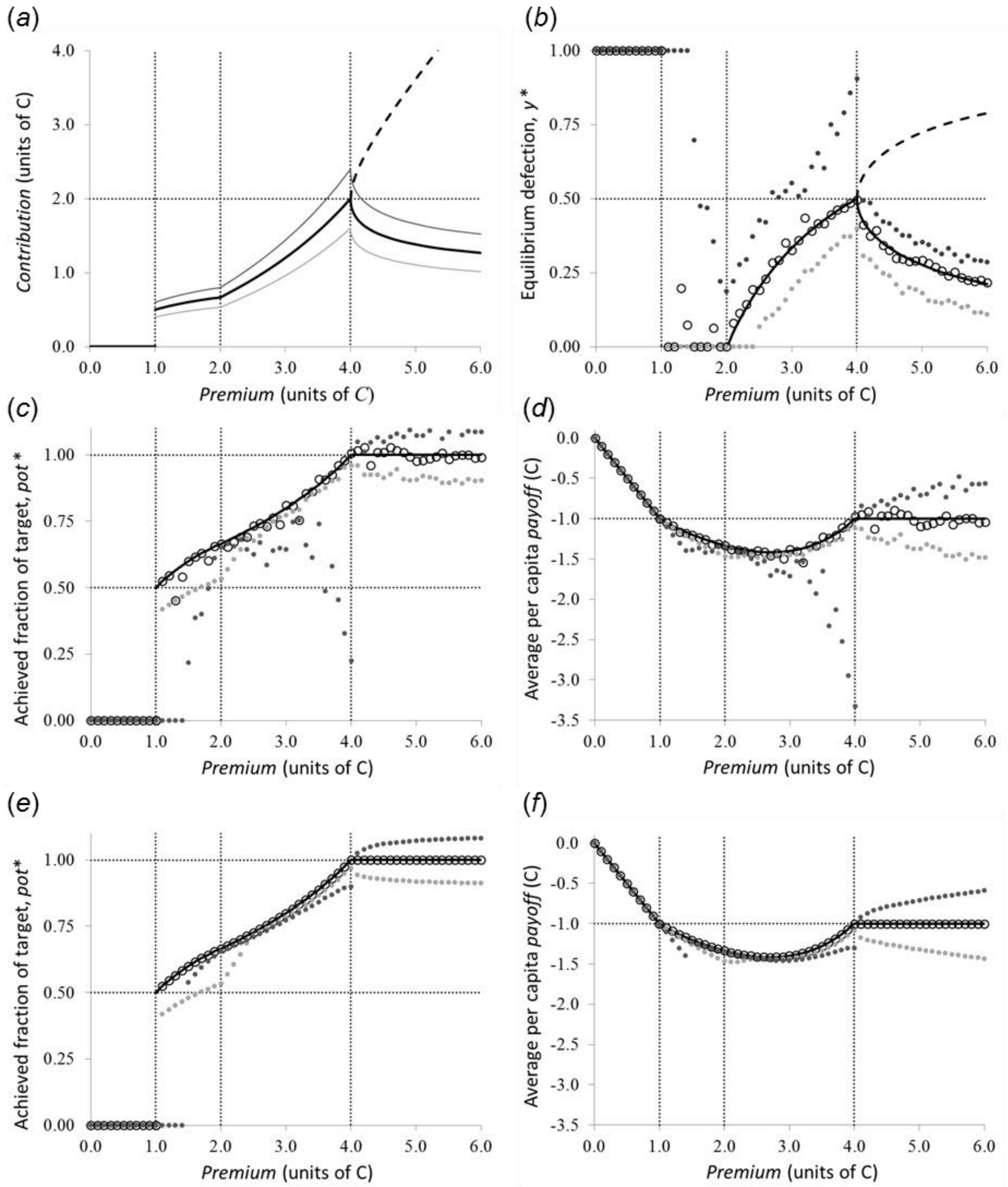

Fig. 2. Model predictions for uncoordinated interactions amongst independent players. Functions of premium predicted from Table 2 and equations (3)-(4) (lines), and observed by simulation (dots). (*a*) Optimal contribution for achieving closest to target (thick black line, dashed for major target-achieving contribution), and 20% above/below optimum (dark/light grey lines). (*b*)-(*d*) Equilibria for simulated populations of *n* = 5 at the optimal contribution

(open circles), and at 20% above/below optimum (dark/light grey dots). (*e*)-(*f*) Equilibria for simulated populations of n = 500.

A discontinuity occurs at the premium of 4C (Fig. 2*a*-*b* lines). For higher values, target success is achieved either by high cooperation with a minor contribution or by low cooperation with a major contribution. The minor optimal contribution declines rapidly from 2C towards convergence with 1 + 1/premium, while the associated defection declines towards convergence with 1/premium (Fig. 2*a*-*b* continuous lines). The alternative major optimal contribution rises towards convergence with premium – 1, while the major defection probability rises towards convergence with 1 – 1/premium (Fig. 2*a*-*b* dashed lines). We focus on the minor contribution and defection as best suited to a government-driven initiative, whilst noting that the major contribution and defection may provide an alternative route to success given rising intra- and international disparities in wealth.

For any premium of at least 4C, target success with both minor and major optimal contributions (Fig. 2*c* line) sets average payoff at a constant –1C (Fig. 2*d* line). Although cooperators obtain a worse payoff than defectors because only they pay the contribution (a cost of unavoidable parasitism), this deficit diminishes for the minor contribution at larger premiums as the higher cooperation sustains ever smaller contributions. Premiums less than 4C obtain target shortfall from the optimal contribution, which worsens the average payoff for premiums down to 1C. With premiums below 1C attracting no cooperation with contributions, they obtain payoff P = –premium. These predictions demonstrate the strengthening motivation for achieving the mitigation target with higher premiums above 4C. For premiums below 4C, they demonstrate the cost to the collective pot and average payoff from undervaluing the premium for a given target, or overestimating the achievable target for a given premium.

Simulations of the game with the Table-1 payoff structure and stochastic defection tested the sensitivity of the model to finite population sizes, and the effects of non-optimal contributions. The simulations mapped y^*_{obs} closely to y^* for populations of n = 5 with the contribution set at optimal, and they had y^*_{obs} falling either side of y^* for contributions either side of the optimum (Fig. 2*b* circles and dots). This close mapping for the optimal contribution validates Proposition 2. Simulation outcomes show that the optimum contribution for maximizing the pot also gave the optimum average payoff per capita. Despite sub-optimal contributions attracting the most cooperation, their lower values reduced pot^* and the associated average payoffs, particularly at premiums above 4C (Fig. 2*c*-*d*, light dots). For supra-optimal contributions, the inflated defection probabilities at premiums of 4C and marginally below caused substantial reductions in pot^*, resulting in by far the worst of all average payoffs (Fig. 2*c*-*d*, dark dots).

Simulated populations of n = 500 at the optimal contribution had a more precise mapping of pot^* and average payoff onto analytical predictions than for n = 5 (Fig. 2*e*-*f* circles and lines). Non-optimal contributions produced deviations in pot^* and average payoff of similar magnitude for n = 500 as for n = 5, except for premiums marginally above 1C and at 4C and marginally below it. In these regions, supra-optimal contributions had less impact on pot^* and average payoff (Fig. 2*e*-*f* compared to *c*-*d*, dark dots) associated with less inflated defection. These simulations highlight the sensitivity of the collective pot and average payoff to population size in the event of overestimating the achievable target and optimal contribution.

4.2. Players with unequal vulnerabilities or benefits

The findings for the size of contribution in Fig. 2 assume that all players face the same vulnerability to natural hazards covered by the insurance, and will benefit equally from actions funded by the collective pot. To accommodate the reality of heterogeneity in the geographic spread of risk and benefit requires matching any regional variation in market price for the premium with variation in either the optimal contribution or the distribution of action funded by the collective pot, or both. In effect, having created an insurance market, its regional variability can set the scale at which to determine the optimal contribution from the predicted defector fraction. The analytical method is the same, whether applied once to a nation of citizens or repeatedly to independent regional or local populations.

4.3. Players with wealth inequalities

Shared interests amongst players, expressed by $r > 0$, raise the optimal contribution for premiums of 1C to 4C (Fig. 3*a*). Although the higher contribution raises equilibrium defection (Fig. 3*b*), the net effect is to increase the achieved fraction of target and average payoff (Fig. 3*c*-*d*). Total co-dependency, at $r = 1$, means that self-interest aligns precisely with public interest regardless of premium. Despite $r > 0$ raising pot^*, target success itself always depends solely on the premium being at least four times larger than the per capita target. Premiums ≥ 4C completely align private with public interests by virtue of the target success, with the same minor and major optimal contributions and y^* as at $r = 0$, and with the same average payoff of –1C (Fig. 3*a*-*d*). Simulations with 5 players achieve approximate alignment with predictions (Fig. 3*b*-*d*), which becomes precise with 500 players, as at $r = 0$. These variations of Fig. 3 from Fig. 2 confirm Proposition 3.

Any positive effects of r on pot^* and average payoff apply regardless of the source of interdependence through interests in each other's wealth. Where the interdependence arises from wealth inequalities, we have assumed that subsidies resolve differences in ability to pay the premium and willingness to pay the contribution. Given that condition, our general inference is that wealth inequalities make no difference for premiums ≥ 4C, while for lower premiums they increase the power to leverage mitigation by discounting the premium. Residual differences in ability to pay the premium that are not resolved by subsidies, however, may lead to poorer players defaulting on payments of both contribution and premium. Their participation ceases in that event, which reduces the size of *n* and therefore raises the value of C, assuming an unchanged mitigation target. The overall consequence for all remaining participants is that the minimum target-achieving premium of 4C will cost more in the local currency, as will the optimal contribution and the average payoff.

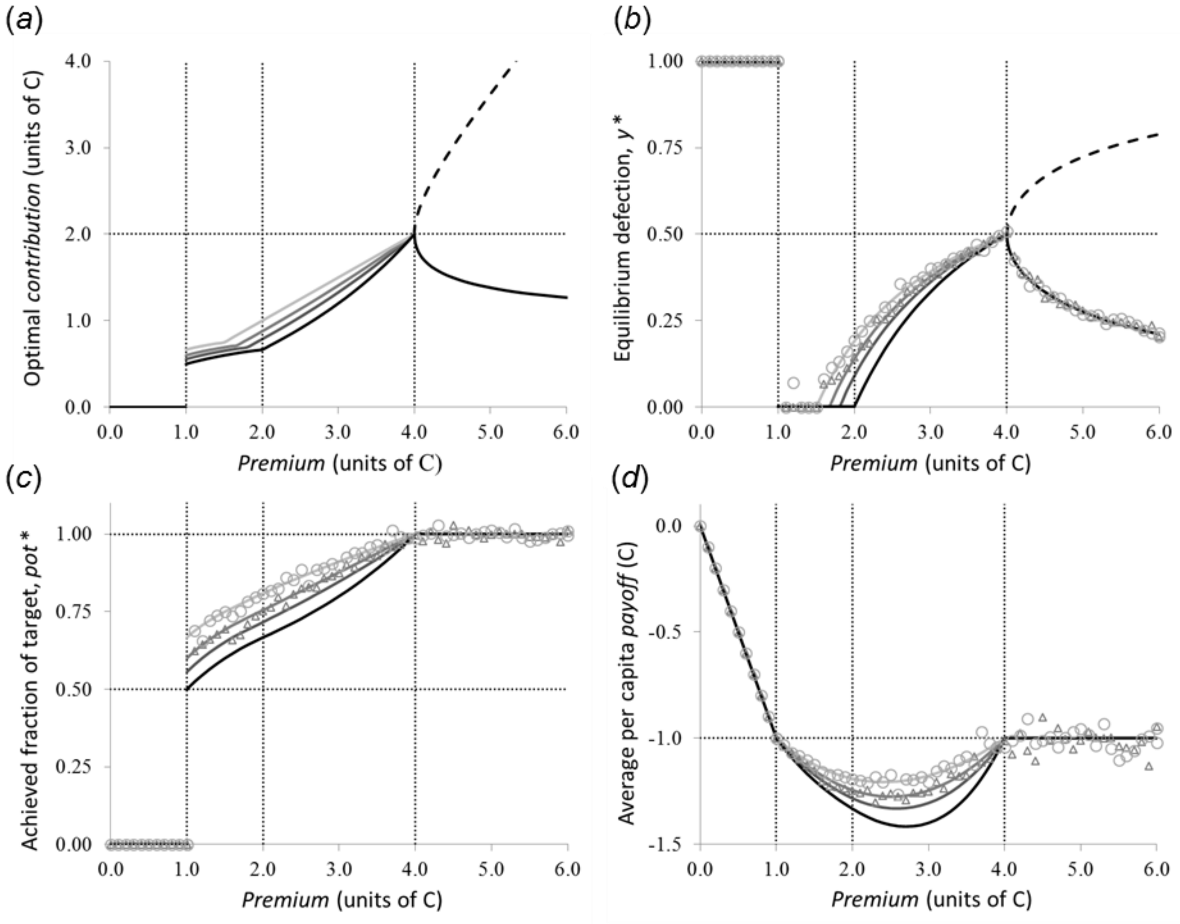

Fig. 3. Model predictions and simulation outcomes for dependent players ($r \geq 0$). Functions of premium predicted from equations (3)-(4), given equation (7), with derivations in Appendix A. Lines plot $r = 0$ (black, independent players as Fig. 2), 0.25 (dark-grey), 0.50 (mid-grey), 1.0 (light-grey). Symbols plot simulation results with 5 players at the optimal contribution, with $r = 0.5$ (grey triangles), $r = 1.0$ (light-grey circles).

5. Discussion

The analysis shows how mitigation that reduces the premium on mandatory insurance can be funded through voluntary contributions. Specifically, it illustrates three intuitive findings. A premium at least four times larger than the per capita mitigation target provides sufficient motivation for payoff maximizing players to achieve the target even without coordinating mechanisms (Proposition 1). Moreover, smaller premiums underachieve relative to the target, with a worse average payoff per capita (Proposition 2), although the target fraction is raised and average payoff improved by subsidies between players that resolve wealth inequalities (Proposition 3). This final result is an example of wealth inequalities raising efficiency in the management of a public good (Baland and Platteau, 1997).

5.1. Mandatory adaptation incentivizes voluntary mitigation

Policy makers increasingly favour voluntary policies for environmental protection, in the form of self-regulation, negotiated agreements and public programmes (Segerson, 2013). In the context of climate change, this has become apparent since the signing of the Copenhagen Accord late in 2009, which marked a global-scale move away from top-down architectures in climate negotiations. The December 2015 Paris Accord sealed the transition to bottom-up initiatives, by centring around voluntary nationally determined contributions. The capacity for voluntary policies to outperform business-as-usual scenarios, however, depends on their effectiveness in improving both environmental outcomes and cost-effectiveness to participants. In the context of corporate targets to regulate environmental pollution, a voluntary policy can sustain free-riders provided a subset of polluters experience a cost of voluntary participation that is less than the costs they would incur under the alternative policy (Dawson and Segerson, 2008). Coupling the voluntary approach with an underlying regulatory structure has the potential to increase its effectiveness, depending on the cost of counterfactual scenarios (Segerson and Miceli, 1998; Segerson, 2013). Here we have quantified how the counterfactual of costly future adaptation brings resilience to the effectiveness of voluntary mitigation, which it otherwise lacks in terms of achieving both a public target and private cost-effectiveness.

The collective mitigation target is achievable amongst homogeneous interactions provided that: (*i*) players face a cost to themselves from no mitigation of at least 4C (£196.97 for the UK scheme), and (*ii*) mitigation funded by achieving the target will have sufficient impact to nullify this cost. While mitigation demands an immediate investment, the consequences of inaction will be realized in a longer-term cost of adaptation. Our approach to aligning public with private needs is predicated on the reality of the individual's tendency for future discounting, in which distant costs are not addressed given the relative importance of nearer costs (e.g. Pryce et al., 2011). We assume that the insurance industry depends on the application of reasonable functions for discounting the future, in order to satisfy shareholders that they will not face bankruptcy due to potentially infinite insurance pay-outs. Accurate functions are further motivated at the national scale if government provides the insurance with a fair-price pledge, or at the international scale if a consortium of countries participating in a risk-sharing agreement have similar preferences and uncorrelated risks.

Mandatory adaptation insurance brings the long-term cost of adaptation into the present, and a market-led premium relieves government of some of the burden of persuasion. Market forces can set the premium on the basis of existing evidence for adaptation costs arising within the lifetime of the payee in the event of no mitigation. Any fraction of the anticipated adaptation costs that would accrue only to future generations could be costed separately by allocating that fraction of the premium to inheritance tax as a single payment in death duty. This would require a further elaboration of the model to weight the duty according to the treasury forecast of annual funds raised through inheritance tax.

Uncertainty about when climate change will tip into a catastrophe, or what target will prevent it, may fatally delay cooperative action (Barrett and Dannenberg, 2014; Dannenberg et al., 2015). Our use of collective mitigation to discount the insurance premium directly addresses this uncertainty, because the size of the premium determines the maximum achievable target (e.g., premiums < 4C cannot achieve target at equilibrium defection: Figs 2-3). With a commercially set premium, adaptation insurance offers a free market for informed personal decisions on the collective mitigation that yields premium discounts. Any uncertainty about the sufficiency of the mitigation target provides a market incentive to reduce the rate of discounting the future (Wagner and Weitzman, 2015), and thereby to raise the premium. This in turn raises the commitment to cooperative action that generates discounts (Fig. 2b; cf. Lewandowsky et al., 2014). We have assumed that mitigation reduces adaptation costs linearly; model refinements could accommodate non-linear discounting to cover residual costs beyond the scope of mitigation. Further extensions of the model could partition out self-insurance (to reduce costs) and self-protection (to reduce risk) from the market-led mandatory insurance (Ehrlich and Becker, 1972), or could model insurance as a public good (Lohse et al., 2012).

5.2. Implications for UK policy

The UK government originally planned for a mandatory annual contribution that would add about £50 to the average household energy bill (DECC, 2013). Achieving the £1.3bn annual target for funding green-energy solutions would therefore allow no more than 2% defection amongst the 26.4 million UK households. Such a small defection probability is an equilibrium outcome given the Table-1 payoffs, and therefore freely chosen, only for an insurance premium valued at £3,300 per household. To date the British public has not been presented with options for anticipating the personal debt burden that will ensue from failing to take any cooperative action, or a mechanism for managing it. In the concurrent political context of large increases in the base rate of energy, this absence of information may have contributed to the public pressure that forced government into announcing plans in December 2013 to reform the contribution (DECC, 2013). Despite the coercion by government that made the contribution obligatory, the policy was defeated within a year. Yet we have seen that voluntary contributions can raise any collective target without altruism, pledges, cliques, local policing, or other heterogeneous interactions associated with a social dilemma.

Given the inevitability of climate change impacts becoming more pronounced in the future (IPCC, 2013), our analysis shows the importance of covering for the likely costs of adaptation, as a motivation for cooperative mitigation. Stern (2007, citing Barker et al., 2006) suggests that stabilizing the CO_2 emissions trajectory at 500-550 ppm might incur costs for 2050 in the order of 1% of GDP. With UK GDP currently worth £1,499bn (2012 value: The World Bank, 2013), a national cost of rectifying greenhouse emissions that is worth 1% of this amount resolves down to £568 per household. If the £1.3bn annual target for green-energy mitigation stabilizes CO_2 emissions (assuming a strong relationship between national and global emissions), an insurance premium of £568 (11.53C) is predicted by equations (2) and (3) to attract 90% cooperation with a target-achieving contribution of £54.47 (1.11C). The year-end insurance invoice equals the magnitude of the *T* payoff of Table 1, which in this case would be zero based on the contribution having achieved the target. Paying the contribution would therefore result in a >10-fold saving in personal outlay.

5.3. Cooperation at national and global scales

Market-led insurance as a method of costing alternatives to mitigation is reviewed in the IPCC Fifth Assessment Report, which emphasizes the need for government oversight (IPCC, 2014b). Three-quarters of the global insurance industry has engagement with climate-change adaptation through investments totalling some US$25 billion (Mills, 2012). The Munich Climate Insurance Initiative exists to develop insurance-related management of climate-change impacts, in partnership with the UNEP Finance Initiative. All such schemes present challenging opportunities for developing interactions between government measures aimed at risk reduction and insurance companies' willingness to provide cover (IPCC, 2014b). Our analysis has demonstrated the potential, in principle, for using insurance to incentivize mitigation of risk. New Zealand's Earthquake Commission (EQC) is a government-regulated insurance scheme for natural disasters including storms, floods, and tsunamis, which is an obligatory component of insurance bought by all owners of residential dwellings and contents in New Zealand. Although the EQC pays owners the value of damaged land or repair costs following a natural disaster, the premium is not linked to mitigation or pre-emptive adaptation such as we propose here, which has been considered as a lost opportunity for risk reduction (Glavovic et al., 2010). The French CatNat system of insurance against flood damage includes deductibles from compensation linked to non-compliance with risk-prevention plans, but they are not adjusted to risk and are set too low to incentivize mitigation of risk (Poussin et al., 2013). A survey has found that Dutch homeowners were willing in principle to invest in measures that mitigate flood damage in exchange for benefits on flood insurance policies (Botzen et al., 2009). Such opportunities remain under-developed for natural hazards associated with climate change (IPCC, 2014b).

Our model of state-enforced insurance demonstrates a potential for aggregation that could lead to effective management of a global commons such as greenhouse gas emissions. Despite all states contributing to global emissions of greenhouse gases, coercion is not currently an option for improving cooperation amongst nation states in the absence of global governance. On the international stage, governments could seek to apply the same strategy of premium discounts to a multinational insurance partnership to achieve international mitigation. The Caribbean Catastrophe Risk Insurance Facility (2007) is the only such multinational pool so far to insure against sovereign risks of climate change and other national catastrophes (Grove, 2012). This not-for-profit company is a public-private partnership owned by a trust and governed by trust deed. It currently holds policies for 16 Caribbean countries, which benefit in low premiums from pooling a wide basin of climatic uncertainties. It therefore represents an organically seeded form of international governance. Similar schemes are currently under consideration for Europe, Africa, and the Pacific (IPCC, 2014a). They use 'parametric' insurance, which pays a predetermined remuneration when parameters are met such as thresholds of hurricane category or average temperature. Reinsurance mechanisms cover rare events that would otherwise leave obligations outstripping capital reserves. Instead of responding to pre-established threats, parametric insurance with reinsurance prepares for future-possible threats independently of their probability (Grove, 2012). This makes it particularly well suited to funding climate-change mitigation through securitized premium discounts, because effective mitigation will reduce the frequency of threshold crossings. The current absence of any such link to mitigation again represents a missed opportunity.

6. Conclusions

We have provided a simple game-theoretic framework for optimizing collective payments towards climate-change mitigation. The method quantifies a currently ignored opportunity for adaptation insurance to leverage collective mitigation through discounts in personal insurance premiums. Although we have focused on insurance, any mechanism for bringing adaptation costs into the present can leverage cooperation with mitigation. The analysis demonstrates the effect of full and fair knowledge about adaptation costs in motivating preventative action for a payoff-maximizing population. Mitigation achieves ambitious targets when it reduces otherwise high costs of adaptation to climate change and it works even for anticipated catastrophes otherwise considered uninsurable. The galvanizing effect of a potential debt burden suffices alone, and independently of any coordinated responses, to align personal with social interests. The prevailing absence of cover for a bleak future, however, perpetuates the association of collective action with a social dilemma, overlooking its potential as an efficient strategy for minimizing personal costs in adaptation.

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Appendix A: Derivation of Table-2 predictions

The following derivations of optimal *contribution* and stable equilibrium defector probability y^* incorporate Hamilton's relatedness coefficient r, to extend the predictions of main-text Table 2 for homogenous interactions ($r = 0$) to coordinated interactions ($r > 0$). For ease of presentation, we code *premium* as 'p' and *contribution* as 'c'. Both are measured in non-dimensionalized currency units of C, the collective target as a per capita value. The intuition behind the predictions from these relationships is given in main-text Results section 4.1.

Step 1. Find pot^* at y^* as a function of contribution, c, for a given premium, p, and relatedness coefficient, r, by substitution of main-text equation (2) with $r = 0$, or equation (7) with $r \geq 0$, into equation (3):

$$pot^* = \left[1 - \frac{c-(1+r)(1-pot^*)\,p}{(2\,pot^*-1)\,p}\right]c\,. \tag{A1}$$

Rearrange in terms of pot^*:

$$pot^* = \frac{1}{4p}\left[(1-r)cp + p \pm \sqrt{c^2p^2 - 2c^2p^2r + 2cp^2 + c^2p^2r^2 + 6cp^2r + p^2 - 8c^2p}\right]. \tag{A2}$$

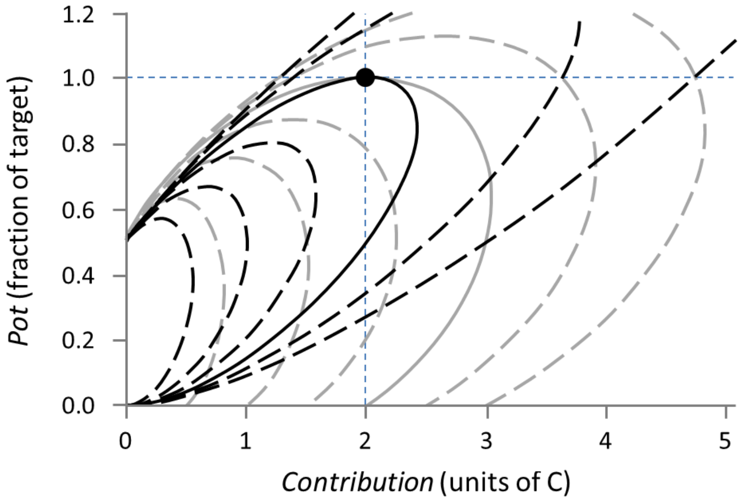

Fig. A1. *Pot** at *y** as a function of *contribution* (equation (A2)), at *premium* = 1C, 2C, …, 6C from smallest to largest ellipse for each of *r* = 0 (black) and 0.5 (grey). Black dot at the intersection of the blue marker lines shows the *contribution* at the maximum *pot* for *premium* = 4 (equation (A4) below), and the corresponding maximum *pot* (equation (A5)).

Step 2. Obtain the optimal contribution for maximizing the pot, $c[pot^*_{\max}]$, by differentiating the larger of the two solutions for pot^* with respect to c:

$$\frac{\mathrm{d}\,pot^*}{\mathrm{d}c} = \frac{1}{4p}\left[(1-r)\,p + \frac{2cp^2 - 4cp^2r + 2p^2 + 2cp^2r^2 + 6p^2r - 16cp}{2\sqrt{c^2p^2 - 2c^2p^2r + 2cp^2 + c^2p^2r^2 + 6cp^2r + p^2 - 8c^2p}}\right]. \qquad \text{(A3)}$$

Then set $\mathrm{d}\,pot^* / \mathrm{d}\,c = 0$ and rearrange in terms of c to obtain the contribution at $pot^*_{\max}$:

$$c\left[pot^*_{\max}\right] = \left(3r + 1 + (1-r)\sqrt{\left(pr + pr^2 + 1\right)}\right)\frac{p}{2pr - pr^2 - p + 8}. \qquad \text{(A4)}$$

This gives the optimal contribution in row 3 of main-text Table 2 with $0 \le r \le 1$, for $(2 + r)/(1 + r) \le p < 4$. The lower limit of p is the value of p when $y^*[pot^*_{\max}] = 0$ (solved from equation (A6) below).

Step 3. Obtain $pot^*_{\max}$ by substitution of equation (A4) into the larger of the two solutions of equation (A2):

$$pot^*_{\max} = \frac{pr - pr^2 + 2 + 2\sqrt{pr + pr^2 + 1}}{2pr - pr^2 - p + 8}. \qquad \text{(A5)}$$

Step 4. Obtain stable y^* at $pot^*_{\max}$ by substitution of equations (A4) and (A5) into main-text equation (7):

$$y^*\left[pot^*_{\max}\right] = \frac{5 - p + pr^2 + 3r - (r+3)\sqrt{pr + pr^2 + 1}}{4 - p + pr^2 - 4\sqrt{pr + pr^2 + 1}}. \qquad \text{(A6)}$$

This gives y^* in row 3 of main-text Table 2 with $0 \le r < 1$, for $(2 + r)/(1 + r) \le p < 4$.

With $r = 0$, equations (A4) to (A6) simplify to:

$$c\left[pot^*_{\max}\right] = \frac{2p}{8-p}, \quad pot^*_{\max} = \frac{4}{8-p}, \quad y^*\left[pot^*_{\max}\right] = 1 - 2/p. \qquad \text{(A7)}$$

These give optimal contribution and stable y^* in row 3 of main-text Table 2 with $r = 0$, for $2 \le p < 4$.

Figure A1 shows $p = 4$C being the lowest premium to achieve target success ($pot^*_{\max} = 1$), with $c = 2$C (black dot), in accordance with equations (A4) to (A7) above. At $r = 0$, however, note that $c = 2$C also has an alternative $pot^* = 0.5$. This is the pot at $y^* = 0.75$ in a bi-stable Stag Hunt game which fails both conditions given below main-text equation (2). Generally for any given c, the alternative $pot^* < pot^*_{\max}$ is the pot at y^* in a bi-stable game set by failing both conditions below main-text equation (7). Main-text analyses and simulations assume an initial condition of $y = 0$, in order to prevent initial strategies from dictating the game outcome.

Step 5. Obtain the target-achieving *contribution* and y^* at $pot^* = 1$ by rearranging equation (A1) in terms of c:

$$c\left[pot^* = 1\right] = \frac{p\left(1 \pm \sqrt{1 - 4/p}\right)}{2}. \tag{A8}$$

The corresponding stable y^* at $pot^* = 1$ obtains from substitution of equation (A8) into main-text equation (7):

$$y^*\left[pot^* = 1\right] = \frac{1 \pm \sqrt{1 - 4/p}}{2}. \tag{A9}$$

Equations (A8) and (A9) give the optimal contribution and y^* (both invariant with respect to r) in row 4 of main-text Table 2, for $p \geq 4$.

Step 6. Find the optimal contribution at $y^* = 0$. From main-text equation (3), $pot^* = c$ at $y^* = 0$. Substituting c for pot^* in the larger of the two solutions of equation (A2), and rearranging in terms of c:

$$c\left[y^* = 0\right] = \frac{(1 + r)\,p}{1 + (1 + r)\,p}. \tag{A10}$$

This gives the optimal contribution in row 2 of main-text Table 2 with $0 \leq r \leq 1$, for $1 \leq p < (2 + r)/(1 + r)$. Given main-text equation (3), it is also the value of $pot^*[y^* = 0]$.

Step 7. Obtain the average *payoff* per player at $y^* = 0$ by substitution of equation (A10) into main-text equation (4):

$$payoff\left[y^* = 0\right] = \frac{-(2 + r)\,p}{1 + (1 + r)\,p}. \tag{A11}$$

For any $0 \leq r \leq 1$ at $p < 1$, note that $payoff[y^* = 0]$ is worse than $payoff[y^* = 1] = -p$. This sets optimal *contribution* = 0 and $y^* = 1$ in row 1 of main-text Table 2, for $p < 1$.

Appendix B: Stepwise trajectories towards equilibria from simulations

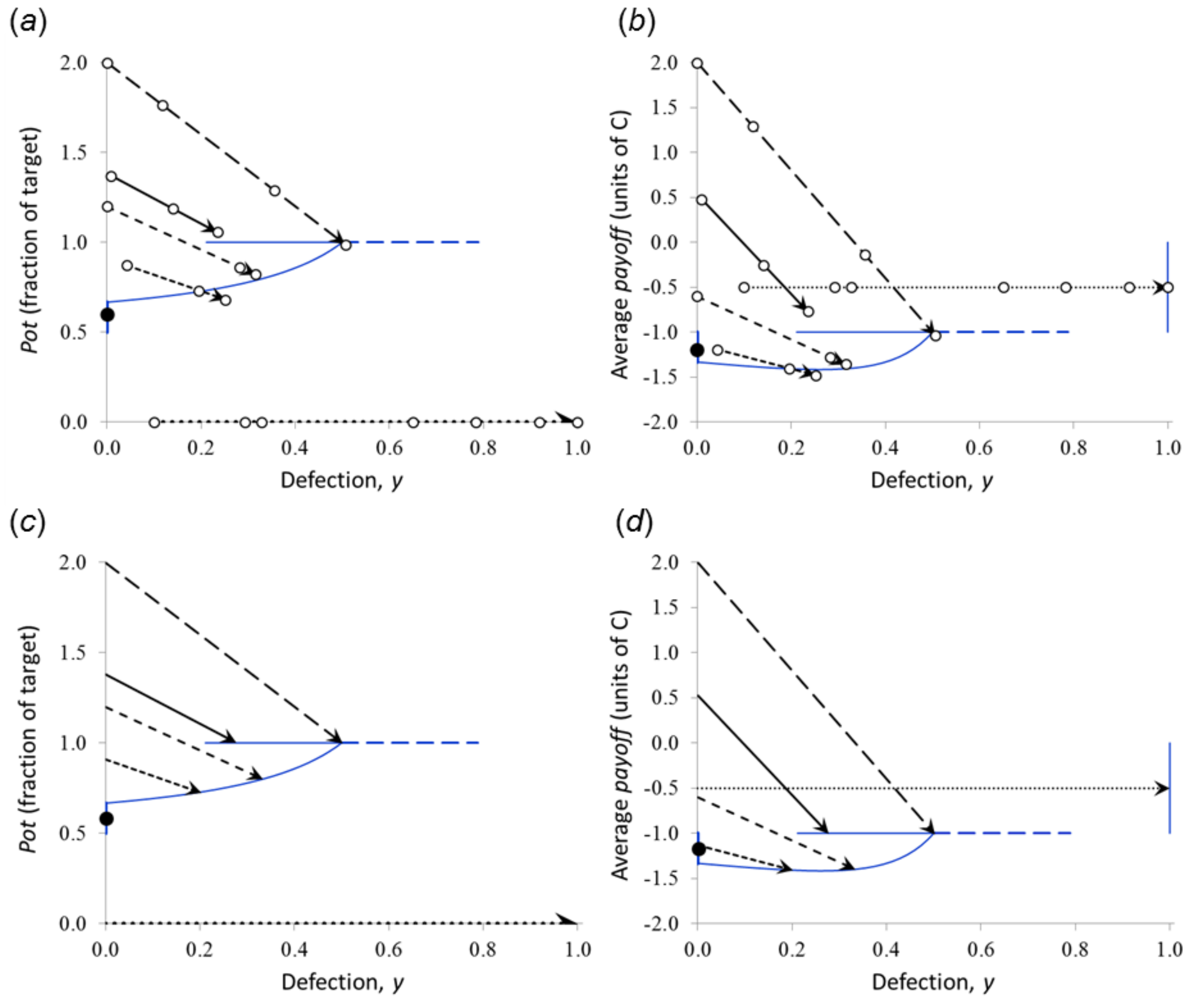

Fig. B1. Examples of within-year trajectories (arrowed) towards year-end *pot* and *payoff* (at arrow head). Simulation runs started with pure cooperation, $y = 0$, and ended in the vicinity of equilibria predicted by main-text equations (2) to (4) (blue lines). Each graph shows one run at each of *premium* = 5 (continuous arrow), 4 (long-dashed arrow), 3 (short-dashed arrow), 2.5 (shorter-dashed arrow), 1.5 (black dot), and 0.5 (dotted arrow), all at $r = 0$. For any *premium* ≥ 1C, there always exists some positive fraction of cooperators for which the benefit to a cooperator of not switching to defection starts to exceed the benefit to a defector of not switching back to cooperation. The simulation finds this balance iteratively. (*a*)-(*b*) Populations of 5 players, with sequential defections marked by circles, continuing until cooperation obtained a positive benefit per capita of not switching to defection that was as large or larger than the benefit per capita of defection not switching back to cooperation. (*c*)-(*d*) Populations of 500 players.

Appendix C: R script for simulation

The following R script provides outputs for main-text Figs 2 and 3, and Appendix B Fig. B1.

```
# Agent-based simulation of cooperative mitigation traded against costly adaptation.
# Stepwise switches from pure cooperation towards equilibrium defection as a function
# of the premium for mandatory adaptation insurance.
# C. P. Doncaster, 16 August 2016
#
rm(list = ls()) ; search()
#########################################################################################
### Input constants ###
#######################
rounds = 50 # Number of rounds over which to average year-end outputs
N = 5 # Number of players
fraction.of.optimum = 1.0 # Fraction of optimum contribution
r = 0.0 # Hamilton's relatedness coefficient, 0 <= r <= 1
outfile1 = "Incentives_stepwise_output.csv" # File to contain stepwise outputs, round 1
outfile2 = "Incentives_year-end_output.csv" # File to contain year-end average outputs
#########################################################################################
### y.star function ###
#######################
y.star = function(){
  # Reports premium, contribution, expected y and payoff, and observed y, pot and payoff
  sum.y = 0 ; sum.pot = 0 ; sum.payoff = 0
  for (i in 1:rounds) {
    y = 0 ; pot = contribution ; payoff = -pot-(1-pot)*p # Start with pure cooperation
    T = -(1-pot)*p ; S = -contribution -(1-pot)*p # Unilateral payoffs with r = 0
    Si = S-r*T ; Ti = 0 ; Ri = -contribution-(1+r)*T # Convert to inclusive fitness payoffs
    if (y*(Si+p) >= (1-y)*(Ti-Ri) && Si+p > 0 && payoff > -p) { # If y = 0 pays best
      y.last = y ; pot.last = pot ; payoff.last = payoff
    }
    else { # If pure cooperation doesn't pay best, then start defection ...
      N.defectors = -1 ; ybest = FALSE
      while (!ybest && N.defectors < N) {
        y.last = y ; pot.last = pot ; payoff.last = payoff
        lim = 0.5 # Defection prob y varies up to lim players either side of y = N.defectors/N
        N.defectors = N.defectors+1 ; y = (N.defectors + runif(1,-lim,lim))/N
        y[y<0] = 0 ; y[y>1] = 1
        pot = (1-y)*contribution ; payoff = -pot-(1-pot)*p
        T = -(1-pot)*p ; S = -contribution-(1-pot)*p
        Si = S-r*T ; Ti = 0 ; Ri = -contribution-(1+r)*T
        if (y*(Si+p) >= (1-y)*(Ti-Ri) && Si+p > 0 && payoff > -p) {ybest = TRUE} else {
          if (i == 1) {
            result = paste(round(p,4), round(y,4), round(pot,4), round(payoff,4), sep = ",")
            write(result, file = outfile1, append = TRUE)
          }
        }
      }
      if (!ybest || y == 1) { # If nothing beats pure defection ...
        y = 1 ; pot = 0 ; payoff = -p
        y.last = y ; pot.last = pot ; payoff.last = payoff
      }
    }
    y = (y+y.last)/2 ; pot = (pot+pot.last)/2 ; payoff = (payoff+payoff.last)/2
    if (i == 1) {
      result = paste(round(p,4), round(y,4), round(pot,4), round(payoff,4), sep = ",")
      write(result, file = outfile1, append = TRUE)
    }
    sum.y = sum.y+y
    sum.pot = sum.pot+pot
    sum.payoff = sum.payoff+payoff
  }
```

```
  average.y = sum.y/rounds ; average.pot = sum.pot/rounds ; average.payoff = sum.payoff/rounds
  result = paste(round(p,4), round(contribution,4), round(expected.y,4),
                 round(expected.payoff,4), round(average.y,4),
                 round(average.pot,4), round(average.payoff,4), sep = ",")
  write(result, file = outfile2, append = TRUE)
  writeLines(result)
} ### end function ###
########################################################################################
### Increment premium, p, from 0 to 6C ###
##########################################
# Write header lines to output file for stepwise values
write("Incentives simulation output", file = outfile1, append = FALSE)
write(paste("Observed traces for ",N," players with ",
            fraction.of.optimum," x optimum contribution and r = ",r,sep=""),
      file = outfile1, append = TRUE)
write("",file = outfile1, append = TRUE)
write("premium, y observed, pot observed, payoff observed",
      file = outfile1, append = TRUE)
#
# Write header lines to output file for final values
write("Incentives simulation output", file = outfile2, append = FALSE)
write(paste("Observed averages of ",rounds," rounds for ",N," players with ",
            fraction.of.optimum," x optimum contribution and r = ",r,sep=""),
      file = outfile2, append = TRUE)
write("",file = outfile2, append = TRUE)
result.header = paste("premium, contribution, y expected, payoff expected, y observed,",
                    " pot observed, payoff observed", sep="")
write(result.header, file = outfile2, append = TRUE) ; writeLines(result.header)
#
# Get defector fraction and average payoff for p from 0 through to 6 in 0.1 increments
#
# 0 <= premium <= 1
for (p in seq(0,1,0.1)) {
  contribution = 0
  expected.y = 1 ; expected.payoff = -p
  y.star()
}
# 1 <= premium <= (2+r)/(1+r)
for (p in seq(1,round((2+r)/(1+r)-0.05,1),0.1)) {
  contribution = fraction.of.optimum*(1+r)*p/(1+(1+r)*p)
  expected.y = 0
  expected.payoff = -((1-expected.y)*contribution + (1-(1-expected.y)*contribution)*p)
  y.star()
}
# (2+r)/(1+r) < premium <= 4
for (p in seq(round((2+r)/(1+r)-0.05,1)+0.1,4,0.1)) {
  a = sqrt((p*r^2+p*r+1)*(1-r)^2) ; b = sqrt((p*r^2+p*r+1)*p^2)
  contribution = fraction.of.optimum*(3*r+1+a)*p/(2*p*r-p*r^2-p+8)
  potmax = (4*(p*r-p*r^2+2)*p+(1-r)*p^2*a+(2*p*r-p*r^2-p+8)*b)/(4*(2*p*r-p*r^2-p+8)*p)
  expected.y = (contribution-(1+r)*(1-potmax)*p)/((2*potmax-1)*p)
  expected.payoff = -((1-expected.y)*contribution + (1-(1-expected.y)*contribution)*p)
  y.star()
}
# 4 < premium <= 6
for (p in seq(4.1,6,0.1)) {
  contribution = fraction.of.optimum*0.5*p*(1-sqrt(1-4/p))
  expected.y = 0.5*(1-sqrt(1-4/p))
  expected.payoff = -1
  y.star()
}
########################################################################################
```