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Using Adaptation Insurance to Incentivize Climate-change Mitigation

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Doncaster, C.P., Tavoni, A., Dyke, J.G. (2017). Using Adaptation Insurance to Incentivize Climate-change Mitigation. *ECOLOGICAL ECONOMICS*, 135, 246-258 [10.1016/j.ecolecon.2017.01.019].

Availability:

This version is available at: <https://hdl.handle.net/11585/657540> since: 2022-02-28

Published:

DOI: <http://doi.org/10.1016/j.ecolecon.2017.01.019>

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1 Original Research Article: Analysis

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3 **Using adaptation insurance to incentivize climate-change mitigation**

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14 *Running header:* Incentivizing cooperation

15

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18

19 *Abstract*

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

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

41 **1. Introduction**

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

56 Game theory has become an influential tool for conceptualizing the difficulty of
57 motivating cooperative action on climate change (Tavoni, 2013). Previous applications have
58 found that successful achievement of a mitigation target requires coordinated responses.
59 These may take the form of altruism (Milinski et al., 2006), or locally interacting groups
60 (Santos and Pacheco, 2011; Shirado et al., 2013), or bottom-up locally operating sanctions
61 (Vasconcelos et al., 2013), or low costs relative to benefits and coordinated pledges where
62 there is uncertainty on impacts (Barrett and Dannenberg, 2012, 2014). Here we demonstrate
63 for the first time that coordination is not a necessary prerequisite for mitigation against
64 dangerous climate change by self-interested individuals, organizations, or nations. We apply
65 game-theoretic principles to a public-goods model of homogeneous interactions amongst

66 cooperators and defectors. We develop a novel mechanism for incentivizing cooperative
67 mitigation that sets its cost against the counterfactual of a large personal cost in adaptation to
68 climate change. The need for adaptation can incentivize mitigation efforts because the costs of
69 adaptation depend on mitigation level (Ingham et al., 2013). We use insurance as a
70 mechanism to bring into the present a future debt burden of natural hazards caused by climate
71 change, in order to incentivize mitigation to reduce climate-change drivers. In the context of
72 public-goods games, an option for players to purchase insurance against the costs of defection
73 can undermine cooperation (Zhang et al., 2013). Our climate-change scenario uses non-
74 optional insurance, however, with the premium itself functioning as the cost of defection,
75 against which players evaluate the utility of cooperation.

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

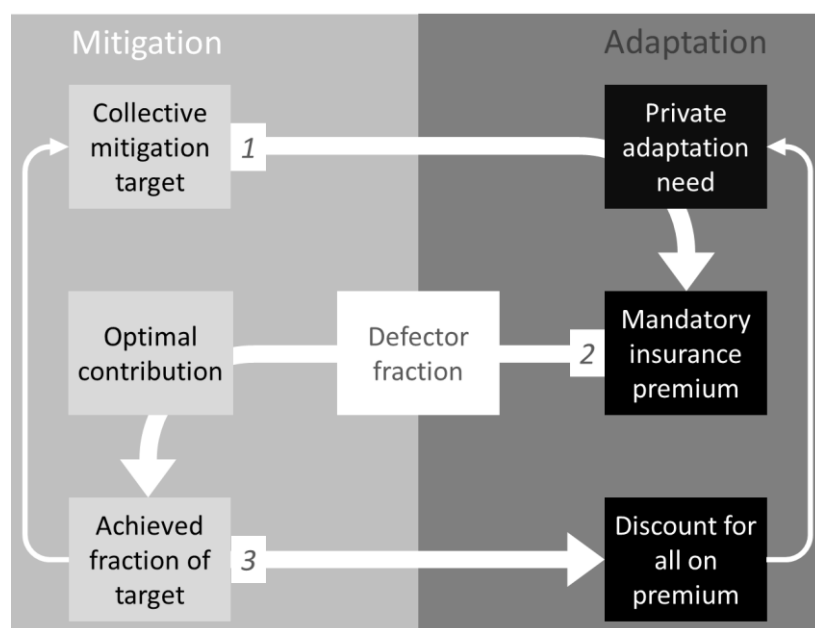
91 yet its policy implication is that willingness to fund public mitigation for emissions reductions
92 can be traded against private costs of adaptation to climate-change impacts.

93 We define the conditions by which a mandatory adaptation insurance will incentivize
94 purely self-interested actors to achieve the proposed mitigation target from voluntary
95 contributions, without additional coordinating mechanisms. We start with the simplest model
96 of independent players with equal ability to pay an insurance premium that is the same for all
97 players. Real-world premiums are likely to vary, however, with geographic variation in risk,
98 and abilities to pay the voluntary contribution will vary with wealth inequality (Tavoni et al.,
99 2011; Burton-Chellew et al., 2013). We therefore consider options for accommodating
100 potentially large regional differences in players vulnerabilities to climate change. We further
101 extend the model to include players with unequal abilities to pay for mitigation or adaptation.
102 We apply the model to players at the scale of households in a nation, and to players at the
103 scale of nations in an international consortium. We discuss ways to adapt existing scenarios
104 for multinational aggregation that would lead to the effective management of a global
105 commons. We consider ways to minimize the political difficulty of approving up-front costs
106 for future benefits.

107 **2. Framework**

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

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



126
 127 **Fig. 1.** Mechanism for linking adaptation insurance against climate-related natural hazards to
 128 publically-funded mitigation for reducing climate-change drivers. (1) A collective mitigation
 129 target defines private adaptation need in the absence of mitigation, which determines the
 130 insurance premium. (2) The premium sets an optimal contribution for the mitigation target
 131 and associated defector fraction, which together determine the size of collective pot as a
 132 fraction of target. (3) This fraction determines the discount for all on the insurance premium,
 133 and informs updating of the mitigation target and adaptation need.

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

148 The framework depends on the insurance industry having adequate tools to build risk and
149 uncertainty into the costs of adaptation, and mitigation effectively reducing this cost by
150 reducing long-term risk. Catastrophe modelling technology is now used extensively by
151 insurers, reinsurers, and governments to calculate fair pricing, and it is considered essential to
152 understanding the natural world (Toumi and Restell, 2014). Here we focus on mitigation to
153 decrease climate-change drivers, such as conversion to renewable energy for emissions
154 reduction, although in principle the framework can apply also to adaptation for building
155 resilience such as flood protection. In the Discussion we consider existing tools for costing
156 adaptation. Prospects of tipping points to bifurcations in the climate-Earth system, leading to
157 raised frequencies and magnitudes of natural catastrophes (Lenton et al., 2008), may render
158 insurance prohibitively expensive without mitigation or other risk-reduction measures (Mills,

159 2005; Toumi and Restell, 2014). We accommodate this possibility by allowing for fairly-
160 priced premiums up to a putative infinite cost, prior to discounting by the value of any
161 investment in cooperative mitigation.

162 **3. Model**

163 *3.1. General model*

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

175 Cooperators pay the voluntary contribution, plus the premium discounted by the achieved
176 fraction of target; defectors pay only the premium discounted by the achieved fraction of
177 target. Self-interested players cooperate with a probability defined by their payoffs for
178 unilateral interactions: Temptation, T (free-ride on others’ contributions) and Sucker, S
179 (contribute when others do not), relative to mutual interactions: Reward, R (everyone
180 contributes) and Penalty, P (nobody contributes). The Table-1 payoff matrix summarizes the
181 problem at hand: a target for voluntary mitigation, combined with a mandatory insurance cost

182 that declines with achieved fraction of target, creates a two-strategy game for n players that
 183 either cooperate with, or defect from, contributions to the mitigation target.

184 **Table 1**

185 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	$T = -(1 - pot) \cdot premium$	$P = -premium$

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

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

198 3.2. Wealth equality

199 Here we develop the theory of two-strategy games that identifies the optimal contribution to
 200 achieve or approach a given target for collective mitigation, at a given premium for personal
 201 adaptation insurance. We assume unordered and uncoordinated (homogeneous) interactions
 202 amongst independent players. The homogeneity implies equal wealth in the sense of players

203 not differing in their abilities to pay the mandatory premium or voluntary contribution. We
204 will expand the model to address unequal wealth in the next section.

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

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

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

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

226 Alternatively, If $P \geq S$, then S is a cost of strongly altruistic cooperation that is a stable
 227 strategy only if cooperators interact preferentially amongst like types (enumerated in section 0
 228 below). It presents a social dilemma when the payoffs for defection exceed those for
 229 cooperation ($P > S$ and/or $T > R$) whilst collective welfare pays better than individual welfare
 230 ($2R > T + S$, Macy and Flache, 2002).

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

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

233 with a stable mixed strategy, $1 > y^* > 0$, if $\textit{pot} > \textit{contribution}/\textit{premium} > 1 - \textit{pot}$. Pure
 234 defection results from failing the left-hand condition only, pure cooperation from failing the
 235 right-hand condition only, and bi-stability from failing both conditions. Note that any
 236 $\textit{contribution} \leq \textit{premium}$ has a bi-stable outcome at $\textit{pot} = 0$, which means it repels the defector
 237 fraction y away from equilibrium y^* towards a pure strategy. Thus in the particular case of
 238 such a game starting at $y = 1$, its initial state of pure defection resists invasion by cooperation
 239 and the *pot* stays empty. If it starts at $y < 1$, however, the presence of cooperation ensures \textit{pot}
 240 > 0 , potentially allowing escape from pure defection. The following analyses assume a start at
 241 $y = 0$ in order to prevent initial strategies from dictating the game outcome. Section 3.4 below
 242 simulates an example of a mechanism for ensuring it.

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

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

246 The contribution that maximizes \textit{pot}^* is obtained by substitution of equation (2) into (3)
 247 to set \textit{pot}^* as a function of *premium* and *contribution*, and solving for the contribution at

248 maximal pot^* (henceforth ' pot^*_{max} '), when the differential $d pot^* / d contribution = 0$. Target
249 success is only achievable in principle if $contribution \geq 1C$, since pure cooperation requires at
250 least this size of contribution to achieve it. The target is then achieved if also $pot^*_{max} \geq 1$. We
251 are now equipped with the necessary tools to assess whether the proposed insurance scheme is
252 feasible.

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

255 We use equations (2) and (3) to assess under which conditions Proposition 1 holds. The
256 optimal contribution for achieving closest to target (including target success itself) is the
257 contribution at pot^*_{max} , for values of $pot^*_{max} < 1$, and otherwise at $pot^* = 1$. Solutions to
258 simultaneous equations (2) and (3) at pot^*_{max} yield the optimal contribution and y^* as
259 functions of premium (Table 2, derivations in Appendix A). The functions depend on whether
260 stable equilibrium defection is pure ($y^* = 0$ or 1) or mixed ($0 < y^* < 1$), and whether this
261 equilibrium achieves target success ($pot^*_{max} \geq 1$ at $contribution \geq 1C$). For example, only
262 $premiums \geq 4C$ satisfy the conditions for target success (equation A7); the optimal
263 contribution is then obtained by substituting equation (2) into (3) and solving for contribution
264 at $pot^* = 1$. This function expresses minor and major contributions $\geq 1C$ that both achieve the
265 target, associated with minor and major mixed-equilibrium defection (bottom rows of Table
266 2).

267 **Table 2**

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

<i>Premium (C)</i>	<i>Optimal contribution (C)</i>	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	$premium \cdot (1 \pm \sqrt{1 - 4/premium})/2$	$(1 \pm \sqrt{1 - 4/premium})/2$

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

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

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

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

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

280 **3.3. Wealth inequality**

281 The personal payoff from helping another with shared characteristics has both direct and
 282 indirect components, which are aggregated by ‘inclusive fitness’ (Hamilton, 1964). In terms
 283 of collective mitigation, a player gains indirect benefit when some of the benefit to others
 284 from its own contribution to emissions reduction feeds back to itself. Such feedbacks arise

285 wherever players have a vested interest in each other's wealth, for example within a
 286 population of individuals that funds public services through taxes, or within a set of nation
 287 states that share trade agreements or subsidies. In the case of a population with unequally
 288 distributed wealth, indirect benefits are obtained in emissions reduction for players that
 289 subsidise those with lower ability to pay premiums. Here we enumerate wealth inequality
 290 amongst players as the assortment of interactions in the form of interests in each other's
 291 wealth that resolves differences in their capacity for cooperation.

292 In the two-strategy game, direct payoffs with $P \geq S$ have a Prisoner's Dilemma outcome
 293 that resists invasion by the cooperative strategy under homogeneous interactions. They may
 294 yet have inclusive payoffs $S^i > P^i$, however, that allow equilibrium cooperation. The threshold
 295 at which inclusive payoffs escape the Prisoner's Dilemma is set by Hamilton's rule
 296 (Hamilton, 1964): $-cost + r \cdot benefit > 0$, where *cost* is the net direct costs to the donor of
 297 cooperation, *benefit* is the direct benefit to the recipient of the donor's cooperation, and *r* is a
 298 'relatedness' coefficient that enumerates assortment of interactions with a value between 0
 299 and 1. In effect, cooperation persists if the cost of benefitting another is outweighed by the
 300 benefit returned through shared interests. Expressed in terms of the negative Table-1 payoffs
 301 for interactions between strategies, a cooperator obtains net payoff $S - P$ from benefitting
 302 another, and the beneficiary receives payoff $T = S - R$ from the interaction. This means that P
 303 $- S$ defines *cost*, and $-T$ defines the cost-cancelling *benefit* of which fraction *r* returns to the
 304 cooperator through interactions with like types. Hamilton's rule is then:

$$-(P - S) - r \cdot T > 0. \quad (5)$$

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

308 Application of Hamilton's rule to a two-strategy game allows enumeration of the effect
 309 of coordinated interactions on equilibrium defection. A value of $r > 0$, indicating positive
 310 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
 311 Doncaster et al., 2013b). By elaboration of equation (1), equilibrium defection in the presence
 312 of assortment:

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

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

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

315 with a stable mixed strategy, $1 > y^* > 0$, if $1 - (1 - r) \cdot (1 - \text{pot}) > \text{contribution}/\text{premium} > (1 +$
 316 $r) \cdot (1 - \text{pot})$. Pure defection results from failing the left-hand condition only, pure cooperation
 317 from failing the right-hand condition only, and bi-stability from failing both conditions.
 318 Equation (7) shows larger values of r decreasing defection at given values of *premium*,
 319 *contribution*, and $\text{pot} < 1$, but r ceasing to have an effect upon achieving the target ($\text{pot} = 1$).
 320 The optimal contribution for achieving closest to target, and the associated y^* , are derived in
 321 Appendix A as the general case of Table 2 extended to $r \geq 0$.

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

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

327 We illustrate the properties of r by considering an application of the two-strategy game to
 328 nation states as players, starting with a simplified scenario of a group of nation-players that

329 are equally wealthy in terms of their ability to pay a premium. Suppose they owe 20% of this
330 wealth on average to trade agreements between them. They might each owe 20%, or one
331 nothing and another 40%, and so on. The nations take relatedness coefficient $r = 0.2$. Its value
332 has quantifiable impacts on the optimal contribution for the collective mitigation target and
333 equilibrium defection, and consequently on the achieved fraction of target and average payoff
334 per player. These impacts are enumerated by equations (3) and (4), given (7) (Appendix A).

335 In an alternative scenario, the group of nations may have no trade agreements but
336 unequal wealth in terms of ability to pay the premium. For the purposes of the Table-1
337 framework, the value of r is the average proportionate redistribution of wealth amongst them
338 that resolves this discrepancy. For example, $r = 0.2$ when the discrepancy is resolved by a
339 20% redistribution of wealth available for paying the premium. Thus, $r = 0.2$ when all nations
340 have equal ability to pay after one has subsidised four others each to the value of 25% of the
341 premium; equally $r = 0.2$ when equality is obtained by four nations each subsidizing a fifth
342 nation to the value of 25% of the premium. We assume that subsidies are paid through an
343 intermediary such as the World Bank, to prevent donors from taking ownership of recipients'
344 choices in paying the contribution. A fully subsidized recipient stands to benefit from paying
345 the contribution just as any other player, by holding on to all of the unspent premium in the
346 event of target success, or otherwise fraction pot^* of it.

347 Combining the trade-agreement and subsidy scenarios, a group of nations may be
348 connected by trade agreements, and by subsidies that resolve outstanding wealth inequalities.
349 In the Table-1 framework of collective mitigation leveraged from discounts on premiums,
350 their average relatedness is aggregated from the two sources of co-dependence. For example,
351 $r = 0.4$ if nations owe 20% of their wealth on average to others, in terms of ability to pay the
352 premium, and additionally one nation subsidises four others to the value of 25% of the
353 premium.

354 3.4. Agent-based simulation

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

367 Each simulation trial had n players, each set the same size of *premium* and voluntary
368 *contribution*. The trial started with a population of pure cooperators and incrementally
369 switched players to defectors for as long as it paid players to make the switch. As the
370 observed defector fraction, y_{obs} , rose in the population, it lowered the fractional size of
371 collective pot, $pot_{\text{obs}} = (1 - y_{\text{obs}}) \cdot \text{contribution}$, which in turn devalued unilateral payoffs T and
372 S . Cooperators defected at an average rate of 1.0 defection per increment (s.d. = 0.29), until
373 cooperation obtained a positive benefit per capita of not switching to defection, $(S^i - P^i)/(1 -$
374 $y)$, as large or larger than the benefit per capita of defection not switching back to cooperation,
375 $(T^i - R^i)/y$. The resulting y^*_{obs} set the year-end fraction of target, pot^*_{obs} , which determined the
376 final invoice, measured as an average *payoff* per capita: $-[pot^*_{\text{obs}} + (1 - pot^*_{\text{obs}}) \cdot \text{premium}]$.
377 Appendix B shows examples of within-year trajectories towards y^*_{obs} and pot^*_{obs} .

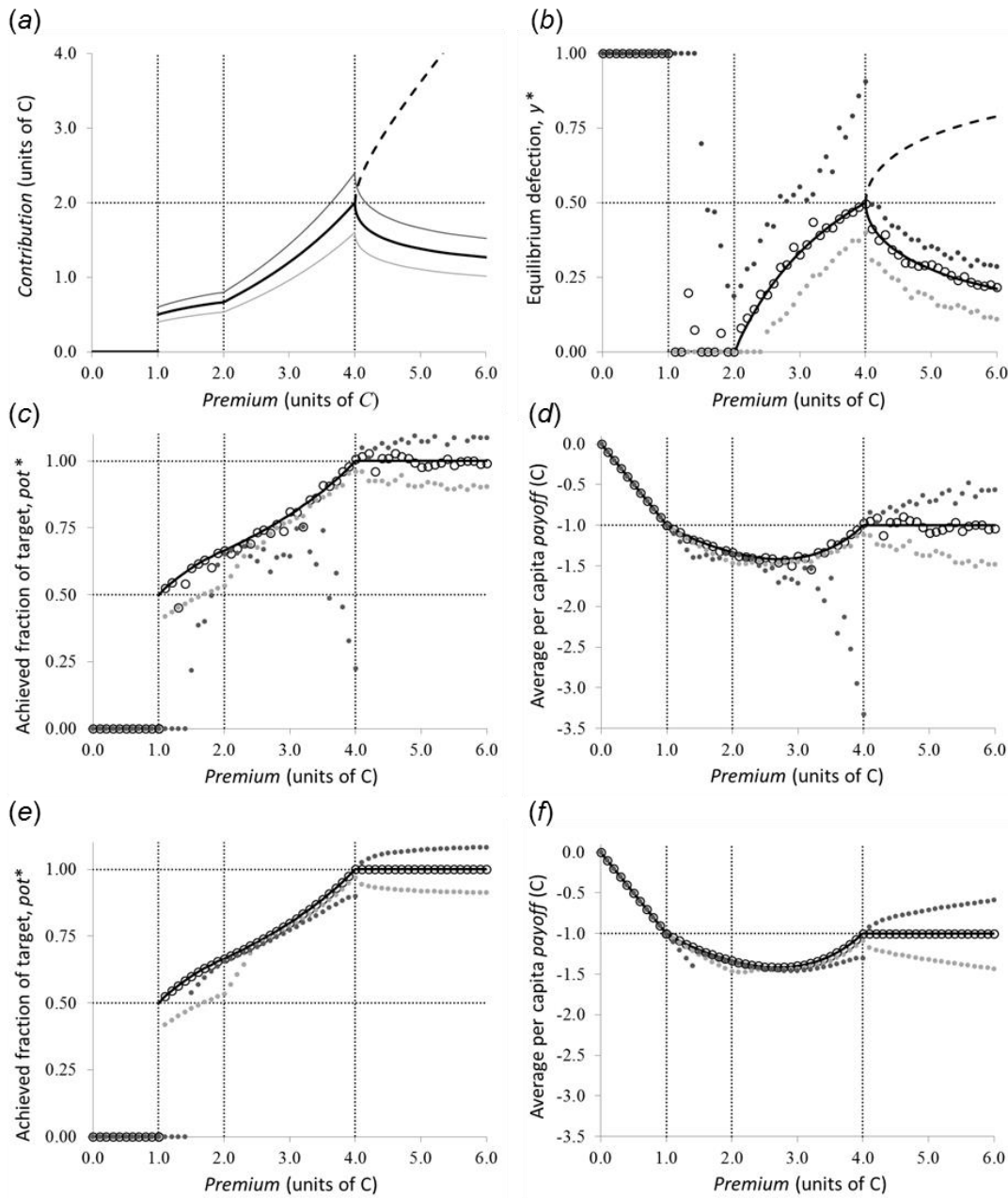
378 The simulation reported values of y^*_{obs} , pot^*_{obs} and $payoff$ averaged over 50 replicated
379 trials, at values of $premium$ from 0 to $6C$ in 0.1 steps. Simulations were run for small
380 populations ($n = 5$), indicative of players at the global scale of nation states, and for large
381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

383 4. Results

384 4.1. Well-mixed populations of independent players

385 The principal finding is that successful achievement of the collective target for mitigation
386 requires a premium for adaptation insurance worth at least four times the value of the target
387 per capita (i.e., $\geq 4C$, Fig. 2a-d). This validates Proposition 1. Premiums $< 4C$ result in an
388 average payoff as much as 42% worse than the payoff for achieving the target (Fig. 2d line).
389 For premiums up to $1C$ (worth £49.24 in the example application), everyone defects (Fig. 2b)
390 because the achievable fraction of target is too small for any resulting discount on the
391 premium to compensate for paying a contribution even if everyone contributed to the
392 collective pot. Premiums $\geq 1C$ initiate cooperation because the average payoff is then better
393 than the $-premium$ that obtains with pure defection. For premiums between $1C$ and $2C$
394 (£49.24-£98.48), the payoff for everyone cooperating with an optimal contribution cannot be
395 bettered by defection (shifting the game from Prisoner's Dilemma to Harmony). Full
396 cooperation fails to achieve the target at these low premiums, and average payoff falls below
397 $-1C$ (Fig. 2c-d lines). Higher premiums up to $4C$ (£196.97) sustain increasing amounts of
398 defection from paying the optimal contribution (shifting the game from Harmony to
399 Snowdrift). Defection rises from zero to half the population of players (Fig. 2b line), as pot^*
400 rises to achieve the target at a premium of $4C$ (Fig. 2c line) and an average payoff of $-1C$
401 (Fig. 2d line). This lowest target-achieving premium is also predicted directly from

402 substitution of equation (2) into (3) at $pot^* = 1$, to obtain: $premium_{x=1} = 1/\left[y^*(1-y^*)\right]$ with a
 403 single minimum of $4C$, at $y^* = 0.5$.



404
 405 **Fig. 2.** Model predictions for uncoordinated interactions amongst independent players.
 406 Functions of premium predicted from Table 2 and equations (3)-(4) (lines), and observed by
 407 simulation (dots). (a) Optimal contribution for achieving closest to target (thick black line,
 408 dashed for major target-achieving contribution), and 20% above/below optimum (dark/light
 409 grey lines). (b)-(d) Equilibria for simulated populations of $n = 5$ at the optimal contribution

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

412 A discontinuity occurs at the premium of $4C$ (Fig. 2a-b lines). For higher values, target
413 success is achieved either by high cooperation with a minor contribution or by low
414 cooperation with a major contribution. The minor optimal contribution declines rapidly from
415 $2C$ towards convergence with $1 + 1/\text{premium}$, while the associated defection declines towards
416 convergence with $1/\text{premium}$ (Fig. 2a-b continuous lines). The alternative major optimal
417 contribution rises towards convergence with $\text{premium} - 1$, while the major defection
418 probability rises towards convergence with $1 - 1/\text{premium}$ (Fig. 2a-b dashed lines). We focus
419 on the minor contribution and defection as best suited to a government-driven initiative,
420 whilst noting that the major contribution and defection may provide an alternative route to
421 success given rising intra- and international disparities in wealth.

422 For any premium of at least $4C$, target success with both minor and major optimal
423 contributions (Fig. 2c line) sets average payoff at a constant $-1C$ (Fig. 2d line). Although
424 cooperators obtain a worse payoff than defectors because only they pay the contribution (a
425 cost of unavoidable parasitism), this deficit diminishes for the minor contribution at larger
426 premiums as the higher cooperation sustains ever smaller contributions. Premiums less than
427 $4C$ obtain target shortfall from the optimal contribution, which worsens the average payoff for
428 premiums down to $1C$. With premiums below $1C$ attracting no cooperation with
429 contributions, they obtain payoff $P = -\text{premium}$. These predictions demonstrate the
430 strengthening motivation for achieving the mitigation target with higher premiums above $4C$.
431 For premiums below $4C$, they demonstrate the cost to the collective pot and average payoff
432 from undervaluing the premium for a given target, or overestimating the achievable target for
433 a given premium.

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

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

454 *4.2. Players with unequal vulnerabilities or benefits*

455 The findings for the size of contribution in Fig. 2 assume that all players face the same
456 vulnerability to natural hazards covered by the insurance, and will benefit equally from
457 actions funded by the collective pot. To accommodate the reality of heterogeneity in the
458 geographic spread of risk and benefit requires matching any regional variation in market price

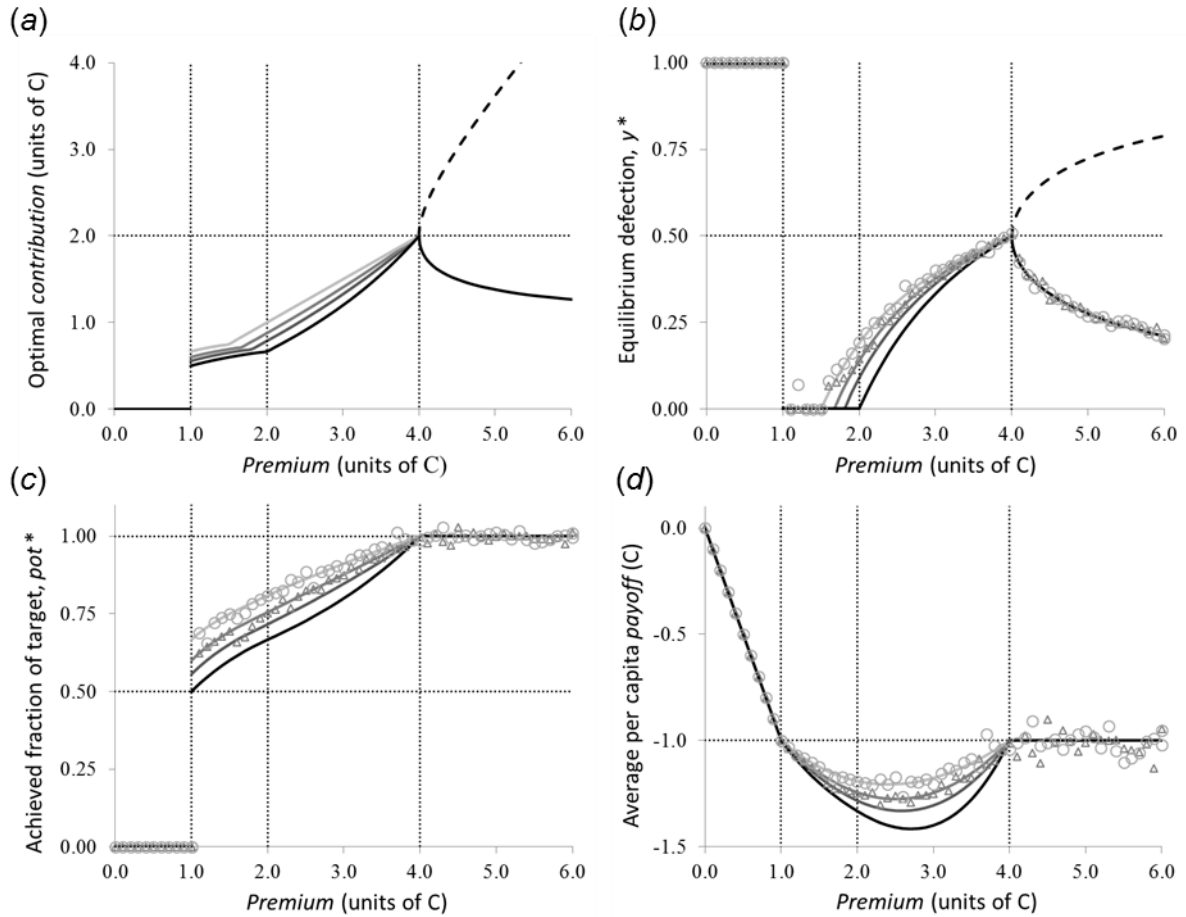
459 for the premium with variation in either the optimal contribution or the distribution of action
460 funded by the collective pot, or both. In effect, having created an insurance market, its
461 regional variability can set the scale at which to determine the optimal contribution from the
462 predicted defector fraction. The analytical method is the same, whether applied once to a
463 nation of citizens or repeatedly to independent regional or local populations.

464 *4.3. Players with wealth inequalities*

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

476 Any positive effects of r on pot^* and average payoff apply regardless of the source of
477 interdependence through interests in each other's wealth. Where the interdependence arises
478 from wealth inequalities, we have assumed that subsidies resolve differences in ability to pay
479 the premium and willingness to pay the contribution. Given that condition, our general
480 inference is that wealth inequalities make no difference for premiums $\geq 4C$, while for lower
481 premiums they increase the power to leverage mitigation by discounting the premium.
482 Residual differences in ability to pay the premium that are not resolved by subsidies,
483 however, may lead to poorer players defaulting on payments of both contribution and

484 premium. Their participation ceases in that event, which reduces the size of n and therefore
 485 raises the value of C , assuming an unchanged mitigation target. The overall consequence for
 486 all remaining participants is that the minimum target-achieving premium of $4C$ will cost more
 487 in the local currency, as will the optimal contribution and the average payoff.



488

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

494 5. Discussion

495 The analysis shows how mitigation that reduces the premium on mandatory insurance can be
 496 funded through voluntary contributions. Specifically, it illustrates three intuitive findings. A

497 premium at least four times larger than the per capita mitigation target provides sufficient
498 motivation for payoff maximizing players to achieve the target even without coordinating
499 mechanisms (Proposition 1). Moreover, smaller premiums underachieve relative to the target,
500 with a worse average payoff per capita (Proposition 2), although the target fraction is raised
501 and average payoff improved by subsidies between players that resolve wealth inequalities
502 (Proposition 3). This final result is an example of wealth inequalities raising efficiency in the
503 management of a public good (Baland and Platteau, 1997).

504 *5.1. Mandatory adaptation incentivizes voluntary mitigation*

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

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

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

543 Uncertainty about when climate change will tip into a catastrophe, or what target will
544 prevent it, may fatally delay cooperative action (Barrett and Dannenberg, 2014; Dannenberg
545 et al., 2015). Our use of collective mitigation to discount the insurance premium directly
546 addresses this uncertainty, because the size of the premium determines the maximum

547 achievable target (e.g., premiums $< 4C$ cannot achieve target at equilibrium defection: Figs 2-
548 3). With a commercially set premium, adaptation insurance offers a free market for informed
549 personal decisions on the collective mitigation that yields premium discounts. Any
550 uncertainty about the sufficiency of the mitigation target provides a market incentive to
551 reduce the rate of discounting the future (Wagner and Weitzman, 2015), and thereby to raise
552 the premium. This in turn raises the commitment to cooperative action that generates
553 discounts (Fig. 2b; cf. Lewandowsky et al., 2014). We have assumed that mitigation reduces
554 adaptation costs linearly; model refinements could accommodate non-linear discounting to
555 cover residual costs beyond the scope of mitigation. Further extensions of the model could
556 partition out self-insurance (to reduce costs) and self-protection (to reduce risk) from the
557 market-led mandatory insurance (Ehrlich and Becker, 1972), or could model insurance as a
558 public good (Lohse et al., 2012).

559 *5.2. Implications for UK policy*

560 The UK government originally planned for a mandatory annual contribution that would add
561 about £50 to the average household energy bill (DECC, 2013). Achieving the £1.3bn annual
562 target for funding green-energy solutions would therefore allow no more than 2% defection
563 amongst the 26.4 million UK households. Such a small defection probability is an equilibrium
564 outcome given the Table-1 payoffs, and therefore freely chosen, only for an insurance
565 premium valued at £3,300 per household. To date the British public has not been presented
566 with options for anticipating the personal debt burden that will ensue from failing to take any
567 cooperative action, or a mechanism for managing it. In the concurrent political context of
568 large increases in the base rate of energy, this absence of information may have contributed to
569 the public pressure that forced government into announcing plans in December 2013 to
570 reform the contribution (DECC, 2013). Despite the coercion by government that made the
571 contribution obligatory, the policy was defeated within a year. Yet we have seen that

572 voluntary contributions can raise any collective target without altruism, pledges, cliques, local
573 policing, or other heterogeneous interactions associated with a social dilemma.

574 Given the inevitability of climate change impacts becoming more pronounced in the
575 future (IPCC, 2013), our analysis shows the importance of covering for the likely costs of
576 adaptation, as a motivation for cooperative mitigation. Stern (2007, citing Barker et al., 2006)
577 suggests that stabilizing the CO₂ emissions trajectory at 500-550 ppm might incur costs for
578 2050 in the order of 1% of GDP. With UK GDP currently worth £1,499bn (2012 value: The
579 World Bank, 2013), a national cost of rectifying greenhouse emissions that is worth 1% of
580 this amount resolves down to £568 per household. If the £1.3bn annual target for green-
581 energy mitigation stabilizes CO₂ emissions (assuming a strong relationship between national
582 and global emissions), an insurance premium of £568 (11.53C) is predicted by equations (2)
583 and (3) to attract 90% cooperation with a target-achieving contribution of £54.47 (1.11C). The
584 year-end insurance invoice equals the magnitude of the *T* payoff of Table 1, which in this case
585 would be zero based on the contribution having achieved the target. Paying the contribution
586 would therefore result in a >10-fold saving in personal outlay.

587 *5.3. Cooperation at national and global scales*

588 Market-led insurance as a method of costing alternatives to mitigation is reviewed in the
589 IPCC Fifth Assessment Report, which emphasizes the need for government oversight (IPCC,
590 2014b). Three-quarters of the global insurance industry has engagement with climate-change
591 adaptation through investments totalling some US\$25 billion (Mills, 2012). The Munich
592 Climate Insurance Initiative exists to develop insurance-related management of climate-
593 change impacts, in partnership with the UNEP Finance Initiative. All such schemes present
594 challenging opportunities for developing interactions between government measures aimed at
595 risk reduction and insurance companies' willingness to provide cover (IPCC, 2014b). Our
596 analysis has demonstrated the potential, in principle, for using insurance to incentivize

597 mitigation of risk. New Zealand's Earthquake Commission (EQC) is a government-regulated
598 insurance scheme for natural disasters including storms, floods, and tsunamis, which is an
599 obligatory component of insurance bought by all owners of residential dwellings and contents
600 in New Zealand. Although the EQC pays owners the value of damaged land or repair costs
601 following a natural disaster, the premium is not linked to mitigation or pre-emptive adaptation
602 such as we propose here, which has been considered as a lost opportunity for risk reduction
603 (Glavovic et al., 2010). The French CatNat system of insurance against flood damage includes
604 deductibles from compensation linked to non-compliance with risk-prevention plans, but they
605 are not adjusted to risk and are set too low to incentivize mitigation of risk (Poussin et al.,
606 2013). A survey has found that Dutch homeowners were willing in principle to invest in
607 measures that mitigate flood damage in exchange for benefits on flood insurance policies
608 (Botzen et al., 2009). Such opportunities remain under-developed for natural hazards
609 associated with climate change (IPCC, 2014b).

610 Our model of state-enforced insurance demonstrates a potential for aggregation that
611 could lead to effective management of a global commons such as greenhouse gas emissions.
612 Despite all states contributing to global emissions of greenhouse gases, coercion is not
613 currently an option for improving cooperation amongst nation states in the absence of global
614 governance. On the international stage, governments could seek to apply the same strategy of
615 premium discounts to a multinational insurance partnership to achieve international
616 mitigation. The Caribbean Catastrophe Risk Insurance Facility (2007) is the only such
617 multinational pool so far to insure against sovereign risks of climate change and other national
618 catastrophes (Grove, 2012). This not-for-profit company is a public-private partnership owned
619 by a trust and governed by trust deed. It currently holds policies for 16 Caribbean countries,
620 which benefit in low premiums from pooling a wide basin of climatic uncertainties. It
621 therefore represents an organically seeded form of international governance. Similar schemes

622 are currently under consideration for Europe, Africa, and the Pacific (IPCC, 2014a). They use
623 ‘parametric’ insurance, which pays a predetermined remuneration when parameters are met
624 such as thresholds of hurricane category or average temperature. Reinsurance mechanisms
625 cover rare events that would otherwise leave obligations outstripping capital reserves. Instead
626 of responding to pre-established threats, parametric insurance with reinsurance prepares for
627 future-possible threats independently of their probability (Grove, 2012). This makes it
628 particularly well suited to funding climate-change mitigation through securitized premium
629 discounts, because effective mitigation will reduce the frequency of threshold crossings. The
630 current absence of any such link to mitigation again represents a missed opportunity.

631 **6. Conclusions**

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

645 **Acknowledgements**

646 We thank Alison Denham, Stuart Kininmonth, Emma Tompkins, and Richard Watson for
647 discussions. We gratefully acknowledge the numerous constructive suggestions of three
648 anonymous reviewers. Tavoni is supported by the Centre for Climate Change Economics and
649 Policy, which is funded by the UK Economic and Social Research Council (ESRC).

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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):

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

Rearrange in terms of pot^* :

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

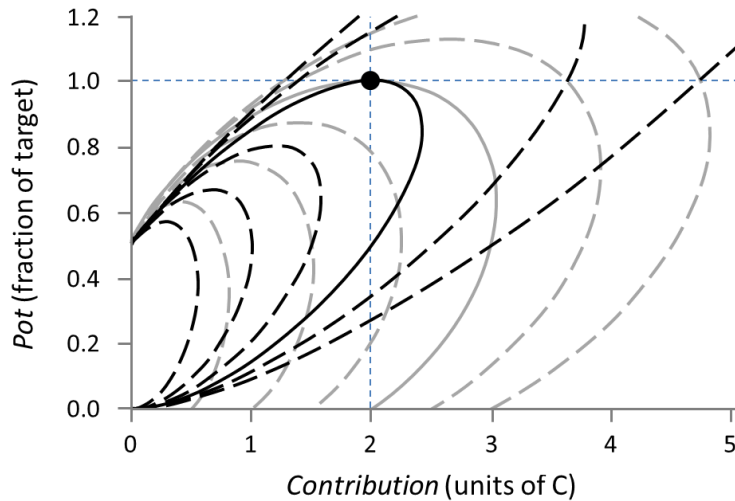


Fig. A1. Pot^* at y^* as a function of *contribution* (equation (A2)), at *premium* = 1C, 2C, ..., 6C from smallest to largest ellipse for each of $r = 0$ (black) and 0.5 (grey). Black dot at the intersection of the blue marker lines shows the *contribution* at the maximum pot for *premium* = 4 (equation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

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

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

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

This gives the optimal contribution in row 3 of main-text Table 2 with $0 \leq r \leq 1$, for $(2+r)/(1+r) \leq p < 4$. 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):

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

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

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

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

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

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

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

Figure A1 shows $p = 4C$ being the lowest premium to achieve target success ($pot^*_{\max} = 1$), with $c = 2C$ (black dot), in accordance with equations (A4) to (A7) above. At $r = 0$, however, note that $c = 2C$ 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 :

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

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

$$y^*[pot^* = 1] = \frac{1 \pm \sqrt{1 - 4/p}}{2}. \quad (A9)$$

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 :

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

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):

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

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

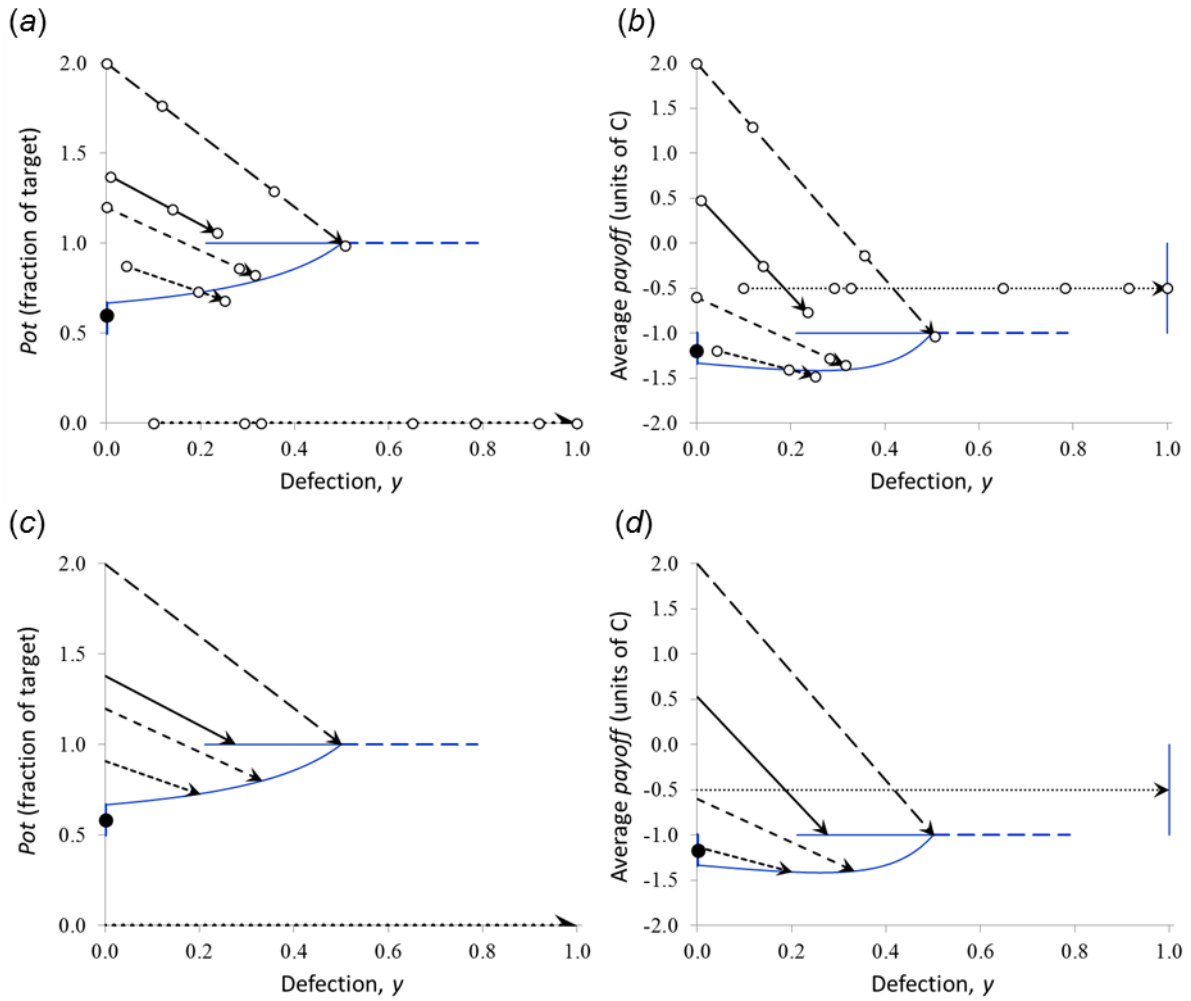


Fig. B1. Examples of within-year trajectories (arrowed) towards year-end *pot* and *payoff* (at arrow head). Simulation runs started with pure cooperation, $y = 0$, and ended in the vicinity of equilibria predicted by main-text equations (2) to (4) (blue lines). Each graph shows one run at each of $premium = 5$ (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 $premium \geq 1C$, 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()
}
#####

```