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Behavioural Economics, Hyperbolic Discounting and Environmental Policy

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Abstract This paper reviews some recent research in "behavioural economics" with an application to environmental issues. Empirical results from behavioural economics provide a reminder that human behaviour is context-dependent, implying that policy may go awry if based upon models of behaviour which are inappropriate to the contexts in which decisions are made. Recognizing that agents may, in some contexts, systematically make mistakes raises challenging questions about the role of "paternalism" in government policy. The paper considers the research into hyperbolic discounting, and examines the implications for environmental policy. We develop a model of resource management under hyperbolic discounting, which shows that if a planner is unable to commit to a policy, the temptation to re-evaluate the policy in future could lead to an inadvertent collapse in the stocks of a natural resource.

Keywords Hyperbolic discounting · Resource economics · Time inconsistency · Fishery · Climate change · Preference reversal

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1 Introduction

Research in behavioural economics[1] has unearthed a litany of so-called anomalies in human behaviour, where people's actual choices do not appear to be explained by standard economic models. These anomalies include so-called bounded rationality (Simon 1957), the use of decision-making heuristics (Gigerenzer and Goldstein 1996), cognitive biases,[2] inconsistencies and systematic errors (McFadden 1999), and self-control problems (Elster 1979; Gul and Pesendorfer 2001). The results from behavioural economics research have captured the popular imagination, leading to bestselling books such as *Predictably Irrational* (Ariely 2008) and *Nudge* (Thaler and Sunstein 2008) among others.

One particularly simple but important modification to the standard model, considered in this paper, is the use of non-constant time discounting. The conventional discounted utility model was introduced by Samuelson (1937), who noted that the assumption of a constant discount rate was "in the nature of an hypothesis, subject to refutation by the observable facts". Empirical evidence has gradually been collected to cast doubt upon the hypothesis of constant discounting, and the literature on hyperbolic discounting has emerged. Hyperbolic discounting refers to the application of time-declining discount rates to trade-offs between present and future consumption.[3] A particularly commonly used model is the quasi-hyperbolic specification, which in discrete time has discount factors $\{1, \beta\delta, \beta\delta^2, \beta\delta^3\}$ (see e.g. Laibson 1997). These preferences can generate time-inconsistent plans (Strotz 1956), and potentially provide an explanation for procrastination, addiction, inadequate saving and various other commonly observed but otherwise perplexing human behaviours (Akerlof 1991). In some cases, plausible evolutionary reasons for these phenomena have been identified (Dasgupta and Maskin 2005).

These various behavioural anomalies pose difficulties for both economic theory and policy, but it is hardly surprising that real humans, in real social contexts, do not "always and everywhere" behave as omniscient, fully-rational utility maximisers. Economic models are useful simplifications of reality that provide insight into specific problems. They do not (and could not) provide a perfect description of reality. Krugman (1994) argues that economic models are akin to geographical maps—accurate but useless at a 1:1 scale (Robinson 1962, p 33); unrealistic but insightful at a 1:100,000 scale.[4] So the fact that behaviour does not always fit the standard models does not undermine the value of standard economic research. Nevertheless, empirical findings in behavioural economics do provide a vivid reminder of the merit of humility in economic modelling, and of the need to ensure that policy recommendations are based on models of human behaviour that are appropriate and sufficiently accurate for the context at hand.

[1] Diamond and Vartiainen (2007) use "behavioural economics" as an umbrella term describing approaches that seek to account for relevant features of human behavior that deviate from the standard economics framework. DellaVigna (2009) groups these deviations into three categories: non-standard preferences, non-standard beliefs, and non-standard decision-making. Mullainathan and Thaler (2000) also proposed three broad categories of deviations: bounded self-interest, bounded willpower and bounded rationality.

[2] Shogren and Taylor (2008) observe that a wide variety of terms are used to describe one or other behavioral failure, including: cognitive bias, anomaly, paradox, heuristic, misperception, fallacy, illusion, or paradigm.

[3] The term originally emerged from a discounting function which conformed to a hyperbola. It is now employed to refer to any schedule of discount rates which declines over time.

[4] In his classic paper on economic methodology, Friedman (1953) argues that important theories may have highly unrealistic assumptions. This can be viewed as consistent with the map analogy of Krugman (1994), provided that the assumptions which are not realistic are non-trivial to the problem at hand. For a critique, see Helm (1984).

If policy recommendations based on mainstream economic assumptions should be made with due modesty, so too should recommendations based on the 'stylized facts' of behavioural economics. For instance, laboratory evidence from dictator and ultimatum games[5] suggests that people really do care about fairness and equity, contrary to the common assumption of self-interest made in most microeconomics. However, List (2007) shows that in the dictator game, these results are sensitive to minor variation in the laboratory conditions. He enlarges the action set of the dictator so that she can take money from, as well as give it to, the other player. The result is that fewer dictators show the high levels of altruism seen in the original experimental paradigm. This is consistent with the view, advanced by Andreoni and Bernheim (2009) and Levitt and List (2007), that "audience effects" and "social norms" have a powerful impact on behaviour. In this case, the ability to take, as well as give, to the other player gives the dictator a greater moral license to give nothing, rather than split the amount 50–50 or in some other proportion. Indeed, while some would regard these results as disappointing, they are more consistent with the observation that "random acts of kindness" are indeed random, rather than widely prevalent as one might infer from the laboratory experiments.

In short, the behavioural economics literature supports the conclusion that context is important to human behaviour, with the implication that the standard microeconomic model will not be applicable in all cases. Indeed, given the subtlety of contextual effects on behaviour, scepticism about any abstract and generalized claims about human behaviour is justifiable, whether derived from the mainstream or behavioural economics.

The context-dependency of human behaviour is of great interest for environmental economics and policy.[6] Environmental economic theory stresses the notion that externalities can be internalised through the creation of new markets or other financial incentives, and assumes that agents respond to those incentives in a rational and consistent manner. Unfortunately, Crocker et al. (1998) argue that the usual assumption of rationality may be particularly problematic for environmental goods and services. When considering the natural environment, people have often not been socialised into making "rational" choices by the pressure of repeated exchanges on a market (Chu and Chu 1990); the underlying problem, after all, is that environmental markets often do not exist in the first place.

Shogren and Taylor (2008) point out that some economists have understood the significance of behavioural economics to environmental issues for at least two decades (e.g. Kahneman et al. 1986). The influence has been substantial in the areas of non-market valuation, the treatment of low-probability but high-gravity events, and the possibility of self-enforcing co-operative arrangements to provide public goods in the presence of altruistic willing punishers. Another obvious area where behavioural economics is relevant is the adoption of measures to increase energy efficiency (Gillingham et al. 2009). Here, information problems, decision-making heuristics,[7] and high short-term discount rates consistent with hyperbolic discounting, result in much lower rates of adoption than might otherwise be expected (e.g. Hausman 1979).

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[5] In the two-player ultimatum game, a "proposer" offers a division of a fixed amount of money, which a "responder" can accept or reject. If the division is rejected neither player receives anything (Guth et al. 1982). In the dictator game, the proposer simply states the division of the money and the responder has no veto power (Kahneman et al. 1986; Forsythe et al. 1994).

[6] The collection edited by Diamond and Vartiainen (2007) considers the implications of behavioural economics in a range of policy areas, including public economics, development, law, labour and health economics, but they do not consider environmental policy.

[7] For instance, having friends or family who have installed energy efficiency measures has a very strong influence on take-up rates (Oxera 2006).

This paper focusses on the nexus between discounting, behavioural economics and environmental policy, with the following structure. Section 2 reviews the recent debates on discounting, particularly with respect to climate-change policy, and considers research on time preference from psychology and economics within that context. The empirical evidence for and against hyperbolic discounting is examined, and then some general policy implications are teased out. Section 3 develops a model of hyperbolic discounting and renewable resource management, in which the behaviour of "committed" and "naive" planners is determined. The model shows that, in theory, if a planner is unable to commit to a policy, the temptation to re-evaluate the policy in future could lead to an inadvertent collapse in the stock of the resource. While at first glance hyperbolic discounting is both a sufficient and plausible explanation for a fish stock collapse, other explanations are likely to have more explanatory power. Section 4 concludes.

2 Debates About Discounting and the Behavioural Evidence

2.1 Clarifying the Debate

Over the past few years, heated debates over time discounting have reached mainstream audiences (e.g. Economist 2006). These were intensified by the controversial review of the economics of climate change by Stern (2007), who employed a lower consumption discount rate, $\rho = 1.4\%$ per annum on average, than in previous research and therefore recommended more rapid reductions in greenhouse gas emissions.[8]

Stern (2007) arrived at this consumption discount rate by adopting a utilitarian ethical perspective that placed as much weight on future generations as the present. He thus employed a utility discount rate, δ, of only 0.1% per annum, to capture the exogenous risks of humanity becoming extinct by some disaster, such as a meteorite strike, rather than any discrimination against future generations.[9]

In contrast to Stern's approach, previous research tended to apply discount rates based on market interest rates, which reflect the sum of many actual individual choices. Historic market interest rates (ignoring past and present financial crises) have averaged around 6%, and most previous research applied consumption discount rates at roughly this level (e.g. Nordhaus and Boyer 2000).

Long debates followed about the merits of the ethical and market approaches to discounting.[10] A long line of philosophers and economists support a utilitarian approach, which gives future generations similar weight to the present (Ramsey 1928; Pigou 1932; Harrod 1948; Solow 1974; Dasgupta 2008; Heal 2009), while others argued that any analysis needed to be consistent with aggregate preferences as revealed by behaviour on markets (Nordhaus 2007; Weitzman 2007).

[8] Stern's implicit carbon price along the stabilization pathway was US $25–35/ton, compared to a business-as-usual pathway of $85/ton. He recommended that atmospheric greenhouse gas concentrations should peak at 450–550 ppmv (parts per million by volume). In contrast, much (but not all) previous economic analysis had used market interest rates of well above 2%, with concentrations reaching around 700 ppmv and carbon prices of considerably less than $20/ton of CO_2, and often in single digits. Current carbon dioxide prices in the European greenhouse gas emissions trading scheme are around $20/ton, and have been as high as around $40/ton.

[9] Stern (2007) set the elasticity of marginal utility, η, to unity. Consumption growth, g, varied from one region and model run to another, but averaged 1.3% per annum. As such, the consumption discount rate, $\rho = \delta + \eta g$, averaged 1.4% per annum.

[10] Beckerman and Hepburn (2007) provide a review of the issues.

There are at least three pragmatic routes to reconciling these differences. First, Weitzman (1998, 2001) shows that taking uncertainty into account implies that the certainty-equivalent consumption discount rate declines over time to a lower bound.[11] For instance, Weitzman (2007) notes that if Stern's 1.4% discount rate is as likely to be correct as a 6% market discount rate, then the certainty-equivalent average discount rate over 100 years is 2%. In other words, the logic of uncertainty makes the arguments about discounting less significant. Similarly, Weitzman (2009) shows that accounting for "unknown unknowns," by assuming the probabilities are themselves uncertain, further bridges the divide between the discount rate of the Stern Review and higher market interest rates.

Second, recall that a discount rate is simply the rate of change of a relative price over time. It may be consistent to apply higher discount rates for aggregate consumption, if aggregate consumption is set to continue growing rapidly, and lower discount rates for (increasingly scarce) natural capital (Sterner and Persson 2008). If climate change disproportionately damages natural capital, a lower discount rate for climate damages, compared with other goods, may be justified.

Third, the use of a declining utility discount rate would also bridge the gap between Stern and his critics. To the extent that evidence from individual behaviour is appropriate for a global commons problem, then empirical evidence of hyperbolic discounting would be relevant. There are, however, various problems with the idea of basing social cost-benefit analysis on hyperbolic discounting (Pearce et al. 2003; Groom et al. 2005). Before considering the problems, we first review the empirical evidence in support of the stylised fact of hyperbolic discounting.

2.2 Evidence for and Against Hyperbolic Discounting

Laboratory and field experiments by behavioural economists and psychologists have found robust evidence of "preference reversals", where subjects choose x today over y tomorrow, but choose y in a year and a day over x in one year. Such preference reversals are not consistent with exponential discounting.

One theory consistent with preference reversals is that agents have "diminishing impatience" and discount the future with a declining discount rate. A large number of such experiments, with a variety of rewards such as money, durable goods, sweets, relief from noise and so on, suggest that impatience in the present is higher than impatience with respect to trade-offs in the future (e.g. Ainslie 1992; Frederick et al. 2002; DellaVigna 2009). Interestingly, these preferences appear in both humans and animals, and while they may seem irrational, there are plausible ways in which they could confer an evolutionary advantage.[12]

However, various scholars have questioned whether the evidence for hyperbolic discounting is as robust as is claimed.[13] First, a majority of the laboratory studies on time preference have employed hypothetical monetary rewards, and involve a variety of potential confounding factors (Chabris et al. 2008). Irrespective of whether the individual is an exponential or hyperbolic discounter, time preferences are not identified by experiments when there exist

[11] Gollier (2002a,b) provides more comprehensive treatments of the theoretical issues.

[12] Dasgupta and Maskin (2005) argue that evolutionary pressure, given uncertainty and waiting costs, may have generated such preferences. Halevy (2008) argues that diminishing impatience might arise from risk preferences in a non-expected utility model in which agents are disproportionately sensitive to certainty (Kahneman and Tversky 1979).

[13] For instance, Sopher and Sheth (2005) only find very weak evidence for hyperbolic discounting. However, like experiments supporting hyperbolic discounting, their experiment involved hypothetical choices between different monetary amounts, rather than real, non-monetary rewards.

(or are presumed to exist) intertemporal arbitrage opportunities. More generally, attempts to measure discount functions have generated conflicting results (Frederick et al. 2002).

Second, hyperbolic discounting is not the only theory consistent with preference reversals. For instance, Rubinstein (2003) argues that the experimental evidence on preference reversals is also consistent with the use of a heuristic based on “similarity relations” (Tversky 1977). That is, when comparing two alternatives, subjects ignore small differences and focus on larger differences. For instance, when subjects are asked to choose between a reward “today” and “1 year from now”, the delay is large. In contrast, the difference between a reward “10 years from now” and “11 years from now” is minor, so the person will instead focus on the rewards on offer.

Third, Read (2001) argues that the apparent evidence of hyperbolic discounting may instead be evidence of “sub-additive discounting”, where discounting over a given period is greater when the period is divided into subintervals than when it is left undivided. This implies an inverse relationship between the discount rate and the size of the delay. In other words, Read (2001) argues that the discount rate is not a function of relative location in time, as proponents of hyperbolic discounting suggest, but is rather a function of the size of the time delay.

Nevertheless, careful reviews of the field (Frederick et al. 2002; DellaVigna 2009) conclude that the evidence for hyperbolic discounting is robust, and does not rely solely on the evidence for preference reversals. More recent evidence, including from functional imaging of brain areas involved in making intertemporal decisions, also supports the quasi-hyperbolic discounting model (McClure et al. 2007). Additionally, the hyperbolic discounting model can reconcile the simultaneous presence of substantial credit card borrowing, at high interest rates, with and substantial illiquid wealth accumulation at lower interest rates (Laibson et al. 2010).

Finally, there is robust evidence that people do have self-control problems of the sort implicated by hyperbolic discounting, and that commitment mechanisms can reduce procrastination and improve people’s task performance (Ariely and Wertenbroch 2002; Gine et al. 2009). Moreover, significant minorities of people will recognize such problems and effectively pay for commitment mechanisms to help solve them (Ashraf et al. 2006; DellaVigna and Malmendier 2004, 2006).

2.3 Some Policy Implications

If hyperbolic discounting provides an accurate description, at least in some contexts, of the time preferences of humans and animals, the policy implications are both interesting and extremely challenging. Hyperbolic discounting might explain a range of otherwise perplexing human behaviours, including drug addiction (Gruber and Koszegi 2001), sub-optimally low savings rates (Laibson 1994, 1997; Laibson et al. 1998; Harris and Laibson 2001), procrastination (O’Donoghue and Rabin (1999a,b); Benabou and Tirole 2004) and various others (Akerlof 1991). The ability to build quantitative models to formally explain these phenomena will prove (and has already proven) valuable in systematically identifying solutions and policy interventions to reduce the impact of these significant social problems.

In Section 2.1, we noted that it might be thought that hyperbolic discounting could also resolve the debates about whether utility discount rates for social cost-benefit analysis should be based on (high) market values, or (lower) ethically-derived values.[14] However, there are at least two significant problems in applying hyperbolic discounting in this context. First, although (time-inconsistent) individual preferences may explain procrastination and addic-

[14] Cropper and Laibson (1999) consider hyperbolic discounting in the context of project evaluation.

tion, using such preferences for social decision-making across generations may not seem appropriate or wise. Second, while the utility discount rate in the Stern (2007) review was indeed the subject of debate, the major area of contention was the overall consumption discount rate. In this context, the possibility of declining consumption discount rates is better addressed through accounting for the uncertainty and ambiguity in future events. In short, the case for incorporating hyperbolic utility discounting into government policy evaluation is weak (Groom et al. 2005).

One of the most difficult policy challenges emerging from the behavioural economics literature, including hyperbolic discounting, relates to the fact that, in some contexts, people systematically make choices that leave them worse off. Preference reversals explained by hyperbolic discounting imply that choices made in the heat of the moment may conflict with the agent's earlier intentions. How is welfare to be evaluated when people's preferences are time-inconsistent?

More generally, if people do not make the best choices for themselves, does this imply that choices do not provide reliable signals of well-being? Clearly, this presents an important challenge to conventional economics. There are at least four possible responses (Bernheim 2009). First, it might be argued that while choices are not always a perfect guide to "true" well-being, they provide sufficient information such that welfare analysis is possible using non-standard objective functions which, for instance, allow for individuals to pursue conflicting objectives simultaneously (Koszegi and Rabin 2008). Second, if choices do not provide a reliable window onto true well-being, other mechanisms of measuring well-being might be exploited, such as self-reported happiness or neurological activity (Kahneman et al. 1997; Kahneman and Sugden 2005; Layard 2005). Third, Bernheim and Rangel (2010) propose a framework that defines welfare directly in terms of choice, regardless of well-being, so that welfare is increased if people can have what they would have chosen to have, irrespective of their well-being, and irrespective of whether they were actually offered a choice.[15] Fourth, several economists have sought to define welfare, again without direct reference to individual well-being, in terms of opportunity sets or "functionings" (Sen 1985; Arrow 1965; Sugden 2004). On this view, policy should focus on providing people with opportunities, rather than what they make of those opportunities. The third and fourth frameworks clearly place intrinsic value on the freedom to choose, and potentially also the freedom to make one's own mistakes.

With the first and second approaches, welfare is still defined in terms of individual well-being. If individual choices do not maximise well-being, then there is a role for government intervention. Ideally, such intervention would, to the extent possible, preserve individual freedoms. With this idea in mind, Thaler and Sunstein (2003) proposed the concept of libertarian paternalism, which recognizes that a planner with influence over the choice architecture will, by act or omission, influence people's choices without necessarily limiting their freedom to choose. They call for this influence to be deployed to nudge people towards making better decisions (Thaler and Sunstein 2008). This begs the question of the definition of a "better decision", but they provide some context-specific examples where this is self-evident. The policy implication is that small nudges (e.g. the careful framing of decisions through the way information is presented, or the judicious specification of default options etc.) can guide, but not force, people away from their own self-destructive biases and lack of self-control. In the context of hyperbolic discounting, self-control problems might be explained to people, with planners providing people with the option to adopt a commitment device if they wish.

[15] However, some theoretical and empirical research suggests that it may be possible to give people too much choice (Iyengar and Lepper 2000; Irons and Hepburn 2007; Kamenica 2008).

Indeed, as discussed above, a large minority of people do take up such an offer, and it does appear to improve their well-being. The policy challenge is, then, to determine suitable commitment devices.

In the context of addiction, (Bernheim and Rangel 2004) argue that the presence of the addictive substance causes the brain to malfunction, such that choices are suspect. In such cases, Bernheim and Rangel (2010) argue that welfare analysis should be based on choices made before the influence of the addictive substance. For instance, a precommitment to stop using the substance would be privileged over an immediate desire to relapse. Similarly, the application of their choice-theoretic welfare framework to hyperbolic discounting, with some refinements, supports the view that the "long-run criterion", or the committed pathway (see Section 3.3.1 below), maximises welfare (Bernheim and Rangel 2010). Welfare would not be based on a "multi-self Pareto criterion", in which an individual is conceived to have many time-dated selves.

In other words, in all these different normative frameworks, it is plausible that estimations of welfare should be based upon what is described as the "committed" pathway, rather than the "naive" pathway, or paths based around the notion of a "sophisticated" individual who engages in game with future selves in search for a multi-self equilibrium (see Section 3.3.1 below for explanations of these pathways). We turn now to compare committed and naive paths in a model of renewable resource management.

3 A Model of Hyperbolic Discounting and Resource Management

3.1 Introduction and Motivation

We examine a model of renewable resource management under hyperbolic discounting. The renewable resource is a fishery, although variations of the model could apply to forestry, water resources, or even Earth's carbon cycle, where the renewable resource is the natural rate of sequestration of carbon dioxide from the atmosphere into terrestrial ecosystems and the oceans. We determine consumption and stock pathways for a planner who is either committed, in the sense that they choose an optimal path at time $t = 0$ and stick to it, or naive, in that they believe themselves to be committed but in fact re-optimize and adjust their plan as time passes. The examination of a series of actual naive pathways in continuous time is one of the contributions of this paper: Strotz (1956) sketched out several anticipated consumption paths for a naive individual, but no actual consumption path.[16] The theoretical model is then discussed with reference to the real-life collapse of the North Atlantic cod and the Peruvian anchovy.

3.2 The Model

Suppose a planner manages a fish stock of size $x(t)$ at time t. In the absence of any harvesting, assume that the net growth rate (births minus deaths) of the fish population, $F(x)$, is given by:

$$F(x) = Ax(t)[\overline{x} - x(t)][x(t) - \underline{x}] \tag{1}$$

[16] Sophisticated pathways are of less interest, and have also been examined in related settings by Barro (1999) and Karp (2005), the latter of whom determines a time-consistent Markov Perfect equilibrium in a model with a stock pollutant (in this case carbon dioxide).

where A is a constant, $\overline{x}$ is the carrying capacity of the stock, which is the equilibrium stock level in the absence of any harvesting, and $\underline{x}$ is the minimum viable stock level.[17] The planner derives utility $u(h)$ from harvesting fish at harvesting rate $h(t)$, where utility is isoelastic in harvesting

$$u(h) = \frac{h(t)^{(1-\eta)}}{1-\eta} \tag{2}$$

where η is the elasticity of marginal utility. The planner discounts utility over time with discounting function

$$D(t) = \exp\left\{-\int_0^t \delta(\tau)d\tau\right\} \tag{3}$$

where $\delta(t) > 0$ is the time-varying discount rate. The planner's objective is to determine the harvesting rate $h(t)$ which maximises discounted utility over an infinite time horizon:

$$\max_{h(t)}\left\{\int_0^\infty u(h)D(t)dt\right\} \tag{4}$$

subject to

$$\dot{x}(t) = F(x) - h(t) \tag{5}$$
$$x(0) = x_0 \tag{6}$$
$$h(t) \geq 0 \tag{7}$$
$$x(t) \geq 0 \tag{8}$$

where x_0 is the initial stock level at $t = 0$.

The analysis can be facilitated by a change of variable from time $t \in [0, \infty]$ to discount function $D \in [1, 0]$, as presented in Duncan et al. (2010). After specifying the Hamiltonian and solving for the unconstrained case ($h > 0$, $x > 0$), the necessary conditions for optimality give rise to the standard equations (transformed back into the t dimension)

$$\dot{x}(t) = F(x) - h(t) \tag{9}$$
$$\dot{h}(t) = \frac{h(t)}{\eta}\left[F'(x) - \delta(t)\right] \tag{10}$$

with $x(0) = x_0$. Note that for values of $0 < \eta < 1$, the non-negativity constraint in Eq. (8) on x can only bind in the limit $t \to \infty$.[18] Similarly, the non-negativity constraint in Eq. (7) on h can only bind in the limit $t \to \infty$, because the optimal solution will not set the harvesting rate to zero while stock can still be harvested.

This system of differential equations is non-linear and will also be non-autonomous if the discount rate is time-varying. Let the time-varying discount rate $\delta(t)$ be specified as follows

$$\delta(t) = \underline{\delta} + (\overline{\delta} - \underline{\delta})e^{-\chi t} \tag{11}$$

[17] The form of the natural growth rate $F(x)$ in Eq. (1) is equivalent to the expression given by Clark (1990, p.23), which is $F(x) = rx(x/K_0 - 1)(1 - x/K)$, when $A = r/(K_0 K)$, $K_0 = \underline{x}$ and $K = \overline{x}$.

[18] See Duncan et al. (2010) for a more detailed analysis.

so that the discount rate declines from $\overline{\delta}$ at $t = 0$ to $\underline{\delta}$ as $t \to \infty$. From (3), the discount function $D(t)$ associated with this discount rate is

$$D(t) = \exp\left\{-\left[\underline{\delta}t + \frac{(\overline{\delta} - \underline{\delta})}{\chi}\left(1 - e^{-\chi t}\right)\right]\right\} \tag{12}$$

Noting that

$$\dot{\delta}(t) = -\chi(\overline{\delta} - \underline{\delta})e^{-\chi t} = -\chi(\delta(t) - \underline{\delta}) \tag{13}$$

allows us to augment the states with $\delta(t)$ to yield the three state autonomous system

$$\begin{bmatrix} \dot{x}(t) \\ \dot{h}(t) \\ \dot{\delta}(t) \end{bmatrix} = \begin{bmatrix} F(x) - h(t) \\ \frac{h(t)}{\eta}[F'(x) - \delta(t)] \\ -\chi(\delta(t) - \underline{\delta}) \end{bmatrix} \tag{14}$$

This autonomous system cannot be employed to analyse stability of the underlying non-autonomous system, but it can be used to determine appropriate trajectories by numerical integration. There are two equilibria of interest of the system, namely a *collapse* equilibrium ($x = 0, h = 0$) and a *sustainable* equilibrium ($x = x_s, h = h_s$) where the harvesting rate equals the net rate of growth. The collapse equilibrium is stable. The sustainable solution, which is a saddle point, must satisfy $F(x_s) = h_s$ and $F'(x_s) = \underline{\delta}$. The latter equation is solvable using Eq. (1) to give a unique solution satisfying the requirement that $h(t) > 0$, namely

$$x_s = \frac{1}{3}\left[(\underline{x} + \overline{x}) + \sqrt{(\underline{x} + \overline{x})^2 - 3\left(\underline{x}\overline{x} + \frac{\delta}{A}\right)}\right] \tag{15}$$

and correspondingly the optimal sustainable harvesting rate is given by

$$h_s = Ax_s(\overline{x} - x_s)(x_s - \underline{x}) \tag{16}$$

The sustainable and collapse equilibria are shown in Fig. 1, which also shows optimal trajectories to these equilibria under constant discounting with $\delta = 0.025$. Trajectories under exponential discounting are shown in Figs. 2 and 3. All figures in this paper employ the following parameter values: $\underline{x} = 1.0$, $\overline{x} = 3.0$, $A = 0.02$, $\eta = 0.7$, $\overline{\delta} = 0.15$, $\underline{\delta} = 0.025$, and $\chi = 0.1$.

3.3 Results

Having analytically determined the two relevant equilibria, and noted their stability, we can now numerically examine some illustrative pathways towards these equilibria, and determine associated utility levels along relevant pathways. Simulations employed the ode113 routine in MATLAB for solving non-stiff differential equations, and are explained in more detail by Duncan et al. (2010).

We firstly examine the trajectories followed by a *committed* hyperbolic planner, who determines the optimal pathway at $t = 0$ and is able to follow it through to equilibrium. After having specified some committed pathways, we can examine how these pathways differ from those of a *naive* hyperbolic planner, who believes herself to be committed but in fact, when the time comes, re-optimises the pathway and decides to harvest a little more of the stock than had been planned.[19]

[19] The third possibility is that the planner is sophisticated, and assuming no commitment mechanism is available, such a planner would seek to find a solution to a multi-self game (Karp 2005).

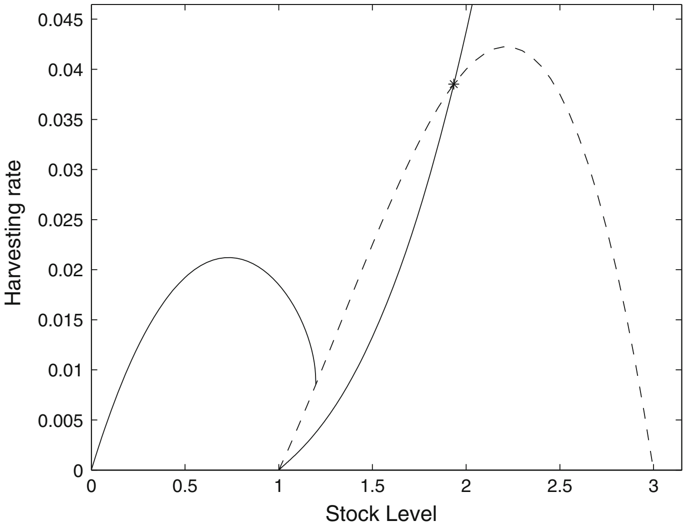

Fig. 1 Phase plane trajectories of optimal sustainable and collapse solutions (*solid*), with a constant discount rate, and with a natural growth rate with critical depensation that follows the *curve* shown by the *dashed line*. The sustainable trajectory converges to the optimal sustainable yield (*) while the collapse solution converges to zero stock

3.3.1 Sustainable Pathways

The optimal sustainable solution approaches the saddle point equilibrium asymptotically along the stable manifold. Example trajectories are shown in Fig. 2, which illustrates pathways projected onto the (h, x) plane. The important feature of these pathways is the harvesting rate is high in the initial period, when the discount rate is high. The result is that fish stocks initially decrease. However, as the discount rate falls over time, the planner reduces the harvest rate, temporarily, to allow the stock to rise gradually towards the equilibrium level, x_s, so that harvest rate can also then increase towards the equilibrium level, h_s.

The committed planner can use some mechanism to hold herself to the optimal sustainable pathway, without succumbing the temptation to reoptimise as time passes. The temptation to reoptimise arises because the planner discounts the future hyperbolically, such that the discount rate now is high, while the future discount rate is expected to be lower. When the future comes, however, instantaneous discount rates are still high, and the planner would prefer to consume more of the stock than had been planned. A commitment mechanism ensures that everything does not come off the rails.

In contrast, the naive planner believes himself to be committed, and thus believes he will follow the committed trajectory. In fact, however, the naive planner reoptimises as time passes. In Fig. 2, the dotted curve shows the trajectory of a continuously reoptimising naive planner. Assuming the sustainable solution is optimal, the naive planner will set the initial harvesting rate $h(0)$ to follow a path to (x_s, h_s). But a moment later, he discards the plan, restarts, setting a new initial harvesting rate, given the new stock level, as if starting on a new path to (x_s, h_s). For each restart, the naive planner intends to harvest at a high rate now, then reduce harvest rates for a period, and then increase harvest rates again as stocks rise towards the long-run stable equilibrium. Each of the $(h(0), x(0))$ pairs,

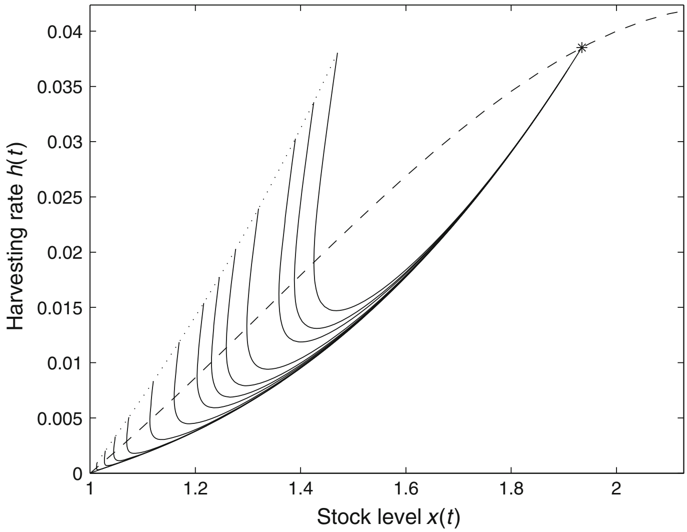

Fig. 2 Plot of trajectories for optimal sustainable solutions (*solid*), with the 'hyperbolic' discount function described by Eq. (12). The *dashed curve* shows the locus of the natural growth function $F(x) = h$ and the location of the sustainable equilibrium, (x_s, h_s), is marked by an *asterisk*. The trajectory of a continuously re-optimising naive planner is shown by the *dotted curve*

connected by the dotted curve in Fig. 2, reflect that intention. Under continual reoptimisation, the result is that the naive planner follows the locus traced out by these $(h(0), x(0))$ pairs. As time passes, harvesting rates are higher than was planned $t = 0$, and stock levels fall.

3.3.2 Collapse Pathways

The equilibrium associated with the collapse solution, $(x, h) = (0, 0)$, is a stable node. For a given initial stock $x(0) = x_0$, there are a variety of permissible initial harvesting rates, $h(0)$, that will converge to the collapse solution. One such pathway will correspond to the optimal collapse trajectory. Figure 3 shows this optimal collapse trajectory for a range of initial stock levels.

For the committed planner, collapse can be optimal if the productivity of the stock is not high enough to justify the "investment" (in the form of foregone consumption) necessary to return stock levels to the sustainable equilibrium. Indeed, there is a critical initial stock level, x_c, below which returns on the stock are not high enough and collapse provides greater utility than sustainable management.

Interestingly, it is possible to find sustainable trajectories which start with $x(0) > x_c$ but which, for a period of time, the stock level falls below x_c. This is acceptable provided that the planner remains committed to the optimal sustainable path, as stocks will subsequently rise. However, if the harvesting policy were stopped and restarted during this period when $x < x_c$, the optimal policy would then be to follow the collapse solution.

3.3.3 Utility Comparisons and Unforeseen Collapse

For given initial stock level, x_0, Fig. 4 compares the utility from the optimal sustainable and collapse pathways. The two curves intersect at the critical initial stock level, x_c. As noted,

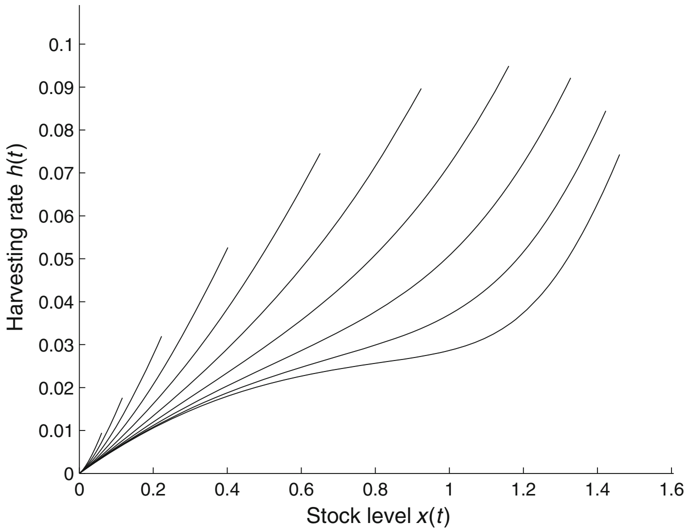

Fig. 3 Plot of trajectories for optimal collapse solutions (*solid*), for a range of initial conditions $x(0)$

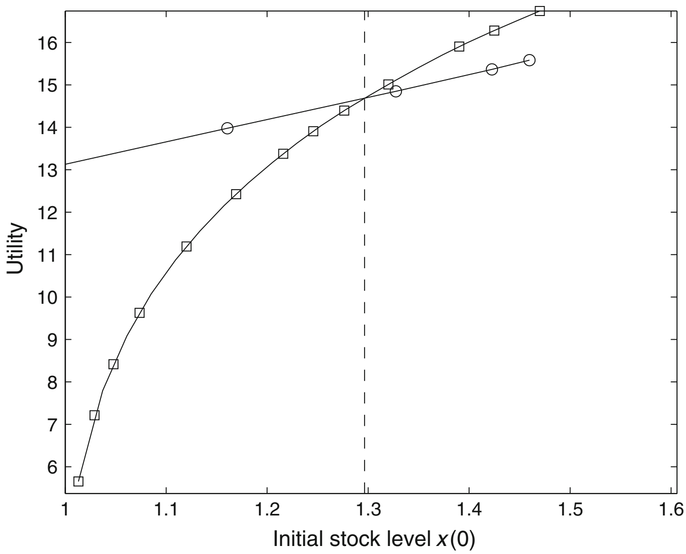

Fig. 4 Utility for both the optimal sustainable (*open square*) and optimal collapse (*open circle*) solutions, plotted against initial stock level, $x(0)$. The critical initial stock level, x_c is shown by the *vertical dashed line*

if initial stock levels are low enough, the optimal sustainable harvest rate is simply too low, and the planner is better off collapsing the stock, which is analogous to liquidating the asset and investing in an alternative higher-yielding asset.

A notable feature of the model is that an unforseen collapse might occur. Under hyperbolic discounting, the optimal sustainable policy involves an initial reduction in stock levels, where the discount rate is high, followed swiftly by a reduction in the harvesting rate and an increase in stock levels as the discount rate declines, as shown in Fig. 2. As discussed above, if the planner is committed to this pathway and follows it through to $t \to \infty$, no problems arise. However, if the planner cannot commit to the policy, and naively re-optimises along this path, then stocks may fall below the critical level, x_c, at which point the new optimal policy is to collapse the stock.

Moreover, even if the trajectory has not yet crossed the critical stock level x_c, if the policy is restarted at time t_r where $x(t_r) < x(0)$, and the new optimization is based on a lower initial stock level, then repeatedly restarting the optimization may drive the initial stock level down to the point where $x(0) < x_c$, making the collapse solution optimal. If the time between restarts becomes small, then the stock trajectory approaches the continuously naive policy shown by the dotted line in Fig. 2, which drives down the stock level until it falls below x_c, at which point a collapse is optimal. For a continuously re-optimising naive planner, a necessary condition for such an unforseen collapse is that $\overline{\delta} > F'(\underline{x})$, and more generally that the time-varying discount rate, $\delta(t)$, is of a profile such that $\dot{x}(0) < 0$ for all $x(0) > x_c$, which is to say that the initial harvesting level, $h(0)$, must exceed the regeneration $F(x(0))$ of the stock for any $x(0) > x_c$, so that stock levels fall along the naive path until the critical stock level is reached.

3.4 Discussion

3.4.1 The Case of the Canadian Cod

In 1977, Canada extended its jurisdiction and took a wider role in the management of fish stocks of Newfoundland. During the course of the 1980s, the Northern Atlantic Fisheries Organisation (NAFO) and the Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) employed virtual population analysis to estimate and forecast Atlantic cod stock levels, including the northern cod. After the collapse of the stock, Walters and Maguire (1996) used more advanced virtual population analysis to show that NAFO had significantly overestimated the true population levels. These overestimates of the current population encouraged harvesting at higher than optimal levels and was one of the principal factors in the demise of the northern Atlantic cod.

Another factor in the collapse was NAFO's consistently over-optimistic predictions of future stock levels. The NAFO forecast in 1982 shows sharp population increases. It became clear a year later that the 1982 prediction for 1983 population levels had been over-optimistic. In 1983, predictions for the next two years show another rise in stock levels. Estimates in 1984, however, again revealed the 1983 predictions to have been too optimistic. The pattern repeats itself for the data available in 1984, 1986 and 1991.

While the initial overestimate of stock levels is, by itself, an adequate explanation for the stock collapse, it is surprising that continual overestimates of stock levels occurred. Fishing interests and policymakers, while wanting to ensure a sustainable catch in the long run, also want to justify high catches in the present. In other words, like people in all endeavours, the present time is given particular salience, which is a key characteristic of hyperbolic discounting (Akerlof 1991). In other words, it is not impossible that hyperbolic discounting made some contribution, alongside the more significant problems of stock overestimation, towards the collapse of the Canadian cod.

3.4.2 The Case of the Peruvian Anchovy

One could similarly argue that the Peruvian authorities managed the Peruvian anchovy in the 1970s in a manner consistent with naive hyperbolic discounting. Upon the advice of experts such as the Instituto del Mar del Peru (1981), they initially made efforts to avoid collapse of the stock. In 1972–1973, with the arrival of El Nino, experts advised the government that opening the stock to fishing would lead to a collapse. Nevertheless, the authorities opened the fishery, and stock levels collapsed.

This decision could be explained by a number of reasons, among them uncertain science and management failure. Time-inconsistent preferences are a further possibility. The economic benefits of opening the resource accrued immediately (i.e. in 1972–1973), whereas the costs—cessation of anchovy fishing in later years—accrued in the future. The salience of the present may have dominated the decision-making process and, in a context of some uncertainty, resulted in an environmental collapse.

4 Conclusion

Behavioural economics, and research on hyperbolic discounting in particular, has useful contributions to make to environmental economic theory, as in other areas of applied economics. Indeed, many environmental economists have effectively been engaged in behavioural economics research over several decades, without perhaps describing their work as such.

The key insights from behavioural economics for environmental policy are not dissimilar to those in other policy areas. Behaviour is context dependent, and policy recommendations should be sure to rely on models that make assumptions appropriate for the context. Environmental issues have the added challenge that often markets are already missing, so the social context is particularly important, because individuals will not have been forced to adapt their behaviour to account for arbitrage pressures in many environmental contexts (Shogren and Taylor 2008). As such, behavioural anomalies may be more likely to be prevalent.

If this is so, recovering consistent preferences may be difficult, which can create challenging problems for normative analysis. The literature on behavioural welfare economics is evolving rather rapidly, and in several exciting directions, and these developments should be of great interest to environmental economists. In the context of hyperbolic discounting, where welfare analysis is also complicated by time-inconsistency, there nevertheless seems concordance in the literature that pre-commitments should be respected. It follows that policy interventions that aim to design commitment devices and provide them for people to adopt may increase welfare.

In environmental policy, greater research on the design of appropriate commitment mechanisms is an important area of future research, not only in fisheries but also in renewable resource policy generally, and climate-change policy in particular. While we do not wish to overstate the notion that hyperbolic discounting is a primary cause of environmental problems—which arise instead primarily from externalities, information problems and other market failures—hyperbolic discounting and other behavioural failures may exacerbate such problems, and indeed the theoretical model in this paper indicates that naive hyperbolic discounting can, even without other market failures, be a sufficient condition for an unforeseen resource collapse.

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