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Game theory and corporate governance: conditions for effective stewardship of companies exposed to climate change risks[†]

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ABSTRACT
Engagement between investors and corporate boards has been suggested as a pathway to mitigate stranded asset and climate change risks. Debate is ongoing as to whether divestment or active ownership strategies are more appropriate to deliver long-term value and environmental sustainability. The paper tests the effectiveness of owner engagement strategies by studying the conditions for cooperation between investors and their companies. Characteristics of investors and companies are modelled in game theoretic frameworks, informed by semi-structured interviews with professionals from the energy and finance industries, and academia, NGO, and regulatory sectors. Conditions for mutual cooperation between investors and companies are characterized as prisoners' dilemmas. A number of parameters are examined for their impact on the development of sustained cooperative equilibria, including: the benefits and costs of cooperation; the degree of strategic foresight; individual discount factors; and mutual history. Challenges in the formation of investor coalitions are characterized and solutions are proposed.

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1. Introduction

Climate change is rapidly becoming a material investment risk. Recent work by the Carbon Tracker Initiative (CTI) (e.g. 2013, 2014), McGlade and Ekins (2015), the University of Oxford Smith School of Enterprise and the Environment (e.g. Caldecott, Horwath, and McSharry 2013, 2015), HSBC (e.g. Spedding, Mehta, and Robins 2013), Standard & Poor's (2013, 2015), Kepler Cheuvreux (Lewis and Voisin 2014), and others has made stranded assets and misallocated capital a key concern of owners of fossil fuel companies. Universal owners are also gaining awareness of undiversifiable climate change value-at-risk (Covington and Thamotheram 2015; The Economist Intelligence Unit 2015). Investors must employ stewardship strategies to mitigate climate change risk on behalf of their beneficiaries. The Kay Review (2012) observes that investors have only two options in their relationships with companies: divestment and engagement. Shareholder engagement and

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active ownership is becoming a popular tool for shareholders wishing to influence the behaviour of their companies (e.g. Orsagh 2014; Kim and Schloetzer 2013 from PWC 2015; Goodman and Fields 2015). A common application of shareholder engagement is the mitigation of Environmental, Social, and Governance (ESG) risks of portfolio companies, such as those arising from climate change (Clark, Feiner, and Viehs 2014).

In July 2012, climate activist Bill McKibben popularised fossil fuel divestment with an article in the *Rolling Stone* (2012). McKibben called on university endowments and pensions to divest from fossil fuel holdings, on the logic that these funds exist to allow their benefactors to enjoy a prosperous future free of the impacts of climate change. Modelled on the divestment campaign which placed economic pressure on apartheid South Africa, more than 501 institutions with collective assets worth over US$3.4tn have joined the Fossil Free divestment campaign, pledging either full or partial divestment of fossil fuel assets (gofossilfree.org 2015). Ansar, Caldecott, and Tilbury (2013) argue that the greatest impact of the divestment campaign might be the stigmatisation of fossil fuel companies.

In their dissenting opinions on fossil fuel divestment, Harvard University (Faust 2013), The Wellcome Trust (Farrar 2015), and the Expert Group of the Norwegian Ministry of Finance (Skancke et al. 2014) all cite active ownership as their preferred management strategy for climate change risks. Divestment and engagement strategies now stand at odds with one another. Central to this debate is the question of what effect, if any, divestment (i.e. exclusion from a universe of investible securities) might have on the actions or outcomes of a company or class of companies. Alternatively, what effect might shareholder engagement and active ownership have on a company's actions or outcomes? Under what conditions might shareholder engagement be effective?

Despite a growing interest from investors in climate change risk management, approaches to these questions have been unsophisticated so far. Divestment decisions have been made largely on the grounds of ethics and mission-alignment of funds, belied by the prominence of faith-based groups and charitable foundations among divesters (gofossilfree.org 2015). Engagement on climate change risk has either focussed on supplementary disclosure (e.g. CDP) or targeted initiatives with extractive companies (e.g. the Aiming for A coalition). There is a demonstrated need for investors to be able to identify conditions for effective stewardship, to make intelligent and systematic engagement and disinvestment decisions corresponding to underlying environment-related risks.

This study examines the relationship between the management and equity owners of companies exposed to climate change risks. Characteristics of companies and shareholders which are deterministic in divestment or engagement decisions over carbon risk are identified and parameterized. In doing so, the paper proposes certain psychological factors (e.g. memory and foresight) and situational factors (e.g. multiplicity of investors, benefits, and costs), which may inform the development stewardship theory (e.g. Davis, Schoorman, and Donaldson 1997) and its relationship to agency theory (e.g. Ross 1973). Game theory concepts are applied to the relationship between companies and equity owners, and elementary models are developed to explore dynamics of engagement strategies. The work is informed by semi-structured interviews with professionals in the oil and gas industry, the financial industry, and NGO, regulatory, and academic sectors.

2. Method

The paper examines how investors and companies might interact with each other to mitigate climate change risks. The subject of study is the decision-making processes of both oil and gas companies and their investors, and critically how their decisions influence each other. The study of how individuals or organizations (hereafter called *agents*) make decisions is called *decision theory*.

Decision theory is the study of how a single rational agent maximizes their outcome, especially under uncertainty, and has found application among engineers, economists, psychologists, computer scientists, and policy-makers (Hansson 2005). Decision theory has its origins in Expected Utility Theory proposed by Daniel Bernoulli in 1738 (translated 1954). Mesterton-Gibbons (2000) provides a high-level overview of decision theory domains based on the number of agents and the number of rewards they receive, adapted in Figure 1. As the decisions and outcomes of investors and their companies are clearly interrelated, game theory tools will be used to examine the decision-making of various agents.

Game theory is the mathematical study of strategic decision-making. Classical Forms are those first described by Von Neumann and Morgenstern (1944) and bolstered substantially by Nash (e.g. 1950), and a number of other economists writing in the 1950s and 1960s. Metagame analysis was invented by Howard (1971), citing a need to develop strategic analysis tools which are easier to understand and are more descriptive of real agent behaviour. Axelrod in the 1980s (e.g. 1980, 1984) rekindled an interest in the field by realizing its potential to study problems of social coordination and cooperation. Smith (1982) was influential in introducing the subject to evolutionary biology. Game theory and its derivative disciplines now span diverse fields ranging from policy (Madani 2013) to transport planning (Rouhani et al. 2013) to project management (Asgari, Afshar, and Madani 2013).

Game theory is used to identify equilibria solutions from which no player is likely to deviate. Various equilibrium concepts exist, differing, for example, in their treatment of rationality, their stability in repeated play, and robustness to diverse agent beliefs (Madani and Hipel 2011). In the following section, classical normal form games are used to examine conditions for effective stewardship. The equilibria developed provide insight into effective engagement strategies between investors and their companies. Challenges of coalition formation among investors are also explored. Table 1 describes equilibria forms used in this paper.

		Number of rewards	
		r=1	r>1
Number of agents	n=1	Scalar Optimization Problems e.g. Mathematical optimization	Vector Optimization Problems e.g. Multi-Criteria Decision Making (MCDM)
	n>1	Game Theory	Vector Game Theory e.g. Vector-Valued MCDM

Figure 1. Decision Theory Fields. Adapted from Mesterton-Gibbons (2000).

Table 1. Selected equilibria for classical form games. Adapted from Gibbons (1992).

Solution concept	Description
Nash Equilibrium	Nash equilibria are a set of strategies chosen by agents wherein no agent can strictly improve their utility by choosing any other strategy given the strategies of the other agents; all agents are playing best responses to each other
Bayesian Nash Equilibrium	Bayesian Nash Equilibrium are a set of strategies chosen by agents which are best responses to the *expected* strategies of the other agents

3. Game theory models

3.1. Social dilemmas between an investor and a company

Engagement between an investor and a company on an ESG issue is characterized as a social dilemma. A social dilemma occurs when agents individually seek higher payoffs for antisocial behaviour to the detriment of their collective interests (Dawes 1980). Stewardship theory seeks to identify when agents are intrinsically 'pro-organisational' and 'collectivist' (Davis, Schoorman, and Donaldson 1997). The prisoner's dilemma is the canonical social dilemma and is used in this paper to explore agent choices between cooperation and defection.

A 1v1 iterated prisoner's dilemma (IPD) is developed as a representation of the interaction between an investor (or a coalition of investors) and a company. In such a scenario, a cooperative outcome is one in which an investor engages on an ESG issue of interest, and the company delivers a corresponding change in behaviour. This is the socially optimal outcome wherein the investor and the company management both benefit from the financial outperformance of successful engagement, as demonstrated by Dimson, Karakas, and Li (2012) and Eccles, Ioannou, and Serafeim (2012). A non-cooperative outcome is one in which the company, the investor, or both fail or refuse to deliver on their engagement. An investor may lose interest in the subject or even divest from the company, and a company board may defect from its commitment to the investor. Characteristic of the IPD, the reward of mutual cooperation vests continually over time, whereas the temptation to defect delivers immediate utility to that agent followed usually by less cooperative future outcomes (e.g. Gibbons 1992). A brief development of the IPD parameterization follows. An extensive mathematical description of the methodology used is available in Appendices A and B.

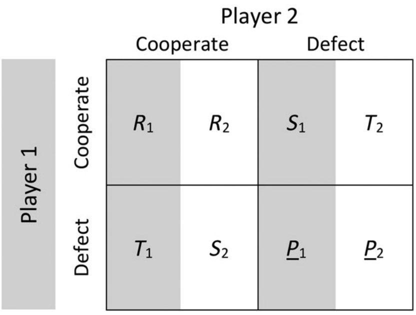


Figure 2. 1v1 Prisoner's dilemma payoffs in matrix form with Nash Equilibrium underlined.

The prisoner's dilemma was introduced by Dresher & Flood in 1950 to model strategic options during the cold war (Aumann and Maschler 1964). It is reproduced in its familiar form in Figure 2. Among other 2×2 games, the prisoner's dilemma is described by its ordered preferences: $T > R > P > S$, leading to the non-cooperative Nash Equilibria (*defect, defect).*

The uncooperative Nash Equilibria is dissatisfying for its failure to predict the cooperative equilibria regularly observed between real individuals and organizations (e.g. Fehr and Fischbacher 2003; Pothos et al. 2011). Repeated interactions between agents have the potential to create conditions of trust and mutual cooperation, resulting in improvements in both private outcomes and the overall system efficiency (Kreps et al. 1982; Axelrod 1984).

As an IPD of indeterminate length, no closed-form solution exists, and no deterministic strategy is dominant (Gibbons 1992). To develop a solution, a mixed-strategy IPD simulation is used to develop Bayesian Nash Equilbrium, per Harsanyi (1973), with Bayesian inferences and evolutionary decision-making as in Goeree and Holt (1999). The simulation was developed in MATLAB according to the methodology developed in Appendix B.

Variables examined in this model include the benefits and costs of cooperation, discount factors of the agents, and foresight and memory horizons. Table 2 describes how these parameters may be interpreted as conditions for cooperation between companies and investors and how IPD payoffs are simplified to a cost and benefit framework. Costs and benefits in this framework capture the business benefits (e.g. firm financial and operating performance (Clark, Feiner, and Viehs 2014)) and associated costs (e.g. personnel salaries (Wong 2010)).

In the simple model developed, payoffs are considered to be symmetrical – which does not reflect the separation and distinction of investor and firm interests, as held by typical agency problems (e.g. Davis, Schoorman, and Donaldson (1997)). As the intention of this paper is to explore conditions for mutual cooperation only, and because the payoffs are arbitrary and relative, this simplification is appropriate. Mutual cooperation would otherwise simply be limited by the less cooperative party (Kruitwagen 2015).

Further, this model considers the relationship of an investor and company management in isolation from other exogenous factors. These exogenous factors, such as changing exposure to risk, or changing opportunity cost for the investor's capital allocation, may

Table 2. IPD parameterization.

Parameter	Symbol	Interpretation
Benefit	$\mathrm{BEN} = [1\ldots10]$	Benefit of cooperation, for example, financial outperformance of company, mitigation of asset and reputation risk, talent attraction, social licence to operate
Cost	$\mathrm{COS} = \left[0\ldots{}^{\mathrm{BEN}}\!/_{2}\right]$	Cost of cooperation, for example, engagement personnel salaries, opportunity costs
IPD Payoffs	Temptation	$T = \mathrm{BEN}$
	Reward	$R = \mathrm{BEN} - \mathrm{COS}$
	Punishment	$P = 0$
	Sucker	$S = -\mathrm{COS}$
Discount factor	$\delta_i = [0\%\ldots100\%]$	Decreased value of future payoffs relative to present payoffs, or probability of game termination on subsequent round
Memory	$Q_i = [1\ldots10]$	Horizon of significance for past activity on which agents base present beliefs
Foresight	$L_i = [1\ldots10]$	The number of iterations an agent foresees in the future for which they calculate future-value payoffs

disrupt both the magnitude and ordinality of the payoffs proposed in this model. Environment-related risks in particular have the potential to manifest rapidly (e.g. Caldecott, Horwath, and McSharry (2013)), changing payoffs and resulting in different equilibria. These intricacies are outside the scope of this paper.

3.2. Social dilemmas between multiple investors

An N-agent IPD (NIPD) is developed as a representation of the coordination between multiple investors. NIPD models are commonly used to examine challenges of free-riding and coordination in social dilemmas (e.g. Ray and Vohra 1999). The NIPD is used here to examine the interest of investors in forming coalitions in their engagements with companies. See Appendix C for the full development of the NIPD.

It is more difficult to develop cooperative equilibria in an NIPD than in the 2-agent IPD, with the challenge increasing with the number of agents (e.g. Komorita 1976). In the NIPD, cooperative rewards are socialized to all agents, sanctions against non-cooperative agents have social externalities, and often elements of anonymity prevent agents from identifying cooperators and defectors (Dawes 1980). Example uses of the NIPD are to describe *tragedy of the commons* resource problems (Hardin 1968), endogenous coalition formation (Ray and Vohra 1999), and energy and climate policy free-riding problems (Nordhaus 2015).

Investors seeking to form coalitions in their interactions with companies face a typical free-riding problem. Collectively they benefit from strong engagement with the company, but individually they would benefit from neglecting their responsibilities and free-riding on the efforts of others. Solutions to the NIPD must overcome both the short-termism temptation of the IPD and the free-riding temptation. Many solution models (i.e. structures of strategies and payoffs that lead to cooperative equilibria) for the NIPD exist, including asymmetric payoffs (e.g Vyrastekova and Funaki 2010), side payments (e.g. Ray and Vohra 1999; Nordhaus 2015), spatial and personality interactions (e.g. Axelrod 1984; Manhart and Diekmann 1989), and social network theories (e.g. Rezaei, Kirley, and Pfau. 2009). The *relaxed* NIPD presented in this paper adds to these solution concepts. The payoff structure of Manhart and Diekmann (1989) is adapted by relaxing the strict dominance of defection payoffs and by giving agents unique weightings, allowing agents to have asymmetric payoffs. As in the IPD, agents use Bayesian inferences and evolutionary decision-making (Goeree and Holt 1999) to develop Bayesian Nash Equilibria (Harsanyi 1973). The simulation was developed in MATLAB according to the methodology developed in Appendix C.

This solution is well suited to investors who have different ownership portions of a company, and thus varying interests in the company's performance. Table 3 develops and interprets the parameters of the NIPD. Weighting and payoffs are again assigned arbitrarily for relative significance only.

Table 3. NIPD parameterization.

Parameter	Symbol	Interpretation
Weighting	$U_i = 0.5 + \text{RAND}\,[0\dots1]$	Equity ownership of a shareholder, that is, how much weight they might add to a coalition
Payoffs	$R_i = \alpha K_i^{\prime\gamma}$ $\alpha = [0\dots1],\ \gamma = [0\dots1]$	Benefit of cooperation, that is, joining the coalition
	$T_i = K_i + DD = [0\dots0.2]$	Benefit of defection, that is, free-riding on the coalition

4. Results

4.1. Social dilemmas between an investor and a company: the IPD

The IPD is resolved in order to examine how parameters in Table 2, which are proxies for the attributes of companies and investors, lead to mutual cooperation. Mutual cooperation is interpreted as a proxy for effective stewardship. The sustained mutual cooperation of investors and companies leads to long-term management of environment-related risks and financial outperformance.

4.1.1. Dependence on payoffs and discount factors

The first parameters examined as conditions for effective stewardship are payoffs and discount factors. The payoffs for effective stewardship generally capture the benefits of stewardship (for example, the financial outperformance of the company and the mitigation of environment-related risk) less the costs of engagement. The defection of either the company or the investor allows them to capture the benefit of stewardship without the costs but may lead to less cooperative outcomes in the future.

Holding other factors constant, payoffs and discount factors are varied to explore their influence on conditions of mutual cooperation, shown in Figure 3. Benefits and costs need only be defined relative to each other; integer values are chosen on a range of 1–10. Discount factors are chosen on intervals between 0% and 100%.

The discount factor is used as a proxy for the discount rate used in discounted cash flow analysis by investors or companies (up to approximately 20% (Haldane and Davies 2011)). As a proxy however, the discount factor can also be used to capture excessive discounting and short-termism (an additional 5–10%, Haldane and Davies 2011) or the likelihood that an investor will sell their position within the year (>100% for the USA and UK, based on average stock holding time (Bogle 2010)).

Conditions for cooperation are strongest between an investor and a company when the benefit of cooperation is large, and the cost of cooperation is small. The social dilemma aspect of the game makes costs much more deterministic in cooperative outcomes than benefits. In engagements between companies and investors, it is critical, therefore, that both parties feel a strong benefit from engaging with each other and have minimal costs for doing so.

Low discount factors for both investors and companies encourage mutual cooperation. Agents with low discount factors place larger weights on future payoffs. For investors and companies in shareholder engagements, it is crucial that they have a low discount factor as the benefit of their engagement activities must vest continually to exceed the short-term payoff of defection.

Section 5 develops a more critical discussion of these findings.

4.1.2. Dependence on memory and foresight horizons

Keeping other factors constant at conditions for high mutual cooperation, horizons of memory and foresight are varied to explore their influence on the development of mutual cooperation, shown in Figure 4.

With a low foresight horizon, it is difficult to establish conditions of mutual cooperation. Closely related to discount factor, the foresight of investors and companies is deterministic in whether they engage or not. While a discount factor examines the

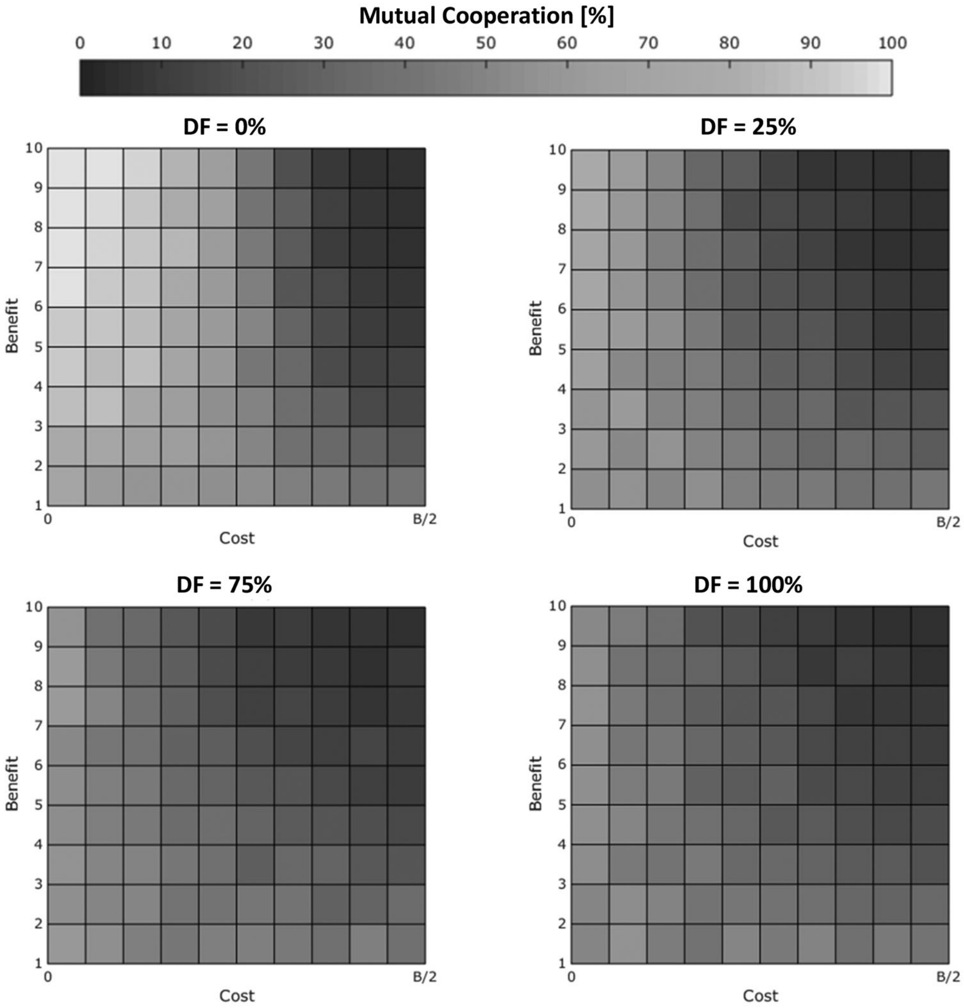


Figure 3. Modelled dependence of mutual cooperation on payoff and discount factors.

weight that agents give to future payoffs, foresight determines whether they consider the value of those future payoffs at all.

Even with longer foresight horizons, mutual cooperation may be hindered by long memories of past history. A longer memory in this sense allows agents to recall past defections which quickly eliminate any potential for present cooperation. Memory horizons indicate the significance of consistency in cooperation, showing that past defections can be deterministic in present cooperation.

4.2. Social dilemmas between multiple investors: the NIPD

The NIPD is resolved in order to examine how parameters in Table 3, which are proxies for the attributes of investors, lead to mutual cooperation, which is used as a proxy for coalition formation. The sustained mutual cooperation of investors leads to the

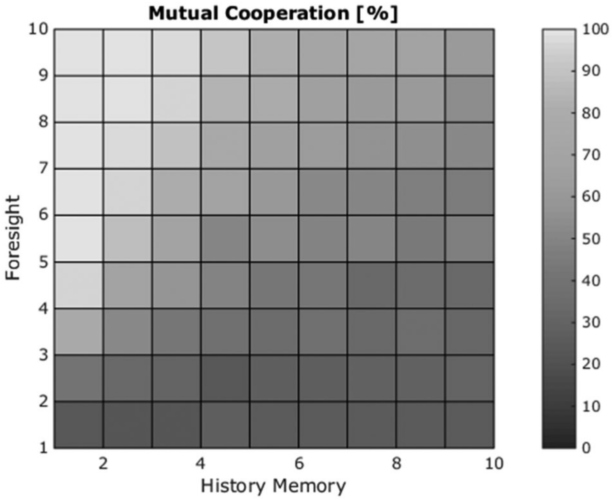


Figure 4. Modelled dependence of mutual cooperation on degree of foresight and history memory.

long-term formation of a coalition to engage on the management of environment-related risks.

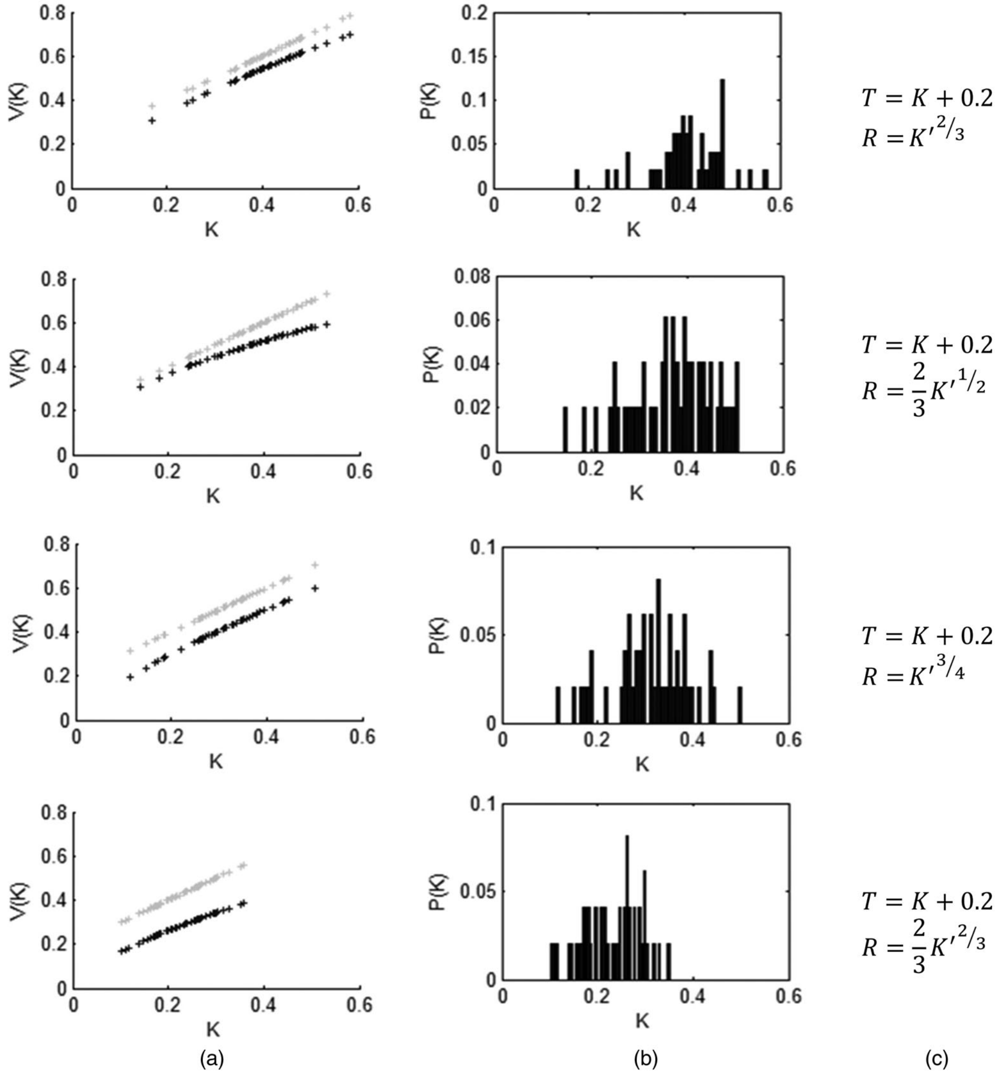
4.2.1. Free-riding temptation

In traditional solution models, mutual cooperation diminishes rapidly with the number of agents, reaching a stable non-cooperative asymptote in the neighbourhood of 20–30 agents (Komorita 1976). In the relaxed NIPD, Figure 5 shows mixed free-riding and cooperation among 50 agents over successive iterations.

The left plots map the defector and cooperator payoffs dependent on the proportion of agents cooperating. The right plots are the probability density distributions of cooperating agents. The diminishing returns of cooperation are expressed by equations of payoffs for cooperation and defection. Even under these relaxed conditions, cooperative equilibria remain elusive. The smaller the difference between payoffs for free-riding and cooperating, the higher the participation in the cooperative coalition.

4.2.2. Cooperation dependence on weighting

Figure 6 shows the simulation of 50 mutually cooperating agents based on the size of the *defection* payoff and agent weighting. For a number of *defection* payoffs (*D*), the larger-weighted agents (i.e. investors with larger holdings) are more likely to cooperate with one-another. This reflects how large institutional investors have been the first to join ethical-based investors in engaging on climate change risks. The 'Aiming for A' coalition, for example, includes 23 pension funds in addition to 32 charity, foundations, and church groups (Aiming for A 2015). It must be noted that diminishing the defection payoff bonus (D) results in the violation of the strict ordinality of the temptation payoff (T) and the reward payoff (R), as required by Equation (18), Appendix C.



$T = K + 0.2$
$R = K'^{2/3}$

$T = K + 0.2$
$R = \frac{2}{3}K'^{1/2}$

$T = K + 0.2$
$R = K'^{3/4}$

$T = K + 0.2$
$R = \frac{2}{3}K'^{2/3}$

Figure 5. (a) Freerider and cooperator payoffs (*V*) dependent on the portion of cooperators (*K*). (b) Population density (*P*) of cooperating agents (*K*). (c) Payoff functions for freeriders (*T*) and cooperators (*R*).

5. Discussion

Discussion topics in this section are supported by interview testimony collected in July and August 2015. Thirteen semi-structured interviews were conducted with experts from the finance and energy industries, and the NGO, regulatory, and academic sectors (collectively ‘NGO’). Interviews were conducted during a period of dramatically falling oil prices and significant shareholder engagement on carbon asset risk. The interviews were thus timely, but the interests and opinions of experts may have shifted significantly since a few years prior.

The success of recent shareholder resolutions with extractive companies is indicative of how engagement on climate change risk is currently conducted. In 2015, shareholder

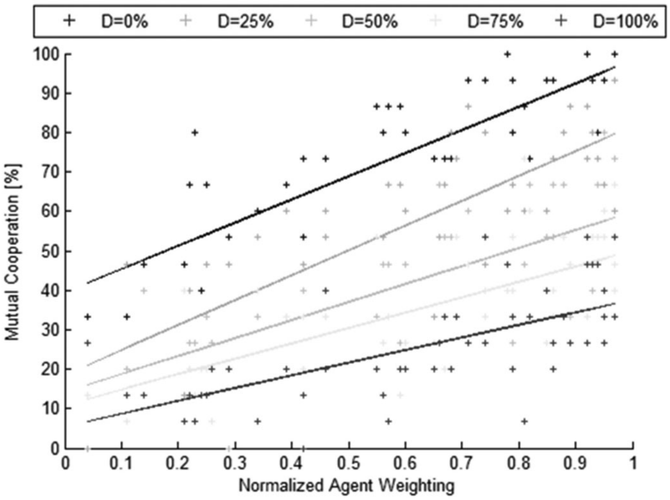


Figure 6. Cooperation dependence on agent weighting subject to various defection payoffs.

resolutions to examine and disclose carbon asset risk were submitted with Shell, BP, and Statoil (LAPFF 2015). Coalitions of investors (such as 'Aiming for A') engaged directly with company management on performance and disclosure objectives. Certain investors also delegated stewardship responsibility to firms who engaged with companies on their behalf (e.g. Hermes Equity Ownership Services). As a result of the multi-year engagement processes, the climate change risk shareholder resolutions with Shell, BP, and Statoil passed with over 98% of the shareholder vote (LAPFF 2015).

However, the vast majority of shareholders are unsophisticated with their stewardship practices – most delegate the decision-making of their votes to company management or to proxy advisory services (McCall and Larker 2014). Where climate change risk resolutions do not have broad coalition and management support, their success has typically been limited to approximately 20% of the vote (CERES 2015). It was the management's support of the resolutions at Shell, BP, and Statoil that led to their resounding success. Company management thus has sufficient agency in the company's action on climate risk to warrant their own representation in the social dilemmas considered.

In social dilemmas, costs are shown to dominate potential benefits in the development of cooperation. By preparing for engagement on climate change risk, company directors reduce their own costs at the time of engagement and thus are more likely to cooperate. As one energy industry contributor notes:

> If one or other party is not [conducting engagement] as a matter of routine … that's where the marginal cost related to the interaction creeps into significant value.

Likewise, investors can demand incremental progress which is not as immediately burdensome to company directors. The dominance of costs in cooperative equilibria may help explain why passive investors, who operate tight business models, have been reluctant to join stewardship efforts (Wong 2010; Johnson 2015). One finance industry contributor suggests:

> I think [engagement is] a challenge for the passives because they're pressed hard on fees.

The IPD shows how the long memories of agents diminish the chance for cooperative equilibria. This indicates that prior defections can be detrimental to current engagement efforts. Investors should then seek consistent small improvements from their companies with sustained engagement over successive years, rather than rapid change and adaptation. This was the strategy employed by Aiming for A, whose landmark shareholder proposals regarding climate change risk passed in 2015 after years of engagement (PIRC 2015). One finance industry contributor describes their engagement approach:

> It's been a very strategic approach, the resolutions didn't come out of the blue, we built extremely good relationships, [the companies] know us, they know where we're coming from.

Large foresight horizons are shown to be necessary for cooperative equilibria. Foresight horizons are related to discount factors, but represent instead the horizon beyond which a decision-maker has no ability or interest to foresee a payoff. Oil and gas company executives have an average tenure of 4.5 years (Reinsvold 2015), with performance incentives usually vesting three years after (Alvarez & Marsal Taxand LLC 2015). It is possible that the reluctance of companies to engage on climate change risks is explained by the bounded near-term foresight horizon of company executives. NGO and finance industry contributors describe executive preoccupation with short-term results:

> The company is so tied to that quarterly earnings call … which makes it really hard to think long term and strategically.
>
> We're not just interested in value over the next three months- we're interested in multiple decades of owning some of these key holdings. We need bring this perspective to companies and CEOs who may have a much shorter cycle.

The existence of a foresight horizon may also help explain why passive investors are reluctant to engage in stewardship activities. Their belief in efficient or near-efficient markets may preclude their interest in any foresight horizon as part of their investment strategy.

The NIPD is known to be a more frustrating social dilemma than the IPD, and increases in difficulty with the number of agents (Komorita 1976; Dawes 1980). Shareholders may have a large potential influence with companies, but only when they are coordinated. Per one energy industry contributor:

> Shareholders are incredibly powerful … what you need to see is a significant weight of shareholders getting behind [this view].

Even with the enhanced cooperation payoffs of the NIPD model above, wide-spread cooperation of the agents is rare. Oil and gas companies in particular have massive disparate shareholder bases numbering in the hundreds of thousands of holders (e.g. BP plc 2014). However, the number of significant shareholders is much less. Less than 10 individual shareholders often control a disproportionate amount of oil and gas companies – over 20% (e.g. BP (2014), Total (2015), Shell (2015), ExxonMobil (Yahoo! Finance 2015b) and Chevron (Yahoo! Finance 2015a)). An engageable number of shareholders might control a dominating interest in an oil and gas company.

Additional NIPD mechanisms may present concepts for the formation of coalitions among shareholders. Resource allocation and side payment mechanisms (e.g. Shenoy 1979; Nordhaus 2015) are familiar game theory subjects which allow agents to come to terms among each other for increased cooperation. This is already in practice by investors, for instance the UN Principles for Responsible Investment's (PRI's) use of a clearing house mechanism to allocate support and resources to engagements by fellow investors (PRI 2015). One interviewee involved in an engagement coalition described the use of shared costs and responsibilities to maximize impact across a portfolio of companies in a structure similar to a social network game. These coalitions are still subject to free-riding, but cost sharing among cooperative investors enables easier coalition formation.

6. Conclusion

In this work, non-cooperative social dilemma games were used to develop insight into the conditions for effective stewardship of companies by their investors. Iterated prisoners' dilemmas were used to explore conditions for mutual cooperation between pairs and groups of agents. The games and insights developed were informed by semi-structured interviews with energy and finance industry professionals and NGO/regulator/academic sector professionals.

Several barriers to mutual cooperation and coalition formation in engagements were identified, including the disproportional impact of costs relative to benefits, low discount factors, short foresight horizons, and sensitive memories. Free-riding temptations increase in larger groups, making coalition formation among large groups of shareholders difficult. Novel solution models like side payment and social network mechanisms can inform the development of structures for stable coalitions of investors.

The long-term interests of asset owners are driving sustainability performance in their investee companies in order to mitigate exposure to environment-related risks. For investors interested in influencing company behaviour, challenges remain in overcoming short-term defection between investors and company boards. Conditions for mutual cooperation have been developed in this paper to give investors insight as to when their engagements of sustainability issues will be more effective. Investors seeking to build stable coalitions with other investors must overcome free-riding incentives to wield stronger influence with companies.

This work offers investors additional insight for making engagement, disinvestment, and divestment decisions. The ultimate significance of this work is that engagement and divestment decisions may eventually be made empirically, based on underlying environment-related risks and the effectiveness of investor stewardship and engagement.

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References

Aiming For 'A' Investor Coalition. 2015. BP Shell AGM 2015 Institutional Co-Filing Group 2nd Feb 2015 Final. Accessed January 24, 2016. http://www.churchinvestorsgroup.org.uk/system/

files/documents/James%20Corah/BP%20Shell%20AGM%202015%20Institutional%20Co-filing%20Group%202nd%20Feb%202015%20Final.pdf.

Alvarez & Marsal Taxand LLC. 2015. *Oil and Gas Exploration & Production (E & P) Incentive Plan Design Report*. Accessed September 3, 2015. http://www.alvarezandmarsal.com/sites/default/files/am_tax_oilandgas_e-preport.pdf.

Ansar, A., B. Caldecott, and J. Tilbury. 2013. *Stranded assets and the fossil fuel divestment campaign*. Smith School of Enterprise and the Environment. Accessed April 3, 2015. http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/SAP-divestment-report-final.pdf.

Asgari, S., A. Afshar, and K. Madani. 2013. "Cooperative Game Theoretic Framework for Joint Resource Management in Construction." *Journal of Construction Engineering and Management* 140 (3): 04013066-1–13.

Aumann, R. J., and M. Maschler. 1964. "The Bargaining Set for Cooperative Games." In *Advances in GameTheory*, Annals of Mathematics Studies No. 52, edited by M. Dresher, L. S. Shapley, and A. W. Trucker, 443–476. Princeton: Princeton University Press.

Axelrod, R. 1980. "Effective Choice in the Prisoner's Dilemma." *The Journal of Conflict Resolution* 24 (1): 3–25.

Axelrod, R. 1984. *The Evolution of Co-operation*. New York: Basic Books, Inc.

Bernoulli, D. 1954. "Exposition of a New Theory on the Measurement of Risk." *Econometrica* 22 (1): 23–36.

Bogle, J. C. 2010. "Restoring Faith in Financial Markets." *The Wallstreet Journal*. Accessed September 3, 2015. http://www.wsj.com/articles/SB10001424052748703436504574640523013840290.

BP plc. 2014. *Annual Report*. Accessed September 3, 2015. http://www.bp.com/en/global/corporate/investors/annual-reporting.html.

Caldecott, B., G. Dericks, and J. Mitchell. 2015. *Stranded Assets and Subcritical Coal: The Risk to Companies and Investors*. Accessed January 24, 2016. http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/publications.php.

Caldecott, B., N. Horwath, and P. McSharry. 2013. *Stranded Assets in Agriculture: Protecting Value from Environment-related Risks*. Accessed January 24, 2016. http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/publications.php.

Carbon Tracker Initiative. 2013. *Unburnable Carbon 2013: Wasted Capital and Stranded Assets*. Accessed April 3, 2015. http://www.carbontracker.org/our-work/.

Carbon Tracker Initiative. 2014. *Carbon Supply Cost Curves: Oil Capital Expenditures*. Accessed April 3, 2015. http://www.carbontracker.org/our-work/.

CERES. 2015. CERES - Shareholder Resolutions. Accessed September 3, 2015. http://www.ceres.org/investor-network/resolutions.

Clark, G., A. Feiner, and M. Viehs. 2014. *Stockholder to Stakeholder*. Smith School of Enterprise and the Environment. Accessed April 3, 2015. http://www.smithschool.ox.ac.uk/library/index.php.

Covington, H., and R. Thamotheram. 2015. *The Case for Forceful Stewardship (Part 1)*. Accessed September 3, 2015. https://preventablesurprises.com/programmes/climate-change/.

Davis, J. H., F. D. Schoorman, and L. Donaldson. 1997. "Towards a Stewardship Theory of Management." *The Academy of Management Review* 22 (1): 20–47.

Dawes, R. M. 1980. "Social Dilemmas." *Annual Review of Psychology* 31 (1): 169–193.

Dimson, E., O. Karakas, and X. Li. 2012. Active Ownership. Review of Financial Studies, Forthcoming, (December), 1–48. Access November 5, 2015. http://papers.ssrn.com/abstract=2154724.

Eccles, R. G., I. Ioannou, and G. Serafeim. 2012. "The Impact of Corporate Sustainability on Organizational Processes and Performance." *Management Science Forthcoming*. Accessed November 5, 2015. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1964011.

The Economist Intelligence Unit. 2015. *The Cost of Inaction: Recognising the Value at Risk from Climate Change*. Accessed September 3, 2015. http://www.economistinsights.com/financial-services/analysis/cost-inaction.

Farrar, J. 2015. "Fossil Fuel Divestment Is Not the Way to Reduce Carbon Emissions." *The Guardian*. Accessed April 3, 2015. http://www.theguardian.com/commentisfree/2015/mar/25/wellcome-trust-fossil-fuel-divestment-not-way-reduce-carbon-emissions.

Faust, D. 2013. *Fossil Fuel Divestment Statement*. Harvard University. Accessed September 3, 2015 http://www.harvard.edu/president/fossil-fuels.

Fehr, E., and U. Fischbacher. 2003. "The Nature of Human Altruism." *Nature* 425 (6960): 785–791.

Gibbons, R. 1992. *A Primer in Game Theory*. Harlow: Pearson Education.

Goeree, J. K., and Holt, C. A. 1999. "Stochastic Game Theory: For Playing Games, Not Just for Doing Theory." *Proceedings of the National Academy of Sciences of the United States of America* 96 (19): 10564–10567.

gofossilfree.org. 2015. Commitments. gofossilfree.org. Accessed September 22, 2015. http://gofossilfree.org/commitments/.

Goodman, A., and R. R. W. Fields. 2015. "Board-Shareholder Engagement: Current & Future Trends." *Ethicalboardroom.com*. Accessed May 8, 2015. http://ethicalboardroom.com/activism/board-shareholder-engagement-current-future-trends/.

Haldane, A. G., and R. Davies. 2011. The Short Long - Speech. Accessed September 3, 2015. http://www.bankofengland.co.uk/archive/Documents/historicpubs/speeches/2011/speech495.pdf.

Hansson, S. O. 2005. *Decision Theory*. Accessed September 3, 2015 http://web.science.unsw.edu.au/~stevensherwood/120b/Hansson_05.pdf.

Hardin, G. 1968. "The Tragedy of the Commons." *Science* 162 (June): 1243–1248.

Harsanyi, J. C. 1973. "Games with Randomly Disturbed Payoffs: A New Rationale for Mixed-strategy Equilibrium Points." *International Journal of Game Theory* 2 (1): 1–23.

Howard, N. 1971. *Paradoxes of Rationality: Theory of Metagames and Political Behavior*. Cambridge, MA: MIT Press.

Ishibuchi, H., and N. Namikawa. 2005. "Evolution of Iterated Prisoner's Dilemma Game Strategies in Structured Demes under Random Pairing in Game-Playing." *IEEE Transcations on Evolutionary Computation* 9 (6): 552–561.

Janssen, M. A. 2008. "Evolution of Cooperation in a One-shot Prisoner's Dilemma Based on Recognition of Trustworthy and Untrustworthy Agents." *Journal of Economic Behavior and Organization* 65 (3–4): 458–471.

Johnson, S. 2015. "Compulsory Stewardship by Passive Managers Moves Closer." *The Financial Times*. Accessed January 24, 2016. http://www.ft.com/cms/s/0/3917d0d0-e812–11e4-894a-00144feab7de.html#axzz3yFP6jymf.

Kanazawa, S., and L. Fontaine. 2013. "Intelligent People Defect More in a One-shot Prisoner's Dilemma Game." *Journal of Neuroscience, Psychology, and Economics* 6 (3): 201–213.

Kay, J. 2012. "The Kay Review of the UK Equity Market and Long-term Decision Making." Accessed April 3, 2015. https://www.gov.uk/government/publications/kay-review-of-uk-equity-markets-and-long-term-decision-making-implementation-progress-report.

Kim, J., and J. D. Schloetzer. 2013. *Global Trends in Board-shareholder Engagement*. The Conference Board. Accessed September 3, 2015. https://www.conference-board.org/publications/publicationdetail.cfm?publicationid=2618.

Komorita, S. S. 1976. "A Model of the N-Person Dilemma-type Game." *Journal of Experimental Social Psychology* 12 (4): 357–373.

Kreps, D. M., P. Milgrom, J. Roberts, and R. Wilson. 1982. "Rational Cooperation in the Finitely Repeated Prisoners' Dilemma." *Journal of Economic Theory* 27 (2): 245–252.

Kruitwagen, L. 2015. "Conditions for Effective Stewardship of Companies Subject to Climate Change Risk." MSc Thesis, Imperial College London.

Kuhn, S. 2014. "Prisoner's Dilemma." *The Stanford Encyclopedia of Philosophy*. Accessed September 3, 2015. http://plato.stanford.edu/entries/prisoner-dilemma/.

Lewis, M. C., and S. Voisin. 2014. *Stranded Assets, Fossilised Revenues*, Kepler Cheuvreux. Accessed April 3, 2015. https://www.keplercheuvreux.com/pdf/research/EG_EG_253208.pdf.

Local Authority Pension Fund Forum (LAPFF). 2015. "And Statoil Makes Three as Transatlantic Gap Grows." *News*. Accessed January 24, 2016. http://www.lapfforum.org/news/and-statoil-makes-three-as-transatlantic-gap-grows.

Madani, K. 2010. "Game Theory and Water Resources." *Journal of Hydrology* 381 (3–4): 225–238.

Madani, K. 2013. “Modeling International Climate Change Negotiations More Responsibly: Can Highly Simplified Game Theory Models Provide Reliable Policy Insights?” *Ecological Economics* 90 (6): 68–76.

Madani, K., and K. Hipel. 2011. “Non-Cooperative Stability Definitions for Strategic Analysis of Generic Water Resources Conflicts.” *Water Resources Management* 25 (8): 1949–1977.

Manhart, K., and C. A. Diekmann. 1989. “Cooperation in 2- and N-Person Prisoner’s Dilemma Games: A Simulation Study.” *Analyse & Kritik* 11 (2): 134–153.

McCall, A. L., and D. F. Larker. 2014. “Researchers: The Power of Proxy Advisory Firms.” *Insights by Stanford Business*. Accessed September 3, 2015. https://www.gsb.stanford.edu/insights/researchers-power-proxy-advisory-firms.

McGlade, C., and P. Ekins. 2015. “The Geographical Distribution of Fossil Fuels Unused When Limiting Global Warming to 2°C.” *Nature* 517 (7533): 187–190.

McKibben, B. 2012. “Global Warming’s Terrifying New Math.” *The Rolling Stone*. Accessed April 3, 2015. http://www.rollingstone.com/politics/news/global-warmings-terrifying-new-math-20120719.

Mesterton-Gibbons, M. 2000. *An Introduction to Game-Theoretic Modelling*. 2nd ed. Providence, USA: American Mathematical Society.

Miller, J. H. 1996. “The Coevolution of Automata in the Repeated Prisoner’s Dilemma.” *Journal of Economic Behavior and Organization* 29 (1): 87–112.

Nash, J. 1950. “Equilibrium Points in N-Person Games.” *Proceedings of the National Academy of Sciences of the United States of America* 39 (1): 48–49.

Neumann, J. Von., and O. Morgenstern. 1944. *Theory of Games and Economic Behavior,* 60th Anniv. Princeton, NJ: Princeton University Press.

Nordhaus, B. W. 2015. “Climate Clubs: Overcoming Free-riding in International Climate Policy.” *The American Economic Review* 105 (4): 1339–1370.

Orsagh, M. 2014. *Shareholder Engagement: Bridging the Gap Between Boards and Investors*. CFA Institute. Accessed May 8, 2015. http://blogs.cfainstitute.org/marketintegrity/2014/03/26/shareholder-engagement-bridging-the-divide-between-boards-and-investors/.

Pettit, P., and R. Sugden. 1989. “The Backward Induction Paradox.” *The Journal of Philosophy* 86 (4): 169–182.

PIRC. 2015. BP AGM - Who’s Next to Aim for A? Accessed September 3, 2015 http://pirc.co.uk/pircnews/bp-agm-who-is-next-to-aim-for-a.

Pothos, E. M., G. Perry, P. J. Corr, M. R. Matthew, and J. R. Busemeyer. 2011. “Understanding Cooperation in the Prisoner’s Dilemma Game.” *Personality and Individual Differences* 51 (3): 210–215.

PRI. 2015. PRI - Clearinghouse. Accessed September 3, 2015. http://www.unpri.org/areas-of-work/clearinghouse/.

PWC. 2015. *Key Issues: Shareholder Engagement*. Center for Board Governance. Accessed May 8, 2015. http://www.pwc.com/us/en/corporate-governance/shareholder-engagement.jhtml.

Ray, D., and R. Vohra. 1999. “A Theory of Endogenous Coalition Structures.” *Games and Economic Behavior* 26: 286–336.

Reinsvold, C. H. 2015. “The Oil and Gas CEO.” *Oil&Gas Financial Journal* 11 (9). Accessed September 3, 2015. http://www.ogfj.com/articles/print/volume-11/issue-9/features/the-oil-and-gas-ceo.html.

Rezaei, G., M. Kirley, and J. Pfau. 2009. “Evolving Cooperation in the N-player Prisoner’s Dilemma: A Social Network Model.” *Lecture Notes in Computer Science* 5865 LNAI: 43–52.

Ross, S. 1973. “The Economic Theory of Agency: The Principal’s Problem.” *The American Economic Review* 63 (2): 134–139.

Rouhani, O. M., D. Niemeier, C. R. Knittel, and K. Madani. 2013. “Integrated Modeling Framework for Leasing Urban Roads: A Case Study of Fresno, California.” *Transportation Research Part B: Methodological* 48 (2): 17–30.

Royal Dutch Shell plc. 2015. *Annual Report 2014*. Accessed September 3, 2015. http://www.shell.com/global/aboutshell/media/reports-publications.html.

Shenoy, P. P. 1979. “On Coalition Formation: A Game-Theoretical Approach.” *International Journal of Game Theory* 8 (3): 133–164.

Skancke, M., E. Dimson, M. Hoel, M. Kettis, G. Nystuen, and L. Starks 2014. *Fossil-Fuel Investments in the Norwegian Government Pension Fund Global: Addressing Climate Issues Through Exclusion and Active Ownership*. Expert Group appointed by the Norwegian Ministry of Finance.

Smith, J. M. 1982. *Evolution and the Theory of Games*. Cambridge: Cambridge University Press.

Spedding, Paul, K. Mehta, and N. Robins. 2013. *Oil & carbon revisited-Value at risk from "unburnable" reserves*, HSBC. Accessed April 3, 2015. http://daily.swarthmore.edu/wp-content/uploads/2013/02/HSBCOilJan13.pdf.

Standard & Poor's. 2013. *What A Carbon-Constrained Future Could Mean For Oil Companies ' Creditworthiness*. Standard & Poor's. Accessed April 3, 2015. http://www.standardandpohttps//www.standardandpoors.com/ratings/articles/en/eu/?articleType=PDF&assetID=1245348784590name2=Content-Disposition&blobheadervalue1=application/pdf&blobkey=i.

Standard & Poor's. 2015. *How Environment and Climate Risk Factor into Global Corporate Ratings*. Standard & Poor's. Accessed January 1, 2016. https://www.environmental-finance.com/content/research/how-environmental-and-climate-risks-factor-into-global-corporate-ratings.html.

Szilagyi, M. N. 2003. "An Investigation of N-person Prisoners Dilemmas." *Complex Systems* 14: 155–174.

Total, S. A. 2015. *Total Annual Report*. Accessed September 3, 2015. http://www.total.com/en/media/news/press-releases/2014-annual-reports.

Vyrastekova, J., and Y. Funaki. 2010. *Cooperation in a Sequential N-person Prisoner's Dilemma: The Role of Information and Reciprocity?* (Unpublished work). Accessed September 3, 2015. www.ru.nl/publish/pages/516298/nice_10-103.pdf.

Wong, S. 2010. "Why Stewardship Is Proving Elusive for Institutional Investors." *Butterworths Journal of International Banking and Financial Law* 2010 (Jul/Aug): 406–411.

Yahoo! Finance. 2015a. Chevron Corporation (CVX). Accessed September 3, 2015. http://finance.yahoo.com/q/mh?s=CVX+Major+Holders.

Yahoo! Finance. 2015b. Exxon Mobil Corporation (XOM). Accessed September 3, 2015. http://finance.yahoo.com/q/mh?s=XOM+Major+Holders.

Appendix A: Development of a 1v1 Prisoner's Dilemma

The canonical Prisoner's Dilemma (PD) was initially developed by Dresher & Flood in 1950 to model strategic options during the cold war (Aumann et al. 1964). The PD's characteristic traits make it one of the most written-of social dilemmas, with interest spanning from economics, psychology, and political science (Dawes 1980), natural resource management (Madani 2010), evolutionary biology (Smith 1982), and artificial intelligence and machine learning (Miller 1996). A single-shot prisoner's dilemma is considered with elements described by Table A1. The notation and methodology used herein are typical of any introductory-level game theory study (e.g. Gibbons 1992; Mesterton-Gibbons 2000).

Pure strategy payoffs are given in matrix form as in Figure 2, subject to the constraint of Equation (1).

$$T_i > R_i > P_i > S_i. \tag{1}$$

The Nash Equilibrium of this matrix-form game is (D,D). Even with asymmetric payoffs, as long as the ordinal nature of each player's payoffs holds, the Nash Equilibrium remains (D,D). Relaxing the order of player *i*'s payoffs results in a *common knowledge* PD, where player *i*, knowing the other's payoffs, will still choose mutual defection, provided $P_i > S_i$ (Kuhn 2014). The one-shot nature of this game lends itself better to study in fields of psychology and sociology, with research on topics such as intelligence (e.g. Kanazawa and Fontaine 2013), trustworthiness (e.g. Janssen 2008), or personality (e.g. Pothos et al. 2011).

Appendix B: Development of a 1v1 Iterated PD

The single-shot game developed in Appendix A is capable of modelling many interactions where two agents interact only once. The uncooperative Nash Equilibrium (D,D) is dissatisfying both for its generally negative connotation and its failure to predict the cooperative equilibria regularly observed between real individuals and organizations (Fehr and Fischbacher 2003; Pothos et al. 2011). Repeated interactions between agents have the potential to create conditions of trust and mutual cooperation, resulting in improvements in both private outcomes and the overall system efficiency (Kreps et al. 1982; Axelrod 1984). The repeated PD is called the *iterated prisoner's dilemma* (IPD).

Deterministic IPD

In the IPD, players engage in a PD game which repeats for multiple rounds. Elements of a deterministic IPD are described in Table A2. A deterministic IPD is characterized by the pure strategies and payoffs of the players being common knowledge.

The payoff of the players may be additive, per Equation (2), or averaged over multiple rounds.

$$V_i = \sum_{t=0}^{\tau} v(a_{i,t}, a_{-i,t}). \tag{2}$$

The strategy space for players is now much more sophisticated, with players able to choose from a variety of rules or sequences of cooperation or defection. Some simple strategies are shown in Table A3. Axelrod (1980) first proposed an open-entry strategy competition where submitted algorithms would compete in an iterated Prisoners' Dilemma. Axelrod (1984) explored the characteristics of successful strategies and drew comparisons to real-life examples of sustained mutual cooperation.

For IPDs of any finite length with complete and perfect knowledge, a single Nash Equilibrium exists. Players use reverse (backward) induction to determine that the strategy to *always defect* strictly dominates all other strategies. While theoretically sound, this equilibrium is unsatisfying, especially at large numbers of iteration (Pettit and Sugden 1989). Similarly, for IPDs of infinite or indeterminate length, no single Nash Equilibrium strictly dominates all others. Players must play strategies which are best responses to each other. The following development of the IPD is typical to introductory-level game theory (e.g. Gibbons 1992; Mesterton-Gibbons 2000).

For an IPD of infinite or indeterminate length, Nash Equilibria may be identified with the inclusion of the discounting factor, δ. The discounting factor represents either the relative value of a payoff received in a future period, as in an infinite IPD, or the probability that the present round will be the final round, as in an indeterminate IPD. The sum of an infinite series of discounted values converges to a convenient expression (Equation (3)), allowing the direct comparison deterministic payoffs and the development of Nash

Equilibria.

$$v + v\delta + v\delta^2 + \ldots + v\delta^\tau = \sum_{t=1}^{\tau=\infty} v\delta^t = \frac{v}{1-\delta}. \tag{3}$$

An additional constraint (Equation (4)) is typically introduced in order to disincentivize strategies in which two players alternate T and S payoffs.

$$R > \frac{T+S}{2}. \tag{4}$$

In the simple case of an IPD between two *Grim Trigger* strategies with symmetrical payoffs, the conditions for a subgame-perfect Nash Equilibrium can be explicitly defined. Mutual cooperation must be preferable in each subgame relative to a temptation payoff followed by perpetual mutual defection. This is described by Equation (5).

$$\frac{R}{1-\delta} > T + \frac{\delta P}{1-\delta}. \tag{5}$$

Following Axelrod's successful computer tournament in 1980, an ongoing annual competition pits a wide range of strategies against each other. Strategies now range in complexity from the original simple strategies as in Table A3, to sophisticated strategies using probabilistic models.

Mixed-strategy IPD

Deterministic IPDs involve explicit assumptions about the cooperative rational nature of the players, and only have cooperative Nash Equilibria for infinite or indeterminate length games. To examine the conditions which best enable routine cooperation from self-interested players, a mixed-strategy IPD is more useful. Following Harsanyi (1973), mixed-strategy weighting can be used to represent belief spaces, allowing the development of Bayesian Nash Equilibrium (BNE). These beliefs may be updated as Bayesian inferences developed from sequential behaviour, as in Goeree and Holt (1999). Thus a mixed-strategy IPD adds the elements of Table A4 to the elements of a deterministic IPD and single-shot PD.

The pure strategy chosen by a player at time *t* is determined randomly by the mixed-strategy expected payoffs of each pure strategy, per Equation (6).

$$s_i = \text{rand}\left\{ \begin{matrix} C \\ D \end{matrix} \right. \text{ with } \begin{matrix} P_C = P(\pi^e_C, \pi^e_D) \\ P_D = 1 - P_C \end{matrix} \tag{6}$$

An evolutionary algorithm, as in Goeree and Holt (1999), is used to weight expected payoffs into probabilities, per Equation (7). A relaxing factor, μ, can be adjusted to suit the importance of payoffs in determining the random development of player actions.

$$P_C = \frac{\mathrm{e}^{\pi^e_C \mu}}{\mathrm{e}^{\pi^e_C / \mu} + \mathrm{e}^{\pi^e_D / \mu}} \text{ with } _{\mu=(0,\,\infty).} \tag{7}$$

Expected payoffs are the mixed-strategy payoffs developed for a bounded horizon of L periods per Equation (8). Mixed-strategy payoffs are weighted by common knowledge beliefs $\theta_{s,i}$ (of a player i to play a strategy s).

$$\pi^e_{s,i} = \sum_{t=t_0}^{t_0+L} \sum_{i=1,2} \sum_{s=C,D} \theta_{s,i} * \theta_{s,-i} * v_i(s_i, s_{-i}) * \delta^{t-t_0}. \tag{8}$$

Common knowledge beliefs are updated after each round. The beliefs are updated based on the number of times a player adopts strategy per Equation (9). By updating beliefs based on observed actions, cooperative actions increase the probability of mutual cooperation and defection actions increase the probability of mutual defection. The history of observed actions is limited by the memory of the player.

$$\theta_{s,i} = \frac{\text{count } (H(Q_i) = s)}{\text{size } (H(Q_i))}. \tag{9}$$

The sequentially updating beliefs result in a Markov chain of mixed probabilities and payoff states per Equation (10).

$$\begin{aligned} \pi^e s,\, i = \delta^0 \sum \left\{ \begin{array}{c} \theta_{C,-i,0} * v_i(S, C) \\ \theta_{D,-i,0} * v_i(S, D) \end{array} \right\} + \delta^1 \sum \left\{ \begin{array}{c} \theta_{C,i,1} * \theta_{C,-i,1} * v_i(C, C) \\ \theta_{D,i,1} * \theta_{C,-i,1} * v_i(D, C) \\ \theta_{C,i,1} * \theta_{D,i,1} * v_i(C, D) \\ \theta_{D,i,1} * \theta_{D,-i,1} * v_i(D, D) \end{array} \right\} + \ldots \\ + \delta^L \sum \left\{ \begin{array}{c} \theta_{C,i,L} * \theta_{C,-i,L} * v_i(C, C) \\ \theta_{D,i,L} * \theta_{C,-i,L} * v_i(D, C) \\ \theta_{C,i,L} * \theta_{D,-i,L} * v_i(C, D) \\ \theta_{D,i,L} * \theta_{D,-i,L} * v_i(D, D) \end{array} \right\} \end{aligned} \tag{10}$$

The updating of beliefs for each round, $\theta_{s,i,t}$, requires a result of the previous round. A Monte Carlo method is used to randomly generate a strategy pair for each round according to probabilities established by mixed beliefs at each round, illustrated by Equation (11).

$$s_i, s_{-i} = \text{rand} \left\{ \begin{array}{lcl} C, C & & P_{C,C} = \theta_{C,i,L} * \theta_{C,-i,L} \\ D, C & \text{with} & P_{D,C} = \theta_{D,i,L} * \theta_{C,-i,L} \\ C, D & & P_{C,D} = \theta_{C,i,L} * \theta_{D,-i,L} \\ D, D & & P_{D,D} = \theta_{D,i,L} * \theta_{D,-i,L} \end{array} \right. . \tag{11}$$

The results presented in Section 4.1 represent the average of 10 complete iterations, with 40 Monte-Carlo-generated pairs in each round. The relaxing factor, μ, was unity.

Appendix C: Development of an NvN IPD

The NvN IPD (NIPD) is an abstraction of the 1v1 IPD which has application to a greater set of social coordination and common problems. The NIPD can be used to describe challenges with pollution, public services, energy and water conservation, etc.; all situations where an individual receives a higher payoff for any defective action, but all payoffs are higher with collective cooperation. Due to the larger number of players involved, conditions for cooperation are often more elusive than in the IPD. In the NIPD, harm from defection is dispersed among multiple players, defection is more anonymous, and any reinforcing punishment strategies directed against a defector have negative externalities on all other players (Dawes 1980).

Many authors have studied the NIPD. For large N, an uncooperative equilibrium of self-optimizing agents develops quickly (e.g. Komorita 1976). In order to provide non-trivial results, authors seek mechanisms which induce cooperation in the population. Some studies use compound games (i.e. large games featuring many 1v1 subgames) and spatial considerations to inspire cooperation (Axelrod 1984; Ishibuchi and Namikawa 2005; Rezaei, Kirley, and Pfau. 2009). Other use evolutionary and personality diversities (whether in behaviour or payoffs) to find conditions which induce cooperation (Axelrod 1984; Manhart and Diekmann 1989; Szilagyi 2003).

Calculation of behaviour and equilibria in the NIPD can be an NP-hard optimization problem. Dawes (1980) suggests that elements of knowledge (e.g. communication and public disclosure), morality, and trust have the greatest impact on the development of cooperation in real social dilemmas.

Deterministic NIPD

An NIPD based on Vyrastekova and Funaki (2010) and Manhart and Diekmann (1989) is developed here. Both works use agent personalities in the form of asymmetric payoffs to explore cooperation. Elements of the NIPD are described in Table A5.

As in the IPD, players face the choice to either cooperate or defect. In the NIPD, the reward for cooperation grows with the number of players cooperating. However, for the same number of players cooperating, the defectors receive a greater payoff. Equations (13)–(16) describe the payoff conditions of the NIPD.

$$\text{with } k = \frac{N_C}{N},\ k' = \frac{N_C + 1}{N}, \tag{12}$$

$$V(D, k') > V(D, k), \tag{13}$$

$$V(C, k') > V(C, k), \tag{14}$$

$$V(C, k') < V(D, k), \tag{15}$$

$$V(C, k = 1) > V(D, k = 0). \tag{16}$$

With payoffs R for cooperation and T for defection, Figure A1 shows how, given Equation (15) above, D dominates C for any k. The Nash Equilibrium of the NIPD is sustained defection by all players. As N becomes large, the threat of future sanctions is insufficient to ensure conditions for cooperation. Any credible threat against a defecting player is diluted with negative externalities to other players, making the conditions for cooperation more difficult.

To develop useful cooperation scenarios from the NIPD, the condition of Equation (15) will be relaxed to Equation (17). To appropriately model the commons and free-riding problems the NIPD simulates, the payoff for additional cooperation will have diminishing returns as in Figure A1.

$$V(C, k) < V(D, k). \tag{17}$$

With symmetric payoffs the Nash Equilibrium occurs at some deterministic $k > 0$. However with asymmetric mixed-strategy payoffs based on each player's individual beliefs, the Bayesian Nash Equilibrium need not occur at a deterministic value of k. This allows for the development of more unique insight and less prescriptive model behaviour.

Mixed strategy NIPD

The NIPD may also be developed in cases where payoffs are asymmetric. Payoffs R and T, for cooperation and defection, respectively, may be weighted by an individual factor U_j. Payoff conditions described as above still hold, with a new K described in Equation (18). Equations (19) and (20) describe asymmetric payoffs R_j and T_j.

$$\text{with} \quad K_i = \frac{\sum_{j=1}^{N_C} U_{j \neq i}}{\sum_{j=1}^{N} U_j}, \quad K_i^{'} = \frac{\sum_{j=1}^{N_C} U_{j \neq i} + U_i}{\sum_{j=1}^{N} U_j}, \tag{18}$$

$$v_i(C, K_i) = R_i = \alpha K_i^{'\gamma}, \tag{19}$$

$$v_i(D, K_i) = T_i = K_i + \beta. \tag{20}$$

As in the mixed-strategy IPD, players develop an expected payoff based on their beliefs of the other players' actions. Elements of a mixed-strategy NIPD are given in Table A6.

Mixed-strategy expected payoffs are given by Equations (21) and (22).

$$\pi_i^e(C, K_i) = \alpha K_i^{'\gamma} = \alpha \left[\frac{U_i}{\sum_{j=1}^{N} U_j} + \frac{1}{\sum_{j=1}^{N} U_j} \sum_{j=1}^{N} U_{j \neq i}(P_C = \theta_{C,j}) \right]^{\gamma}, \tag{21}$$

$$\pi_i^e(D, K_i) = K_i + \beta = \left[\frac{1}{\sum_{j=1}^{N} U_j} \sum_{j=1}^{N} U_{j \neq i}(P_C = \theta_{C,j}) \right] + \beta. \tag{22}$$

The expected payoffs are now dependent on a joint probability distribution of N discrete variables, each with the value U_j or 0 according to a probability $\theta_{C,j}$. To determine

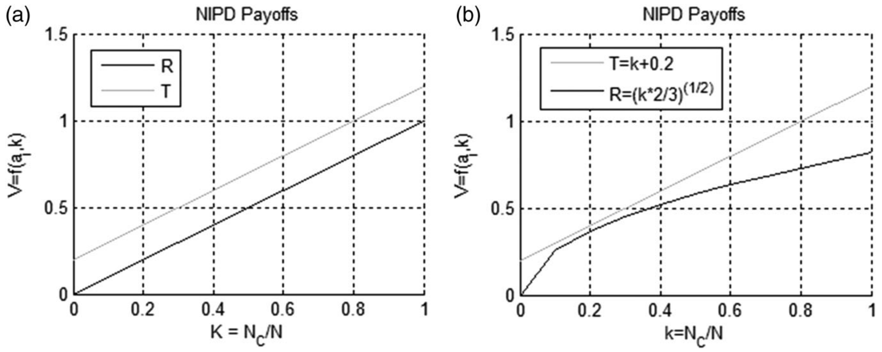

Figure A1. (a) Pure NIPD Payoffs. (b) Relaxed NIPD payoffs, example.

the probability density function deterministically would require the evaluation of 2^N states, a computationally demanding task as N gets large. A Monte-Carlo method is used to sample states of U_j to develop a probability density function with sufficient confidence. Expected payoffs are calculated from the probability density function and players choose their action with the same evolutionary algorithm as in Equation (7).

Table A1. Elements of a single-shot PD.

Game	$g = g_i(A, v)$
Players	$i = \begin{cases} 1 \\ 2 \end{cases}$
Action space	$A_i = [\text{COOPERATE, DEFECT}] = [C, D]$
Pure strategy	$a_i \in A_i$
Pure strategy payoffs	$v_i = f(a_i, a_{-i})$

Table A2. Elements of a deterministic IPD.

Game	$G = G(s, V, \tau)$
Game length	$\tau = [1, \infty]$
Strategy	$s_i = (a_{i,1}, ..a_{i,t}, \ldots a_{1,\tau})$
Discount factor	$\delta_i = [0, 1)$
Payoff	$V_i = V(\delta_i, s_i, s_{-i})$

Table A3. Simple iterated prisoners' dilemma strategies.

Strategy	Description
Grim trigger	Cooperate until opponent defects, then always defect
Tit-For-Tat	Always reciprocate opponent's last move
Pavlov	On a payoff of P or S, change strategies

Table A4. Elements of a mixed-strategy IPD.

Subgame History	$H_{t-1} = \{a_{1,1}, a_{2,1}; a_{1,2}, a_{2,2}; \ldots a_{1,t-1}, a_{2,t-1}\}$
Discount factors	$\delta_i = (0 \;\; 1)$
Beliefs	$\theta_{s,i} = \begin{cases} \theta(H_{t-1,-i}) \\ 1 - \theta(H_{t-1,-i}) \end{cases}$
Foresight	L_i
Memory	Q_i
Expected payoffs	$\pi_i^e = F(V_i, \delta_i, \theta_i, L_i)$

Table A5. Elements of an NIPD.

Game	$g = g_i(A, v)$
Players	$i = 1, 2, \ldots, N$
Action space	$A_i = [\text{COOPERATE, DEFECT}] = [C, D]$
Pure strategy	$a_i \in A_i$
Pure strategy payoffs	$v_i = f(a_i, k)$

Table A6. Additional elements of a mixed-strategy NIPD.

Subgame history	$H_{t-1} = \{a_{i,1}, a_{j\neq i,1}; a_{i,2}, a_{j\neq i,2}; \ldots a_{i,t-1}, a_{j\neq i,t-1}\}$
Beliefs	$\theta_{s,i} = \begin{cases} \theta(H_{t-1,-i}) \\ 1 - \theta(H_{t-1,-i}) \end{cases}$
Expected payoffs	$\pi_i^e = F(v_i, \theta_i)$