Discounting for Environmental Accounts
Report for the Office for National Statistics
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Executive summary

We recommend that the Office for National Statistics discounts natural capital for use in environmental accounts using the schedule of discount rates given in HM Treasury's Green Book. Specifically:

1) The increased relative scarcity of natural capital and its lack of substitutability with other consumption goods justify inflating the estimated costs and benefits within environmental accounts. This holds even when discounting is undertaken on a real basis. This is a theoretically equivalent approach to the use of dual discount rates, but has the advantage of ensuring consistency between different fields of valuation within the ONS.
2) There are strong arguments for preferring the use of a Social Rate of Time Preference over discount rates based on financial market yields when constructing environmental accounts.
3) The parameter values that are used to calibrate the Ramsey Rule within the Green Book are consistent with recent best estimates in the academic literature.
4) We recommend incorporating a risk premium into the discount rate within environmental accounts. Given that the systematic risk component of natural capital appears to be low, and as there is some evidence that financial markets have historically over-rewarded risk-bearing, this risk premium should be small. Therefore, while justified on different grounds, our opinion is that the 1% "catastrophe" adjustment to the standard Ramsey Rule within the Green Book recommended rate is appropriate.
5) Our recommendation is that the costs and benefits of natural capital are discounted over their entire life and not restricted to 50 years.
6) The Green Book recommends a declining schedule of discount rates for valuing costs and benefits with a maturity of over thirty years. This schedule is consistent with recent best estimates in the academic literature and is appropriate for use by the ONS in environmental accounts.

Introduction

This report provides guidance on social discounting for the purposes of natural capital accounting. The choice that confronts the ONS is ostensibly between market rates and the Social Rate of Time Preference (STP). The appropriate discount rate to use to establish the value in present value terms of the stream of benefits from natural capital assets depends on many factors, and is also influenced by the purpose of the accounts. Two possible purposes are to:

1) Establish a value of natural capital that can enter into the ONS National Accounts and serve as a measure of wealth over time;

2) Provide a benchmark valuation of Natural Capital as an input for Cost Benefit Analysis (CBA) of public projects, so that the impact of public projects on typically non-marketed environmental resources can be systematically evaluated across government projects.

There are many theoretical principles that can be used to determine the appropriate discount rate for these purposes, but consistency is an important practical and pragmatic principle also. This is one of the main principles guiding our recommendations.

If 1) is the purpose then in principle provided there is *consistency across time* and *consistency across national accounts*, then it seems clear that in ensuring a measure of wealth is comparable across time, one could use either observable market rates or the Social Rate of Time Preference, as in the Treasury Guidelines for Cost Benefit Analysis: the Green Book. There are arguments on each side, but consistency is an important principle here. Ultimately though, our arguments err on the side of using the STP, as in the Green Book, unless good reason can be provided to deviate.

If 2) is the purpose of the accounts, as seemed likely from previous discussions with the ONS, then consistency *across government departments* is one of the chief organising principles. In this case the arguments for following the Green Book and using the STP therein are stronger. Doing so would be consistent with practices across government.

In each case, though, there are reasons to potentially deviate from the standard Green Book discounting approach. In theory, environmental goods should be treated differently from consumption goods when their substitutability is less than perfect. This leads to a practice known as “dual discounting”. Uncertainty is another aspect that can be incorporated into the discount rate, be it surrounding growth or project based risk. We explain both dual discounting and the role of uncertainty, as well as some of the arguments for and against market rates.

Market rates of return or Social Rate of Time Preference

Different governments use different discounting approaches. Many look towards market rates of return on government gilts, a “risk-free” measure of the opportunity cost of government funds (e.g. US, The Netherlands, Norway). Other countries embed their discounting procedures in theoretical measures of social welfare, and use the STP (UK, France). Typically the STP is represented by the Ramsey Rule, as in the Green Book (p. 97, Annex 6). It measures the welfare preserving rate of increase in consumption that *society* requires to compensate for reduction in consumption today by one unit, in a risk free world. The Ramsey rule stems from the discounted utilitarian measure of social welfare. Strictly, the STP is the correct discount rate when consumption is the numeraire, and market rates are appropriate when the numeraire is production. In the abstract frictionless economy the two rates would be identical.

In the absence of perfect competition, there has long been discussion about which of these perspectives on discount rates, market rates or STP, is best suited to the appraisal of government projects. In brief, one argument focusses on the source of funds for public expenditure. Some argue that if public investment displaces private investment, the market rate is most appropriate. Alternatively, if projects are funded by general taxation (consumption) then the STP might be more appropriate. Distortionary taxes mean that these two rates would be different (e.g. Lind 1982).

Another argument states that market rates may not reflect *social* values due to externalities, whereas since the STP stems directly from a social welfare function it might be better suited to evaluate whether projects are welfare enhancing. On the other side, calibrating the social welfare function is not straightforward and, some would argue, a little arbitrary. Arguments exist that it is better to use directly revealed preference (market rates) as an observable measure of how society trades off costs and benefits over time (Lind 1982). This argument is not a straightforward clash of normative versus positive arguments, of the type that beset Nordhaus and Stern after the Stern Review, since the Ramsey Rule can be calibrated using estimates that stem from revealed preference (see following section). It is rather an argument about the appropriate means of measuring social welfare.

Yet the arguments become particularly heated when projects span long-time horizons, Here different arguments prevail and the focus on normative (prescriptive) vs positive (descriptive) approaches becomes more pertinent. In this context market rates have the weakness that financial markets do not span periods longer than 40 years, and so there is no revealed rate of return for these longer horizons. Furthermore, it is frequently argued that even if such markets did exist the principle of revealed preference fails over long time horizons, since the people affected by long-term investments are simply not operating in today's markets. Future generations' preferences would only be reflected in market rates to the extent that current generations think about them in making inter-temporal decisions. This may result in more or less weight than future generations would choose for themselves.

In the case of natural capital, and valuing the flows of services that arise from it, the current time horizon is 50 years. This extends beyond the time horizon of most risk free financial instruments, but not dramatically so. However, the flow of services from many types of natural capital is reproducible and in principle could extent into the infinite future. Ignoring such flows would undervalue them, and ignoring the loss of them as a result of public investment would skew public decision making. We recommend that the valuation of natural capital should extend beyond the 50 year horizon. With long time horizons the arguments against using market rates as the discount rate become stronger, and the ethical arguments become more important. Perhaps more importantly, long-time horizons make issues of uncertainty more important. These issues are discussed below.

Our recommendation, on the balance of these arguments, and on the basis of harmonising with the current practice in the Green Book, would be to discount the flows from natural capital using the STP. This comes with the caveat that within that framework there are some good reasons to deviate from the 3.5% that is recommended for the medium term due to i) certain features of environmental goods; ii) the uncertainty associated with long-time horizons; and, iii) project based, systematic risk. We first discuss the parameterisation of the STP, and then discuss these caveats.

Parameters for the Ramsey Rule

The Green Book uses the STP as the social discount rate (SDR): the test rate for project appraisal. With a discounted Utilitarian inter-temporal social welfare function, the STP is characterised by the so-called Ramsey Rule:

$$SDR = \delta + \eta g = STP \qquad (1)$$

The STP captures two reasons for discounting: 1) the utility discount rate, δ; and, 2) the wealth effect ηg, where g is the growth rate of aggregate consumption and η is the elasticity of marginal utility. δ and η determine the shape of the inter-temporal welfare function in the discounted Utilitarian model. For instance, if η is a constant then the utility function is iso-elastic: $U(C_t) = (1-\eta)^{-1} C_t^{1-\eta}$. This is a typical assumption in applied cost-benefit analysis.

The Ramsey rule represents the welfare preserving rate of return to consumption, i.e. the rate at which consumption has to grow in the future in order to compensate for a loss of consumption (more saving or investment) today. In this sense it is an efficiency condition. A project that can beat this rate of return will more than compensate for the welfare loss today with returns in the future, and increase intertemporal social welfare as measured from today.

There are two dimensions to the STP. First, the more impatient is society, the higher the STP via δ. Second, the wealth effect reflects the fact that when we appraise projects we are interested in the state of well-being of our future selves or future generations. If we are richer in consumption terms in the future ($g > 0$), then with diminishing marginal utility ($\eta > 0$) future benefits add less to social welfare, or more to social welfare if the future is poorer ($g < 0$).

Of course, it being a theoretical construct there is no actual guidance within the Ramsey model of what values these parameters should take. As we now explain, these parameters must be calibrated according to one or other empirical method, or informed by a value judgement, depending upon one's interpretation of the Ramsey Rule. The STP also needs some prediction of future growth, g.

The utility discount rate, δ

The utility discount rate is the appropriate discount rate to use when the numeraire is utility, as opposed to consumption. The utility discount rate reflects *pure time preference,* which in the context of CBA represents the extent to which society treats future utility differently to present utility. There are several reasons why society might wish to place lower weight on future utilities than the present one. Each interpretation of δ leads to different means by which to estimate the parameter. One common interpretation, which we address in the section on risk, is that we should discount future utilities because of the prospect of some catastrophe. With this interpretation δ reflects a hazard rate. However, in this section we focus on the *pure time preference* interpretation, and frame δ as a societal preference parameter, ignoring catastrophic risk.

Along these lines, one set of interpretations is based on shorter, intra-generational time horizons, of say 40 years or less. In this case δ reflects, at the societal level, how individuals discount their own utility. Following the principle that CBA should represent the preferences of the affected population, a sensible approach would then be to estimate this parameter via revealed preference or experimental methods. Here δ is a measure of society's preference for the present, or impatience. Its estimation typically comes from looking at how individuals discount their own utility.

Another interpretation of δ relates to contexts in which intergenerational impacts are being considered, and horizons greater than 40 years are relevant. In such contexts CBA must address the fact that those facing the costs are not the same people that will receive the benefits. The discount rate then reflects an inter-personal discount rate which compares the utility of one generation with that of another. Hence in this case δ reflects a position on intergenerational equity and there is a need to consider matters of ethics and intergenerational justice.

There are two key traditions that typically inform the ethical debate concerning δ. First, the tradition of impartial Utilitarianism proposes that it is unethical to treat people or generations differently just because they appear at different points in time. Within this tradition is it argued that $\delta = 0$ is the correct approach. Ramsey was famously of this opinion. On the other hand there are those who take an alternative normative stance and argue that agent relative ethics are more important, and $\delta > 0$ is more appropriate. Arrow (1999) has an insightful discussion which makes the point that otherwise acceptable moral standards, such as equal treatment, do not have to be adhered to if they cause unacceptable levels of hardship in practice. A final normative stance is to assume that revealed preference is the appropriate source of information, i.e. what is commonly referred to as the *positive* stance. The arguments that took place after the Stern Review between Stern and Nordhaus centred on a disagreement between the equal treatment tradition and the revealed preference positive approach. This was couched as a normative vs positive debate, but in fact they are both distinct normative positions on intergenerational equity.

More recent evidence on the pure rate of time preference comes from a survey of experts undertaken by Drupp et al. (2015). When asked about public projects with time horizons great than 100 years, the responses had a mean (median, mode) of 1% (0.5%, 0%). These recommendations evidently contained both pure time preference and catastrophic risk elements, as well as a mixture of normative and positive approaches. See Table 1. This is broadly consistent with the Green Book value of 0.5%.

One final point concerns the pure rate of time preference and whether this differs from one type of good to another. There is some evidence that people discount different goods in different ways, treating for instance environmental goods differently to typical consumption goods or money when making inter-temporal decisions (e.g. Iannou and Sadeh 2016). Such matters may become important when considering natural capital.

The elasticity of marginal utility, η

The parameter η also has numerous interpretations. This leads to several proposed methods to estimate the elasticity of marginal utility. For brevity we look at three interpretations here, and discuss the empirical estimates for each. First, η can be thought of as a measure of the desire to smooth consumption. The wealth effect provides one reason to discount future changes to well-being; we may be richer in the future. With decreasing marginal utility, our well-being is higher with more even consumption streams than one in which we are rich in future and poor now. η is a measure of the curvature of utility and so is a measure of the desire to smooth consumption and generally substitute consumption from richer period to poorer ones.

Given this, one set of empirical methods estimates the elasticity of inter-temporal substitution, which is the reciprocal of η. The approach taken is to estimate the Ramsey Rule directly using interest rate and consumption growth data. This is what Groom and Maddison (2013) call the the 'Euler equation' approach. This approach estimates the reduced form relationship between aggregate consumption growth and the rate of interest that the Ramsey Rule in its optimality form essentially represents, (e.g. Groom et al. 2013, Cowell and Gardiner 1989).[1] Similar methods look at *individual* savings behaviour, e.g. Blundell et al. (1994).

Estimates using this method yield values which range from 0.8 to 2. The Green Book guidance is heavily influenced by Cowell and Gardiner (1989) and Blundell et al. (1994) which indicate that a reasonable value might be $\eta = 1$. The most up-to-date evidence on this matter comes from Groom and Maddison (2013), which

[1] The optimality form of the Ramsey Rule equates the STP with the risk free return on capital: $r = \delta + \eta g$. It reflects the outcome of a social planner problem in which the optimal savings path is determined.

indicates that a value of 1.5 is justified using these, and indeed a variety of other, methods. See Table 2.[2]

A second interpretation of η is closely related but leads to alternative empirical estimates. The desire for consumption smoothing can just as easily be interpreted as inequality aversion. This thought experiment works best when one things about intergenerational discounting, but is valid nonetheless for shorter time horizons. The wealth effect means that if future generations are richer or poorer than us today, there is an inequality introduced in our levels of income. This is then reflected by a higher discount rate if growth is positive, or a lower one if growth is negative. The parameter η effectively determines the extent to which we are averse to this inter-temporal inequality. For instance, a value of $\eta = 1$ means that someone 10 times richer has a marginal utility that is 10 times smaller. If $\eta = 2$ someone 10 times richer has a marginal utility that is 10^2 times smaller, and so forth. This would make us less inclined to transfer a marginal unit of consumption to them since the social value would be lower than if we added the marginal unit to the poorer party. η is then a measure of this aversion to inequality. If there is growth, the richer parties are in the future, and so we would be less inclined to give up income now for an investment that pays off in the future. We, today, are the poor party, the future is rich, hence we should discount marginal returns more heavily the higher is η. If growth is negative (as it has been in many developing countries over the past few decades), the reverse is true.

This interpretation yields another source of empirical estimates. It is possible to establish some level of societal inequality aversion. Some estimate have come from introspection on inequality aversion by experts. Dasgupta (2008) suggests a value of 2 for intergenerational projects on the basis of his personal (albeit expert) opinion on inequality aversion. Similar arguments can be found in the work of Christian Gollier (e.g. Gollier 2012). There are also some estimates from experimental work on inequality aversion. Amiel et al (1999) estimate values of around 0.8 among students in the US.

Another influential method is the Equal Absolute Sacrifice method. This assumes that the progressivity of income tax schedules reflects societal inequality aversion and is arranged so that individuals sacrifice the same amount of *utility* in paying their income taxes. Stern (1977) describes the method, and many estimates have stemmed from it. Evans and Sezer (2002) provide estimate of between 1 and 2 for the UK using this method. More refined methods found in Groom and Maddison (2013) point to an estimate of 1.5.

In short, there is some controversy in general about how to estimate these parameters. One can argue about the appropriate methods, revealed versus

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[2] Stern (1977) presents various different methods by which one can estimate η, and provides practical examples. The estimates range from 0-10 in that paper. However, many of the examples come from outside the UK (e.g. Korea) or use methods that are seen as less appropriate, e.g. the Frisch equation (see Groom and Maddison, 2013). In the end, one can narrow down the estimates that are appropriate to CBA to between 0.5 and 2. Furthermore, one should recognise that in that paper Stern states "..enough has been said to prevent any reader taking such numbers away for direct use in CBA…". This places greater weight on the concerted efforts of Blundell et al. (1994) and Groom and Maddison (2013) for such purposes.

stated preferences, inequality aversion versus consumption smoothing. η can also be thought of as representing risk aversion for instance. Ultimately Groom and Maddison (2013) show in a meta-analysis that in the UK, more or less irrespective of which method one uses, it is difficult to argue against $\eta = 1.5$. Yet $\eta = 1$ is outside of the confidence interval of their meta-analysis. Drupp et al. (2015) survey experts on this matter for intergenerational projects. The responses reflect a range of different perspectives on η and the average response is $\eta = 1.3$.

Table 1. Estimates of the Elasticity of Marginal Utility (Groom and Maddison 2013).

Methodology	η	Standard error
Equal sacrifice (Weighted)	1.515	0.047
Equal sacrifice (Historical)	1.573	0.481
Euler equation	1.584	0.205
Additive preferences (Rotterdam)	3.566	2.188
Additive preferences (CEM)	2.011	1.337
Subjective wellbeing	1.320	0.168
Pooled estimate	1.507	
Parameter homogeneity	Chi-sq(5) = 2.46 (p = 0.783)	

Source: Groom and Maddison (2013)

Table 2: Drupp et al. (2015) Survey Results for intergenerational discounting

Variable	Mean	StdDev	Median	Mode	Min	Max	N
Real growth rate per capita (g)	1.70	0.91	1.60	2.00	-2.00	5.00	181
Rate of societal pure time preference (δ)	1.10	1.47	0.50	0.00	0.00	8.00	180
Elasticity of marginal utility of consumption (η)	1.35	0.85	1.00	1.00	0.00	5.00	173
Real risk free interest rate (r)	2.38	1.32	2.00	2.00	0.00	6.00	176
Social Discount Rate (SDR)	2.27	1.62	2.00	2.00	0.00	10.00	181
SDR lower bound	1.12	1.37	1.00	0.00	-3.00	8.00	182
SDR upper bound	4.14	2.80	3.50	3.00	0.00	20.00	183
Social Rate of Time Preference (SRTP)	3.48	3.52	3.00	4.00	-2.00	26.00	172
Number of responses							197

The SRTP is imputed from the individual determinants: the rate of societal pure time preference, and an interaction term of the real growth rate of per-capita consumption and the elasticity of marginal utility of consumption.

Growth, g

The final parameter in the STP reflects a prediction about future levels of income. *g,* is the growth rate of per capita consumption. The Green Book uses data from the ONS for the 50 year post-war period form 1949 to 1998. During this period per capita consumption grew at a rate of 2.2% per annum. Groom and Maddison (2013) recalculate for the post-war period up to 2013 and find growth of 2.3%. Both Pearce and Ulph (1999) and Groom and Maddison (2013) look at the pre-war period, from the mid to early 1800s to the present day, and find much lower average growth rates between 1% and 1.3%. The Green Book uses the post-war period to parameterise the STP, rounding down to 2%. The underlying assumption is that recent history is a better predictor of future growth than the longer historical record. The mean prediction of the experts surveyed by Drupp et al. (2015) for the long-term global average growth rate is 1.7%.

Discounting and Relative Prices

"Dual" discount rates, i.e. different discount rates for different types of good, have been the subject of discussion for many years (Weikard and Zhu 2005, Baumgartner et al. 2014). The general point is that, beyond the typical marketed consumption goods that are evaluated in CBA, non-marketed goods associated with the environment and possibly health should enter as separate arguments of social welfare and should therefore be treated differently in CBA to reflect some of their special characteristics, such as substitutability, and future trajectories. Formally, environmental goods (E) should appear as a separate argument in the utility function alongside consumption (C): $U = U(C, E)$.

In the case of environmental goods for instance, it is often argued that the shadow price (social value in some numeraire) of non-marketed environmental goods, such as habitat, wildlife or environmental quality in general, will be increasing over time as these services become scarcer relative to typical consumption goods, or as demand for these services increases. The precise trajectory of this increase in the shadow price will depend on three factors: 1) the rate of growth of the environmental goods in question, and hence how scarce they are becoming over time; 2) the substitutability of these environmental goods with typical consumption goods, reflecting how difficult it is to maintain well-being; and 3) growth in income and consumption. Intuitively, an environmental good that is becoming scarcer and which is not easily substituted by other goods will face a rapid increase in its shadow price in the future.

There are two entirely equivalent ways of dealing with this issue in CBA. Weikard and Zhu (2005) has the most helpful exposition of this point. The first is to recognise that the increase in the shadow price reflects a change in relative prices of environmental goods compared to consumption goods, and ensure that these increasing values are reflected in the shadow or "accounting" prices that are used to establish the benefits associated with the environment in CBA. These suitably valued benefits (or costs) can then be placed in present value terms using the appropriate consumption discount rate. Indeed, some provision for accounting for relative prices is already made in the current Green Book Guidelines (pp. 20-25).

Example 1: The equivalence of pricing and discounting (Weikard and Zhu, 2005, p876)

Suppose a project *i* offers a flow of ΔC_i units of consumption each year for 50 years, and a flow of environmental benefits in each year over the same period, ΔE_i. This flow of environmental benefits can be valued in units of consumption by multiplying by the shadow price of environment today, p_0, multiplied by the change in environmental goods, ΔE_i to obtain: $B_{i0} = p_0 \Delta E_i$. Now suppose that the shadow price of environmental goods, p_0, is increasing over time at an annual rate of g_P percent. In this case at time *t* the flow of environmental benefits will be worth $B_{it} = p_0 \exp(g_P t)\Delta E_i = p_t \Delta E_i$. If the appropriate consumption discount rate is ρ_C percent (see Appendix for a formal definition), then the present value of the benefits of this project can be evaluated as follows:

$$PV = \Sigma_{t=0}^{50} \Delta C_i \exp(-\rho_C t) + \Sigma_{t=0}^{50} p_t \Delta E_i \exp(-\rho_C t) \qquad \text{(A)}$$

Alternatively, we could assume that the flow of environmental benefits remains at B_{i0} units each year and reflect the increasing value of the environment by discounting environmental benefits at a lower rate, one which nets out the growth in the shadow price of the environment. The appropriate discount rate would be equal to the consumption discount rate minus the growth rate of the shadow price: $\rho_E = \rho_C - g_P$. The present value would then be calculated as follows:

$$PV = \Sigma_{t=0}^{50} \Delta C_i \exp(-\rho_C t) + p_0 \Sigma_{t=0}^{50} \Delta E_i \exp(-\rho_E t) \qquad \text{(B)}$$

Note that (A) and (B) are equivalent since the second term on the right hand side is identical in each case given the definition of ρ_E. They simply have different interpretations. (A) shows that one can account for the relative scarcity of environmental goods by converting the environmental benefits into consumption terms using the appropriate and increasing shadow price and then discounting using the consumption discount rate, ρ_C. (B) shows that this is equivalent to discounting today's valuation of environmental benefits (B_{i0}) using a net "environmental" discount rate, ρ_E, which is net of the growth of environmental values over time.

Weikard and Zhu (2005) prove that the rate of change of relative prices is equal to the difference between the social discount rates for consumption, ρ_C, and environment, ρ_E. That is, $g_P = \rho_C - \rho_E$ (see Appendix). This stems from calculating the rate of change of the shadow price, which is the marginal rate of substitution between environmental and consumption goods: $p = U_E / U_C$. So, there is a theoretical and welfare equivalence between (A) and (B) The only question that remains is whether there is any advantage in approaching the issue of relative scarcity via pricing (A) or discounting (B).

Equivalently, one could simply base future valuations of the environment on today's shadow prices, assume they remain constant in real terms over time, and reflect the change in relative prices in a separate discount rate for environmental goods. This is the essence of "dual" discounting. While the mechanics and emphasis of these two options differ, and one or other approach may be preferred for procedural reasons, the practical outcome will be the same in each case. Example 1 shows the equivalence between these approaches.

The theory behind dual discounting or relative prices is shown more formally in the Appendix to this report. Of course the question remains how to determine the change in the relative prices with which to evaluate environmental goods. Two inputs are required to solve this problem, a theoretical one and an empirical one. The Appendix shows one theoretical approach which assumes a constant elasticity of substitution (CES) welfare function with consumption and environment as the arguments. In that case, expressed in terms of dual discount rates, the difference between consumption and environmental discount rates, respectively ρ_C and ρ_C, can be reduced to a very simple formula:

$$\rho_C - \rho_E = \frac{1}{\sigma}\left(g_C - g_E\right) \qquad (2)$$

Where g_C is the growth rate of consumption goods, g_E is the growth rate of environmental goods (typically per capita, annualised), and σ is the elasticity of substitution between environmental and consumption goods. Equation (2) is the difference between the consumption and environmental discount rates, but also, as explained in Example 1, defines the rate at which relative prices between environment and consumption should change if one takes the pricing approach rather than the dual discounting approach to environmental scarcity. It is essentially the inflation term for environmental values.

Specifically, in Equation (2) if $\sigma \to \infty$, environment and consumption are perfectly substitutable and there is no difference in the dual discount rates, and relative prices remain constant (essentially the environment becomes a regular part of the consumption bundle and has no special impact on social welfare). If $\sigma = 0$, then no amount of additional consumption goods can compensate for *any* loss in the environmental goods. While these represent extreme cases, they are probably not unrealistic extremes for certain types of natural capital stocks or flows. The typical case is likely to lie in between these extremes though.

Equation (2) is expressed in terms of differences in the consumption and environmental discount rates, but as discussed this simply reflects the rate of change in the relative prices of consumption and environment. In terms of implementation, our preference would be, wherever possible, to reflect these changes in relative prices in the valuation of environmental goods, rather than taking the dual discounting approach. This has the benefit of not necessitating a large departure from the Green Book discounting guidelines, and follows the Green Book guidance on accounting for relative price changes. Indeed, this is precisely the approach that the Dutch government took in their recent review of CBA practices (Discontovoet 2016).

There are two caveats to this advice. As shown in the Appendix, the STP for consumption when environmental goods are taken into account separately, and utility is given by $U = U(C, E)$, differs from the standard case shown in the Green Book where social welfare is assumed to be: $U = U(C)$. Strictly speaking the relative pricing approach that we recommend would require the eventual consumption units to be discounted using ρ_C rather than $\rho = 3.5\%$ from the standard Ramsey Rule. Some work would have to be undertaken to see how much this adjustment would change outcomes. Secondly, when substitutability becomes very limited, and $\sigma \to \infty$, future valuations are likely to be very high since the inflation factor for environmental assets will be very large indeed, so that environmental goods and services become the pivotal limiting factor in any decision. It is clear then that the extent of substitutability, irreversibility and the degree to which environmental assets are essential, are critical factors that should guide decision-making and valuation. Discounting may not be the appropriate means of incorporating irreversibility and non-substitutability of environmental assets into the decision making process. The literature on option value and quasi-option value in CBA is more relevant here.

Risk and discount rates

In corporate finance, it is generally accepted in both the academic and business worlds that the discount rate for a project should reflect its systematic risk, or “beta” (e.g., Graham and Harvey, 2001). This approach is motivated by the seminal work on portfolio theory and the Capital Asset Pricing Model (CAPM) that led to Nobel Prizes in Economics for Harry Markowitz and William Sharpe. Since beta varies between projects, the private sector does not use a “one size fits all” discount rate. Instead, a specific rate reflecting the beta is applied to the expected benefits from the project being considered when estimating the Net Present Value.

In economics, there has been a preference instead for discounting “certainty equivalent” cash flows at a risk-free social discount rate (e.g., Zeckhauser and Viscusi, 2008). For example, a social planner may be considering the value of a project that pays off either £90 if the economy weakens or £115 if the economy strengthens, each with 50% probability. While the expected benefit is (90+115)/2 = £102.5, the planner, being averse to pro-cyclical risk, might willingly swap the project for a certain payoff of £100 instead. In this case, £100 is the certainty equivalent and is the value that should be discounted at the risk-free rate. The resultant present value will be the same as that calculated using the corporate finance CAPM approach if risk is treated consistently in both cases. Therefore there is no theoretical reason to prefer the economist approach to the corporate finance approach, or vice-versa.

The current Green Book treatment of risk in the discounting process is not, in our opinion, entirely clear. In Section 5.66 and Box 13, HM Treasury expresses a preference for working with expected benefits rather than certainty equivalents. However, it then discounts these at a fixed 3.5% for horizons of less than or equal to 30 years. There is, therefore, no explicit adjustment for project-specific risk when calculating the Net Present Value.

Assume, for the moment, that this 3.5% represents a risk-free rate – we will return to this assumption shortly. There are two potential theoretical justifications for using such a risk-free rate to discount the expected benefits from all ecosystem services. The first relies on the seminal theorem of Arrow and Lind (1970). Under the assumption that the risks of social projects are uncorrelated with those in the private sector, and assuming that governmental risk can be diversified between many tax payers, the case for ignoring risk in the discount rate is theoretically robust. This argument has been pervasive in the practice of social cost-benefit analysis over the last half-century.

More recently, however, this approach has come under sustained criticism (e.g., Baumstark and Gollier, 2014; Lucas, 2014), specifically over the realism of the assumption that benefits from social and private capital are independent. The pro-cyclicality of certain public investments, such as transport and energy infrastructure, is self-evident to those who question the relevance of the result. Baumstark and Gollier (2014), in particular, argue that the inappropriate use of the Arrow-Lind theorem has led to serious distortions in major areas of governmental decision making, including nuclear power and public-private partnerships. We broadly agree with this critique.

The second reason for applying a risk-free rate to all projects concedes that, while *theoretically* it is appropriate to adjust the discount rate for beta (or to work instead with certainty-equivalent, not expected, cash flows), *empirically* the risk premium is likely to be so small as to make no practical difference to the exercise being undertaken. There are, again, two possible justifications for this position. The first relies on the famous “equity premium puzzle” of Mehra and Prescott (1985), who demonstrate that the very large risk premia observed in financial markets are extremely difficult to justify from standard economic theory. This is because aggregate consumption levels are largely unaffected when there are major shocks in the City of London, making financial risks largely unsystematic from a utility of consumption perspective. Given that market risk premia look irrationally large, it is argued that these are irrelevant for social valuation. Instead small, possibly trivial, risk premia are justified, which will have such limited impact on the estimated valuation that they can be safely ignored.

Despite a vast literature on this topic over the last three decades, the equity premium puzzle remains largely unresolved. However, important work by Robert Barro (e.g., Barro, 2009) has shown that the theoretical risk premium may be close to the levels that are observed in financial markets if there are rare, but highly severe, economic “crashes” that simultaneously affect project returns and consumption levels. We will return to this point below.

The second argument for not incorporating a risk premium is that, while transport and energy infrastructure might be pro-cyclical, natural capital is not. In particular, equity investment in forestry has been found to have almost no systematic risk, with an estimated beta close to zero (Cascio and Clutter, 2008).

We are, though, unaware of a broader empirical literature on beta estimates of ecosystem services beyond forestry, requiring further research in this area.

So far, we have based this discussion on the assumption that the Green Book is interpreting its discount rate of 3.5% as being risk-free. But, as this rate includes 1% for "catastrophe risk", this assumption needs re-examining. The Green Book (p.97) defines catastrophe risk as follows:

> *"Catastrophe risk is the likelihood that there will be some event so devastating that all returns from policies, programmes or projects are eliminated, or at least radically and unpredictably altered. Examples are technological advancements that lead to premature obsolescence, or natural disasters, major wars etc."*

This definition appears to capture the type of catastrophe risk – natural disasters and major wars – described by Barro (2009) that will simultaneously cause major disruption to both aggregate consumption and project benefits. As he shows, the threat of such events, even if highly unlikely, should lead to significant risk premia in individual discount rates, which the Green Book implicitly appears to assume is the same for all projects. However, discussion of "technological advancements that lead to premature obsolescence" most likely reflects a sector-specific risk that does not more generally impact upon the macro-economy. This is a very different type of threat to that of war or natural disaster. The appropriate risk premium will now depend on whether such technological advances are correlated with overall economic activity. If not, then the risk is unsystematic and the appropriate risk premium is zero. Instead, the expected cash flow should be adjusted to incorporate the possibility of very low realised benefits. However, as premature obsolescence seems unlikely for natural capital, this issue is largely irrelevant for environmental accounts.

The definition of catastrophic risk in the Green Book does not appear to capture the possibility of a disaster so catastrophic (such as an asteroid impact) that civilisation is eradicated and future societies do not exist to reap the benefits from any current investment. In the Stern Review (Stern, 2007), the discount rate is increased by 0.1% to allow for this effect. There is a clear distinction between this risk of losing the people who gain utility from a project as a result of population annihilation, and the threat of losing the payoffs from a project due to a more minor disaster. The former is correctly incorporated by Stern into the risk-free rate, the latter is better reflected in the project specific risk premium to reflect its systematic component.

In conclusion, therefore, the Green Book effectively appears to add a project risk premium of 1% onto a risk-free rate of 2.5% for all Net Present Value exercises. This is, at least in part, implicitly justified through Robert Barro's work on valuation in the presence of major, but non catastrophic, disasters. The exact justification for why the appropriate value is 1%, and why it does not vary by project, is less clear to us. We are also unsure why premature obsolescence necessarily impacts on the discount rate, particularly for natural capital.

International governmental guidance on incorporating risk premia into the discount rate is mixed. For example, when estimating the social cost of carbon, the US Environmental Protection Agency uses three distinct real discount rates: 5%, 3%, and 2.5%. The highest value incorporates “the possibility that climate damages are positively correlated with market returns” (Greenstone et al., 2013, p. 34). Reflecting the positivist position taken to discounting in the United States, this is a standard corporate finance argument. The 3% rate is broadly a risk-free rate under both positivist and normative arguments, while the 2.5% rate reflects declining discount rates (see below). In France, for short time horizons, a risk premium of 2% multiplied by an estimate of the project (or sector) beta, is added to a real risk-free rate of 2.5%. Norway and the Netherlands, by contrast, add a fixed risk premium of 1.5% and 3% respectively to all short-term projects, while Germany does not incorporate a risk premium at all (OECD/ITF, 2015; Discontovoet, 2016).

Our opinion is that it is correct to incorporate a risk premium into the discount rate. However, as forestry betas appear to be low and as financial markets may offer higher returns to risk than might be appropriate for a social planner, the overall 1% catastrophe risk premium incorporated into current Green Book recommendations appears to be of the correct approximate magnitude for natural capital.

Declining discount rates

Natural capital often provide benefits over very long time horizons, requiring the Office for National Statistics to take a view on whether discount rates should vary depending on the maturity of the asset being valued. This issue becomes increasingly important if natural capital is valued over its entire life, as we would recommend, and not just the first 50 years. In Table 6.1 of the Green Book, HM Treasury recommends that, for projects with benefits lasting for more than thirty years, the discount rate should decline with maturity, reaching approximately 3% after 100 years.[3] In supplementary guidance, it also reconciles the very low discount rates of approximately 1.4% used in the Stern Review (Stern, 2007) with the higher 3.5% short-term Green Book recommendation (HM Treasury, 2008).

The short-term Green Book parameterisation of the Ramsey Rule is based on the assumption that growth will average 2% above inflation. While, as we have discussed above, this is broadly consistent with historic average real growth rates and surveys of future long-term growth, it is an extremely difficult parameter to forecast with any accuracy. A third world war, concerted terrorist action, pandemics (Almond, 2006), or other major shocks could lead to realised growth that is significantly below this estimate. By contrast, the emergence of new technology might take economic growth beyond even the levels seen in the 20th Century.

[3] Table 6.1 in the Green Book gives forward discount rates, while the horizon discount rate reported here is a spot rate. Forward rates are instantaneous and used for discounting between two adjacent time periods. Spot rates are used to bring future cash flows back to a time zero present value.

This uncertainty over growth influences long-term discount rates within a Ramsey framework. The following thought experiment illustrates this point. Imagine that there will either be significant and long-lasting political turmoil, in which case there will be no real growth, or a new highly efficient green energy source becomes available, leading to average real growth of 4%. Applying in each case the Ramsey rule with pure time preference of 0.5%, catastrophe premium of 1% and elasticity of the marginal utility of consumption of 1, the discount rate would be either 1.5% or 5.5% if the true future average growth rate were known to us now. Using these two discount rates separately, the present value of a certain £1m at the following time horizons is:

Horizon (Years)	10	20	50	75	125
1.5% Discount Rate	861,667	742,470	475,005	327,376	155,505
5.5% Discount Rate	585,431	342,729	68,767	18,033	1,240

However, we currently do not know what the future holds and are instead in a world of uncertainty. If we believe that each of these two outcomes has a 50% chance of occurring then, in a seminal study, Weitzman (1998) argued that the correct procedure is to take the simple average of the two present values to determine the Expected Net Present Value (ENPV). The appropriate cost of capital at any horizon is then the discount rate that reconciles the ENPV to the future certain payoff of £1m:[4]

Horizon (Years)	10	20	50	75	125
ENPV	723,549	542,600	271,886	172,704	78,373
Horizon discount rate	3.29%	3.10%	2.64%	2.37%	2.06%

The crucial observation here is that the horizon discount rate is below the simple average of the two Ramsey rule discount rates: (1.5%+5.5%)/2 = 3.5%. Further, the longer the horizon of the project, the lower the appropriate discount rate becomes. In the limit, as the time horizon approaches infinity, the horizon discount rate tends to the lowest possible realisation of the Ramsey rule: 1.5% in this case.

Following some debate over what became known as the "Weitzman-Gollier puzzle", it is now broadly, if not universally, accepted that risk-free discount rates should decline with an increasing time horizon (Arrow et al., 2013; Cropper et al., 2014).[5] There are a range of motivations, from uncertainty over future market-based interest rates or growth, to expert disagreement on the Social Discount Rate, which all theoretically lead to this effect (see, for example, Freeman and Groom, 2016). This literature has motivated Table 6.1 in the current Green Book as well as guidance given by other international governments. For example, the current French and Norwegian guidelines have declining risk-free discount rates, while the preference in Germany and the United States is for a lower fixed discount rate for very long-term projects than those with a shorter horizon

[4] So, for example, at 10 years, the ENPV of £723,549 = (£861,667 + £585,431)/2. The horizon discount rate of 3.29% is then determined by realising that £723,549 = £1m/(1+3.29%)^{10}

[5] For a discussion of the Weitzman-Gollier puzzle see, for example, Gollier (2009), Weitzman and Gollier (2009), Freeman (2010) and Traeger (2013).

(OECD/ITF, 2015, Greenstone et al., 2013). The Dutch also recognise the case for declining risk-free discount rates, but do not incorporate this into their recommendations since their baseline risk-free rate is currently 0%, reflecting the low real yields in financial markets at the time of writing under a positivist approach (Discontovoet, 2016).

We believe there are strong arguments for declining discount rates to be used in the valuation of ecosystem services. However, there are two key issues for the Office for National Statistics to consider in relation to how the maturity of the project should influence the discount rate:

Is the rate of decline of the discount rate in the Green Book reasonable? The speed with which the discount rate declines with project maturity in a Ramsey rule framework is driven by uncertainty over growth. The more uncertain we are, the faster the discount rate declines. Mathematically, uncertainty can be represented by a probability density function (pdf) of possible future outcomes. In a recent paper (Freeman and Groom, 2016) we argue that governments are, to some degree, ignorant about this pdf and are likely to know (at best) a limited number of stylistic features about the future. For example, the Treasury might be able to estimate with reasonable precision the mean value of future real growth and its associated standard deviation, but it is unlikely to know other statistical characteristics such as its skewness and excess kurtosis. In this position of relative ignorance about the future, we demonstrate that the appropriate rate of decline of long-term discount rates can only be established within very wide bounds. This makes it difficult for the Office for National Statistics to confidently assert that any single term structure of discount rates is better than another.

More positively, we can compare the speed of decline in discount rates in the Green Book with other schedules in the literature. For example, in Freeman et al. (2015), we estimate the speed of decline of the term structure based on an econometric estimation of the statistical properties of market based interest rates. We then compare this with other well-cited papers that use a related approach (two models in Newell and Pizer, 2003, and one model in Groom et al., 2007) as well as the Green Book. These are presented in the Figure 1 below. As can be seen, even within a single theoretical setting, small differences in modelling and data choices can lead to large differences in the term structure of discount rates, illustrating the central message of Freeman and Groom (2016). However, we can see that the Green Book schedule does not outlie the other models in this figure. From this perspective, and by comparing with other international guidance, the rate of decline reported in the Green Book appears reasonable.

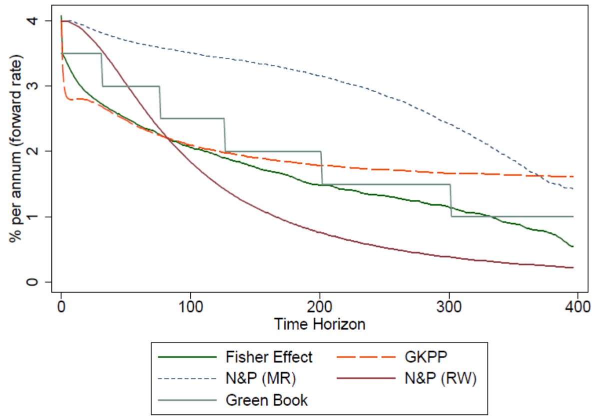

Figure 1. The Green Book term structure of discount rates compared against various academic models that estimate this term structure based on uncertainty over future market interest rates. These models are: "Fisher Effect" - Freeman et al. (2015); "GKPP" - Groom et al. (2007); "N&P (MR)", "N&P (RW)" - respectively the mean reverting and random walk models of Newell and Pizer (2003). Figure source: Freeman et al. (2015). Reproduced under personal use copyright permission from Elsevier.

Risk and the term structure of discount rates. The argument that discount rates should decline with the time horizon is dependent on the assumption that the risk premium is zero. In a body of recent work, Christian Gollier (2012, 2014, 2016) and co-authors (Dietz et al. 2015) have demonstrated that the term structure of risky discount rates can increase with the time horizon.

As a consequence, in French governmental guidance, while the (forward) risk-free rate declines from 2.5% to 1.5% in year 2070, at the same time the (forward) risk premium for a beta = 1 project increases from 2% to 3%. For such projects, therefore, the overall real discount rate is fixed at 4.5% for all time horizons (OECD/ITF, 2015). By contrast, the Norwegian government has both a declining risk-free rate and risk premium. These forward rates respectively decline from 2.5% and 1.5% for horizons less than 40 years, to 2% and 1% for horizons less than 75 years, to 2% and 0% for projects with maturity over 75 years. This is broadly consistent with Gollier (2016) if the beta of social projects is positive but less than one. The Dutch government chooses parameters so that the term structure of the risk premium is flat.

In related work, Freeman (2016) has argued that care is needed when looking at the term structure of the risk premium. This is because the uncertainty that drives these effects also influences the expected cash flow in a world where benefits are uncertain. To adjust for uncertainty in the denominator of the Net Present Value equation by changing the discount rate, but not the numerator by leaving the expected return unaltered, can lead to biases in valuation.

In conclusion, we believe that the Green Book is correct to reduce the discount rate with the time horizon of the project, and that the rate of decline reported in the Green Book lies within standard estimates. While there are arguments for an offsetting increase in the risk premium with project maturity, this is likely not to be relevant for ecosystems services where the beta may be low and risk premiums a small influence to the overall discount rate.

Appendix Dual Discounting in Theory

Suppose that instantaneous utility depends on consumption C and a stock of environmental goods, E. Intertemporal Social Welfare is then given by:

$$W = \int_0^\infty U(C_t, E_t)\exp(-\delta t)dt$$

where δ is the utility discount rate (which here does not differ between environmental and consumption goods). There is no uncertainty.

The social discount factor with which to "price" changes in the quantities of each of the arguments, consumption and environment, from the perspective of today (t = 0) is given by:[6]

$$P_i(t,0) = \frac{U_i(C_t, E_t)}{U_i(C_0, E_0)}\exp(-\delta t) \quad \text{for} \quad i = C, E$$

The associated discount rates are given by the rate of change of this price over time. For C and E respectively this leads to two separate social discount rates:

$$\rho_C(t) = \delta - C\frac{U_{CC}(t)}{U_C}g_C - E\frac{U_{EC}(t)}{U_C}g_E \qquad \text{(A1)}$$

$$\rho_E(t) = \delta - E\frac{U_{EE}(t)}{U_E}g_E - C\frac{U_{CE}(t)}{U_E}g_C \qquad \text{(A2)}$$

This should be compared to the standard single good framework of Ramsey in which the social discount rate for consumption goods is simply:

$$\rho = \delta - C\frac{U_{CC}}{Uc}g_C$$

Which is usually written as $\rho = \delta + \eta g$. This is the typical framework for the analysis of dual (meaning separate) discounting of environmental benefits and costs on the one hand, and consumption goods on the other.

What this means is quantities of consumption (an index of all consumption of apples, oranges, etc. usually measured in money terms) should be discounted using ρ_C , and quantities of environmental goods (changes in air quality, or changes in benefit from forested areas or ecosystem services in general) should be discounted using ρ_E .

Weikard and Zhu (2005) show that the pricing and discounting approaches in Example 1 are equivalent from a welfare perspective. The show that the rate of

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[6] Adapted from (Traeger 2011, p 216), for instance.

change in the shadow price of the environment, p, is equivalent to the difference between A1 and A2. They do this by first reminding us that the shadow price for the environment in terms of consumption is given by: $p = \frac{U_E}{U_C}$, and that the rate of change of this is given by:

$$\frac{\dot{p}}{p} = \frac{\dot{C}}{C}(\eta_{CC} + \eta_{EC}) + \frac{\dot{E}}{E}(\eta_{EE} + \eta_{CE}) \qquad \text{(A3)}$$

Which is just the difference between (A1) and (A2) with $\eta_{ij} = -x_i \frac{U_{ij}}{U_i}$.

If more structure is placed on the preferences more can be said. For instance, following Hoel and Sterner (2007) suppose that preferences are Constant Elasticity of Substitution (CES):

$$U(C,E) = \frac{1}{(1-\eta)}\left[(1-\gamma)C^{1-\frac{1}{\sigma}} + \gamma E^{1-\frac{1}{\sigma}}\right]^{\frac{(1-\eta)\sigma}{\sigma-1}}$$

then it can be shown that (Hoel and Sterner 2007, p 9-12 and Appendix):

$$\rho_C = \delta + \left[(1-\gamma^*)\eta + \gamma^* \frac{1}{\sigma}\right] g_C + \left[\gamma^*\left(\eta - \frac{1}{\sigma}\right)\right] g_H$$

$$\rho_E = \delta + \left[(1-\gamma^*)\left(\eta - \frac{1}{\sigma}\right)\right] g_C + \left[\gamma^*\eta + (1-\gamma^*)\frac{1}{\sigma}\right] g_H$$

and hence:

$$\rho_C - \rho_E = \frac{1}{\sigma}(g_C - g_H)$$

where $\gamma^* = \gamma E^{1-\frac{1}{\sigma}}\left((1-\gamma)C^{1-\frac{1}{\sigma}} + \gamma E^{1-\frac{1}{\sigma}}\right)^{-1}$.

We can now say the following in the Hoel and Sterner framework:

1) $\rho = \rho_C$ if either i) $\gamma^* = 0$; ii) $g_c = g_E$; or, iii) $\eta\sigma = 1$. This illustrates the importance of relative growth and substitutability in this analysis.
2) $\rho_C = \rho_E$ if either i) g_C [illegible] g_E ; or, ii) E and C are perfect substitutes, i.e. $\sigma \to \infty$
3) If $g_C > g_E$ and [illegible]1 then [illegible] will tend to 1 over time. This means that the limits of the two discount rates are:

$$\rho_C = \delta + \frac{1}{\sigma}(g_C - g_E) + \eta g_E$$
$$\rho_E = \delta + \eta g_E$$

This implies a term structure of social discount rates as consumption patterns change.

4) Substitutability is a key issue: all the results depend on σ : the elasticity of substitution between E and C .

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