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ABSTRACT

Disagreements about normative aspects of social time preferences have led to estimates of the Social Cost of Carbon (SCC) that differ by orders of magnitude. We investigate how disagreements about the SCC change if planners are non-dogmatic, i.e., they admit the possibility of a change in their normative views, and internalise the preferences of future selves. Although non-dogmatic planners may disagree about all the contentious aspects of social time preferences, disagreements about the SCC reduce dramatically. Admitting the possibility of a change in views once every 40 years results in a 4.6-fold reduction in the range of recommended SCCs.

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Non-dogmatic climate policy

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Abstract

Disagreements about normative aspects of social time preferences have led to estimates of the Social Cost of Carbon (SCC) that differ by orders of magnitude. We investigate how disagreements about the SCC change if planners are *non-dogmatic*, i.e., they admit the possibility of a change in their normative views, and internalise the preferences of future selves. Although non-dogmatic planners may disagree about all the contentious aspects of social time preferences, disagreements about the SCC reduce dramatically. Admitting the possibility of a change in views once every 40 years results in a 4.6-fold reduction in the range of recommended SCCs.

Keywords: Social cost of carbon, non-dogmatism, social discounting

Disagreements about social time preferences are a major source of contention in climate change economics. The Social Cost of Carbon (SCC) – the welfare cost of a ton of carbon dioxide (CO₂) emissions – is perhaps the most important indicator of the optimal intensity of climate policy, but is highly sensitive to parameters of social time preferences that capture e.g. social impatience and aversion to intertemporal consumption inequalities. While one might hope that new data or improved estimation methods could resolve disagreements about their values, estimates of these parameters from market observables are suspect due to pervasive market imperfections, and the fact that most of those who will be affected by

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climate policies are not yet born (see e.g. Heal, 2017).¹ Disagreements about social time preferences thus have an irreducibly normative character (Dasgupta, 2008; Drupp et al., 2018).

This paper examines how disagreements about the SCC might change if advocates of diverse normative theories of intertemporal social welfare were *non-dogmatic* (Millner, 2019). Non-dogmatic planners favour idiosyncratic theories of intertemporal social welfare, but exhibit some humility; they admit the possibility of a change in their normative views, and internalise the preferences of their future selves. We show that although such planners may disagree on all the contested aspects of social time preferences, disagreements about the SCC would decrease dramatically if they were even mildly non-dogmatic. Even if each planner admitted the possibility of a change in their views only once every 40 years, the range of recommended SCC values shrinks by almost a factor of five. Thus, even a small amount of humility about normative judgements can help to defuse seemingly intractable disagreements about the appropriate level of climate policy.

The theory of non-dogmatic social time preferences was developed in Millner (2019). That paper motivated non-dogmatism as a normative principle in its own right, arguing that planners should exhibit a degree of humility when forming their normative judgments. It then showed that although non-dogmatic planners may disagree about every free parameter of their intertemporal welfare functions, they all agree on the long-run social discount rate, i.e. the rate of decline of the social value of marginal payoffs at long maturities. Since current CO₂ emissions cause persistent warming that lasts for significantly more than a hundred years (Ricke & Caldeira, 2014), it is intuitive that non-dogmatism will reduce disagreements about climate policy variables like the SCC. However, it is not at all obvious how much reduction in disagreement can be expected. While Millner (2019) used a calibrated version of his model to demonstrate a substantial reduction in disagreements about long-run social discount rates, his analysis focussed on evaluating exogenous, marginal, policies. By contrast, this paper focusses on endogenous, optimal, policies. Since SCCs are calculated along optimal consumption paths, they are complex functions of the distribution of non-dogmatic planners' preferences. Reductions in disagreement about the value of marginal long-run projects thus may not translate into equivalent reductions in

¹Incomplete long-run futures markets and the presence of uncorrected climate externalities imply that current market equilibria are likely inefficient, and therefore cannot even reveal the attitudes of *current* market participants towards long-run outcomes. As Arrow et al. (2003) state, 'using market observables to infer social welfare can be misleading in imperfect economies. That we may have to be explicit about welfare parameters...in order to estimate marginal rates of substitution in imperfect economies is not an argument for pretending that the economies in question are not imperfect after all.'

endogenous variables, and could be greater, or smaller, than might be expected based on calculations with exogenous consumption paths. An entirely new modelling approach is required in order to assess the consequences of non-dogmatism for disagreements about the SCC.

Operationalising the formalism developed in Millner (2019) in a fully optimising climate-economy model raises several technical challenges. First, since non-dogmatic planners' preferences may change over time, we would expect them to be time inconsistent. This changes the appropriate equilibrium concept from individual intertemporal optimisation to sub-game perfect equilibrium, as sophisticated planners play a game against their future selves. As each non-dogmatic planner may have a different identity in each time period, the relevant dynamic game has a large number of players. This potentially significantly increases the difficulty of the numerical exercise. Second, since climate-economy models usually have a number of endogenous state variables, and future preferences are uncertain in the non-dogmatic paradigm, curse of dimensionality problems similar to those that arise in numerical stochastic-dynamic optimisation raise their head. Third, since we need to solve the model repeatedly from the perspective of many different non-dogmatic planners, the computational demands multiply. We show that all of these difficulties can be overcome with judicious simplifications of the problem. The baseline version of the model can be solved on a laptop computer in about twelve hours.

Related literature

Disagreements about social time preferences are at the heart of the extensive debate about optimal climate policy that followed the publication of the Stern Review of the Economics of Climate Change (Stern, 2008; Nordhaus, 2007; Dasgupta, 2008; Weitzman, 2007; Dietz & Stern, 2008). The extent of these disagreements has been documented in a recent survey of economists (Drupp et al., 2018). It is well known that the SCC is highly sensitive to these disagreements (see e.g. Heal & Millner, 2014; Anderson et al., 2014, and Figure 2 below).

Time consistency and violations thereof have been explored in the context of climate policy by Karp (2005); Gerlagh & Liski (2017); Karp (2017); Iverson & Karp (2018). These papers all focus on a single notion of intertemporal social welfare; they do not consider issues that arise from disagreements about social time preferences. Barrage (2018) studies a model of climate policy in which planners and consumers have different intertemporal

preferences. This paper, by contrast, focusses on first-best policies, but accounts for diverse viewpoints on how to measure intertemporal social welfare.

Alternative approaches to resolving disagreements about social time preferences in the context of climate policy include Dietz & Matei (2016); Heal & Millner (2014). The former paper focusses on an incomplete dominance relation in a non-optimising model, while the latter studies utilitarian aggregation of time preferences, also in a non-optimising model.

The notion of ‘non-dogmatic’ social time preferences builds on and reinterprets a prior literature in which altruistic agents internalize others’ preferences. See e.g. Ray (1987); Saez-Marti & Weibull (2005); Galperti & Strulovici (2017), and the discussion in Millner (2019). Alternative approaches to dealing with disagreements about intertemporal social preferences are explored in Gollier & Zeckhauser (2005); Feng & Ke (2018); Chambers & Echenique (2018); Millner & Heal (2018). While these papers examine a variety of aggregation techniques, non-dogmatism makes no attempt to aggregate preferences; disagreements are left intact, but each planner is required to exhibit some humility when forming his/her normative judgements. We show that this is enough to dramatically reduce disagreements about the SCC.

1 Non-dogmatic social time preferences

We begin with a brief description of non-dogmatic social time preferences and their properties. The primitives of the model are a set of N planners, indexed by i , each of whom advocates some plausible normative theory of intertemporal social welfare. We assume that intertemporal social welfare according to planner i at time τ , denoted by V_τ^i , can be represented by a time invariant function on the domain of infinite bounded consumption streams of the form $\mathbf{C}_\tau = (c_\tau, c_{\tau+1}, c_{\tau+2}, \dots)$.² Thus,

$$V_\tau^i(\mathbf{C}_\tau) = G^i(c_\tau, c_{\tau+1}, c_{\tau+2}, \dots) \quad (1)$$

for some functions $G^i(\cdot)$ that are strictly increasing in each of their arguments. Consider how these planners evaluate a sequence $\boldsymbol{\pi} = (\pi_0, \pi_1, \dots)$ of marginal changes to $\mathbf{C}_\tau$. Using

²We suppress population size for the sake of clarity in this section. Population is reintroduced in Section 2.

a first order Taylor expansion in the small quantities π_s , we have

$$V_\tau^i(\mathbf{C}_\tau + \boldsymbol{\pi}) - V_\tau^i(\mathbf{C}_\tau) \propto \sum_{s=0}^{\infty} \pi_s (1 + r^i(s))^{-s}, \quad (2)$$

where we define planner i 's social discount rate at maturity s via:³

$$r^i(s) = \left(\frac{\partial V_\tau^i / \partial c_{\tau+s} |_{\mathbf{C}_\tau}}{\partial V_\tau^i / \partial c_\tau |_{\mathbf{C}_\tau}} \right)^{-\frac{1}{s}} - 1. \quad (3)$$

It is clear that generically $r^i(s) \neq r^j(s)$ for all s if $i \neq j$; the planners do not agree on the value of marginal payoffs at any maturity.

Non-dogmatic social time preferences are a subclass of the general preferences in (1) that can be written in the following recursive form:

$$V_\tau^i = F^i(c_\tau, V_{\tau+1}^1, \dots, V_{\tau+1}^N, V_{\tau+2}^1, \dots, V_{\tau+2}^N, \dots),$$

where there exists a $t > 0$ such that the functions F^i are strictly increasing in $V_{\tau+t}^j$ for all $j = 1 \dots N$. The interpretation of this restriction on preferences is as follows: each planner at time τ favours her own idiosyncratic theory of intertemporal social welfare, but admits the possibility that her normative views may change in the future, i.e., a future self may advocate one of the other plausible theories. Each planner is non-dogmatic – instead of imposing their current preferred theory on their future selves, they *internalize* the preferences of future selves. Current welfare depends directly on the welfare measures that future selves may advocate, and not just on future consumption values according to the current self's preferred theory. Finally, non-dogmatism is persistent: planners are *always* non-dogmatic. Internalization and persistence together yield a recursive preference system in which current preferences depend on future preferences, each of which is in turn recursively defined. Note that although non-dogmatic planners are required to admit the possibility of a future change of heart and internalize future preferences, the functions $F^i(\cdot)$ are idiosyncratic. Non-dogmatic planners are thus free to advocate their preferred theory of intertemporal social welfare unequivocally.

If we assume further that preferences are additively time separable the functions $F^i(\cdot)$

³We suppress the dependence of the social discount rate on the consumption path $\mathbf{C}_\tau$ in order to keep the notation uncluttered.

can be shown to be linear, i.e.,

$$V_\tau^i = U^i(c_\tau) + \sum_{s=1}^{\infty} \beta_s^i \sum_{j=1}^N w_s^{ij} V_{\tau+s}^j \quad (4)$$

where $\beta_s^i > 0, w_s^{ij} > 0$ for all $s = 1 \dots \infty, i, j = 1 \dots N$, and the intratemporal weights w_s^{ij} satisfy $\sum_{j=1}^N w_s^{ij} = 1$ for all i, s . This interdependent preference system defines time preferences that are complete on the set of bounded utility streams, and are increasing in all utilities, if the coefficients β_s^i satisfy $\max_i \sum_{s=1}^{\infty} \beta_s^i < 1$. We assume this condition from now on. The central result of Millner (2019) is as follows:

Theorem 1. *Assume that planners' preferences satisfy (4), and let $r^i(s)$ be the social discount rate at maturity s according to planner i . Then*

$$\lim_{s \rightarrow \infty} r^i(s) = \lim_{s \rightarrow \infty} r^j(s)$$

for all $i, j \in \{1, \dots, N\}$.

In words, all non-dogmatic planners agree on the long-run social discount rate, despite arbitrary disagreements about the coefficients β_s^i, w_s^{ij} and utility functions $U^i(\cdot)$.⁴

Although this result may be surprising at first, it has an intuitive origin. Current planners' attitudes towards consumption in the distant future are mediated through the preferences of their future selves. Since each of those future selves' preferences are also dependent on *their* future selves, the entire preference system in (4) must be unravelled backwards to the present in order to understand current planners' attitudes to future consumption. For example, suppose that the planners only place positive weight on selves one time step ahead, i.e. $\beta_s^i = 0$ for $s \geq 2$. To understand these planners' attitudes to consumption at some future time $\tau + s$, notice that only planners at $\tau + s$ care directly about consumption in that period. Planners at time $\tau + s - 1$ care directly about consumption in period $\tau + s - 1$, but indirectly about consumption in period $\tau + s$ via a *mixture* of the preferences of the selves at time $\tau + s$. After s steps back to the present, planners' concerns about $\tau + s$ are mediated through s iterates of a mixing operator that blends

⁴Millner (2019) presents an explicit formula for the consensus long-run social discount rate, but this is not needed for our current purposes.

their intertemporal weights, and acts on utilities at time $\tau + s$.⁵ As s becomes large, this mixing process converges, and all planners' utility weights decline at the same geometric rate. In addition, marginal utilities at large maturities are dominated by the planner whose marginal utility function decreases slowest for large (small) consumption values if asymptotic consumption growth is positive (negative). Thus, in the limit as $s \rightarrow \infty$, all planners agree on both the rate of decline of utility weights, and on the rate of decline of marginal utility, i.e., they agree on the social discount rate. Millner (2019) presents a formal treatment of this descriptive argument, and shows that it generalises to the case where planners care about all future selves.

Equation (2) indicates that the fact that non-dogmatic planners agree on the long-run social discount rate should have especially significant consequences for disagreements about policies with long-run effects, climate policy being an archetypal example. We turn to this application of the theory next.

2 Application in a DICE-like model

In order to illustrate the implications of non-dogmatic time preferences for disagreements about the SCC, we investigate their implications in a version of the DICE integrated assessment model of climate policy (Nordhaus, 2017). DICE combines a Ramsey-style growth model with a dynamical climate module. The climate module quantifies the CO₂ emissions intensity of economic output, how emissions accumulate in the atmosphere, how the stock of CO₂ changes global average temperatures, and finally how those temperature changes feed back into the economy via climate change damages. DICE is arguably the simplest and most widely used model in climate economics, and has been used in a variety of high-profile policy applications.

The standard version of the DICE model has 6 endogenous state variables (capital, two temperature variables, and three carbon cycle variables), 2 control variables (savings and the emissions control rate), and also relies on several exogenous time series (for TFP, population, non-CO₂ forcings, and mitigation costs). DICE uses a discounted utilitarian social welfare function with an iso-elastic utility function to measure intertemporal social

⁵For example, suppose that there are only two planners. Then we can write (4) in this example as

$$\begin{pmatrix} V_\tau^1 \\ V_\tau^2 \end{pmatrix} = \begin{pmatrix} U^1(c_\tau) \\ U^2(c_\tau) \end{pmatrix} + \begin{pmatrix} \beta_1 w_1 & \beta_1(1 - w_1) \\ \beta_2(1 - w_2) & \beta_2 w_2 \end{pmatrix} \begin{pmatrix} V_{\tau+1}^1 \\ V_{\tau+1}^2 \end{pmatrix} = \sum_{s=0}^{\infty} \begin{pmatrix} \beta_1 w_1 & \beta_1(1 - w_1) \\ \beta_2(1 - w_2) & \beta_2 w_2 \end{pmatrix}^s \begin{pmatrix} U^1(c_{\tau+s}) \\ U^2(c_{\tau+s}) \end{pmatrix},$$

where $\beta_1, \beta_2, w_1, w_2 \in (0, 1)$. The matrix in this expression is the mixing operator in question.

welfare:

$$V_{\tau}^{DICE} = N_{\tau} \frac{c_{\tau}^{1-\eta}}{1-\eta} + \beta V_{\tau+1}^{DICE} = \frac{1}{1-\eta} \sum_{s=0}^{\infty} N_{\tau+s} \beta^s c_{\tau+s}^{1-\eta}, \quad (5)$$

where N_{τ} is population, c_{τ} is per capita consumption, $\eta \geq 0$ is the elasticity of marginal utility, and $\beta = (1 + \rho)^{-1}$, where $\rho > 0$ is the pure rate of social time preference. The parameters ρ and η capture social impatience and aversion to intertemporal consumption inequalities respectively. Our object is to provide a counterfactual analysis of the SCC that preserves much of the standard structure of the DICE model, but allows us to investigate how non-dogmatism might reduce disagreement amongst planners who favour different values of ρ and η . While there are other normative choices in the model that could be interrogated (e.g. its treatment of population ethics and uncertainty (Fleurbaey et al., 2018)), much of the debate in the literature has focussed on these two parameters. As our goal is to demonstrate the consequences of non-dogmatism in a well-known benchmark model, we make minimal changes to the DICE framework itself.

In order to bring the non-dogmatic preferences (4) into contact with the DICE model in a computationally tractable manner, we make three simplifying assumptions, on time inconsistency issues, the set of planner preferences we consider, and on how to model the climate system. We describe each of these simplifications in turn.

2.1 Time (in)consistency issues

Since non-dogmatic planners' preferences may change over time, intuition might suggest that they are necessarily time inconsistent. However, this is not the case:

Proposition 1. *The time preferences in (4) are time consistent if and only if $\beta_s^i = 0$ for all $s \geq 2$, $i = 1 \dots N$.*

Proof. Johnsen & Donaldson (1985) show that history independent and consequentialist⁶ time preferences are time consistent iff they have the form

$$V_{\tau}^i(x, \mathbf{c}) = F_{\tau}^i(x, \{V_{\tau+1}^j(\mathbf{c})\} | j \in \mathcal{I}_{\tau+1})$$

where x is current consumption, $\mathbf{c}$ is an arbitrary stream of future consumption, and $\mathcal{I}_{\tau+1}$ indexes a set of events (preference changes in our setting) that occur at the beginning of

⁶Preferences are consequentialist if they only depend on reachable nodes of a decision tree, i.e., they do not depend on unrealised events or plans not carried out. The preferences in (4) are both consequentialist and history independent.

period $\tau + 1$. Applying this constraint on preferences to (4) yields the result. $\square$

Thus, although non-dogmatic planners' preferences may change over time, they need not be time inconsistent. This is a direct consequence of preference internalisation: if current planners internalise the preferences of future selves in the next time period only, their preferences satisfy a recurrence relation that is reminiscent of a stochastic Bellman equation; they are thus time consistent. In our simulations we will work with the following system of non-dogmatic time preferences:

$$V_\tau^i = N_\tau U^i(c_\tau) + \beta_i \sum_{j=1}^N w_{ij} V_{\tau+1}^j. \quad (6)$$

As these preferences are time consistent, the numerics are vastly simpler than what would be necessary in a dynamic game between sophisticated, time inconsistent, non-dogmatic planners (see Iverson & Karp, 2018, for a discussion of the numerical difficulties that occur in solving such games).

The constraint on preferences in (6) is less severe than it may appear. An alternative choice that has received axiomatic support in the literature (Galperti & Strulovici, 2017), is an exponential model of the form:

$$V_\tau^i = N_\tau U^i(c_\tau) + \gamma_i \sum_{s=1}^{\infty} (\alpha_i)^s \sum_{j=1}^N w_s^{ij} V_{\tau+s}^j. \quad (7)$$

These preferences are time inconsistent. However, Millner (2019) observes that if we require (7) to approximate Discounted Utilitarian (DU) time preferences in the 'dogmatic limit' where $w_s^{ij} \rightarrow 0$ if $j \neq i$, then we must take γ_i to be large, while holding $\alpha_i \gamma_i$ fixed. Call the limit as $\gamma_i \rightarrow \infty$, while $\alpha_i \gamma_i$ is fixed, the DU limit of (7). As we approach the DU limit, (6) becomes a very good approximation to (7). Moreover, as we will work with a finite horizon model in our simulations, there is a unique sub-game perfect equilibrium of the dynamic game between sophisticated exponential non-dogmatic planners. That equilibrium must converge to a solution of (6) in the DU limit. Thus the models in (6) and (7) are mutually consistent if we require preferences to reduce to discounted utilitarianism in the dogmatic limit. This requirement is essential for consistency with the survey data we calibrate our model to. We now turn to a description of that data.

2.2 Calibrating preferences

To implement (4) in a quantitative application we need to calibrate preferences to a sample of plausible normative theories of intertemporal social welfare. We follow Millner (2019), who calibrates the model to data from a survey of economists who have published papers on social discounting (Drupp et al., 2018). The survey elicited 173 respondents’ views on the appropriate values of the parameters ρ and η of the discounted utilitarian intertemporal welfare function in (5). To demonstrate how non-dogmatism reduces disagreements about the SCC, we need to solve non-dogmatic versions of the DICE model for each of these parameter values. That is, we run many versions of the DICE model assuming that a different planner is in complete control of policy in each run; however, each planner is non-dogmatic.

In the version of the model used by Millner (2019) planners are assumed to have symmetric switching probabilities w_{ij} that take the following form:

$$w_{ij} = \begin{cases} 1 - x & j = i \\ \frac{x}{N-1} & j \neq i \end{cases} \quad (8)$$

Thus, planners stick to their current theory in the next period with probability $1 - x \in [1/N, 1]$. Conditional on switching (which occurs with probability $x \in [0, 1 - 1/N]$), they switch to any of the plausible alternative normative theories with equal probability. The variable x thus measures the ‘degree’ of non-dogmatism. Note that this model does not imply that switching probabilities are uniformly distributed over the space of possible preferences. Regions of (ρ, η) space that are more common in our sample will be switched to more often, on average, than sparsely populated regions. In the dogmatic case where $x = 0$, the preferences in (6) coincide with the standard discounted utilitarian preferences in (5).

A direct implementation of this calibration methodology leads to 173 different intertemporal optimization problems, and 173 different value functions that must be solved for in each time step of the model.⁷ Since this problem is prohibitively costly to implement computationally, we simplify the dataset. We use a k -means clustering algorithm to assign each data point in the sample of (ρ, η) pairs to one of $M \ll 173$ clusters, in such a way that the within cluster variance is minimised. All points within a cluster are identified with the centroid of that cluster, and a weight $m_i = \frac{\# \text{ points in cluster } i}{N}$ is assigned to cluster i .

⁷Since we work with a finite horizon model, value functions depend explicitly on time.

The switching probabilities between clusters, denoted w_{ij}^C , are then assumed to be proportional to their weight, so that the uniform switching probabilities at the individual level in (8) are reflected at the level of clusters:

$$w_{ij}^C = \begin{cases} 1 - x + xm_i & j = i \\ xm_j & j \neq i \end{cases} . \quad (9)$$

Figure 1 illustrates the dataset, and its partition into 10 clusters. Note that since the clustering algorithm invariably loses some of the variation in the data, our results will necessarily provide a lower bound on the reduction in disagreement about the SCC due to non-dogmatism.

2.3 Simplifying the climate dynamics

Our final simplification relates to the way DICE represents climate dynamics, i.e., the relationship between CO₂ emissions and temperature change. As we observed above, DICE uses 5 state variables to represent the climate system. The climate model in DICE builds on an early simple climate model (Schneider & Thompson, 1981), which aimed to represent the lags between emissions and warming that were thought to occur because of the dynamics of heat transfer between the atmosphere and the oceans (Nordhaus & Boyer, 2000). More recent work with sophisticated earth systems models has however shown that the inertia in the climate system as represented in DICE is overstated, largely because it neglects feedbacks in the climate system, and the saturation of carbon sinks in particular (Dietz & Venmans, 2019). To a very good approximation over time scales of a century or more, emitting a ton of CO₂ causes an almost immediate,⁸ permanent, increase in temperature that is independent of initial CO₂ concentrations (Matthews et al., 2009; Ricke & Caldeira, 2014). With the 10 year time step that DICE uses, the relationship between temperature T_τ and emissions e_τ in successive time steps is very well approximated by:

$$T_{\tau+1} - T_\tau = \mu e_\tau$$

⁸Peak warming after an emissions pulse occurs after about 10 years in modern earth systems models. The falloff in temperature response after the peak is very small over a period of 100 years (Ricke & Caldeira, 2014). Dietz & Venmans (2019) consider a simple two state model that allows one to fit the short-run peak in the temperature response curve, but show that such a model is virtually indistinguishable from a one state model in which warming is immediate.

Figure 1: Recommended values for the pair of parameters (ρ, η) from the Drupp et al. (2018) survey. Points with the same colour are assigned to the same cluster by a k -means clustering algorithm, and cluster centroids are marked with a cross. Ten clusters are used in this example. Note that cluster sizes are not fully represented in this figure as there may be several data points at the same value of (ρ, η) .

for some $\mu > 0$. Summing this relationship, we find

$$T_\tau - T_0 = \mu \sum_{t=0}^{\tau} e_t.$$

The Intergovernmental Panel on Climate Change’s central estimate is that 1 trillion tons of CO₂ emissions will cause approximately 2°C of warming (Collins et al., 2013) – this allows us to calibrate the value of μ . Dietz & Venmans (2019) provide a valuable discussion of the scientific literature that demonstrates the linear relationship between temperature change and cumulative emissions, and of the deficiencies of the climate model in DICE on this dimension.

Using this simple ‘cumulative carbon’ model of the climate system allows us to reduce the number of climatic state variables in DICE from five down to one – cumulative CO₂ emissions. Although this is a simplification, this model is more representative of the state of the art in climate science than the more complex climate model that DICE deploys.

2.4 Numerics

Other than the changes to the climate model and social time preferences described above, the version of the DICE model we work with is virtually identical to that in Nordhaus (2017).⁹ Given our simplifications, the model depends on the pair of state variables $S_\tau = (K_\tau, \text{CO}_{2,\tau})$, where K_τ is the capital stock, and $\text{CO}_{2,\tau}$ is the stock of CO₂ in the atmosphere. Letting Z_τ denote the pair of controls (i.e., consumption and the emissions control rate) at time τ , our modified DICE model can now be written as a set of equations of motion of the form:

$$S_{\tau+1} = H(S_\tau, Z_\tau, \tau)$$

These equations depend explicitly on time τ through the exogenous time series in the DICE model. The model can now be solved using methods from numerical stochastic dynamic programming (see Appendix A for further details). Formally, we find numerical

⁹There are two other minor differences. We do not include exogenous non-CO₂ forcings, as modelling their effects correctly would require extra state variables. These forcings have only small effects on the SCC. In addition, unlike the version of DICE in Nordhaus (2017), we constrain the emissions control rate to lie in $[0,1]$.

approximations to the M time dependent value functions $V_\tau^i(S_\tau)$ defined through

$$V_\tau^i(S_\tau) = \max_{Z_\tau} N_\tau U^i(Z_\tau) + \frac{1}{1 + \rho_i} \sum_{j=1}^M w_{ij}^C V_{\tau+1}^j(H(S_\tau, Z_\tau, \tau)).$$

The SCC is the welfare cost of an addition ton of CO₂ emissions in consumption units. According to planner i at time τ in state S_τ , the SCC is given by¹⁰

$$SCC_\tau^i(S_\tau) = \left| \frac{\partial V_\tau^i / \partial \text{CO}_{2,\tau} |_{S_\tau}}{\partial V_\tau^i / \partial K_\tau |_{S_\tau}} \right|. \quad (10)$$

Each run of the model with a different planner ‘in charge’ starts out with the same initial values of the state variables S_0 . However, the trajectories of state variables from $\tau = 1$ onwards are endogenous to planners’ preferences, and stochastic (due to the possibility of a change in preferences). Thus SCCs for $\tau \geq 1$ are random variables, which are computed at different values of S_τ for each planner.

3 Results

Our first main result – Figure 2 below – plots the distribution of SCCs in the initial period of the model as a function of the ‘non-dogmatism’ parameter x in (9). We work with the values $x = \{0, 2.5\%, 5\%, 10\%, 20\%\}/\text{yr}$, which correspond to a change in normative views roughly once every $\{\infty, 40, 20, 10, 5\}$ years on average. Even for $x = 2.5\%/\text{yr}$ non-dogmatism gives rise to a dramatic reduction in disagreement about the SCC. Dogmatic SCCs fall in the range 3-459\$/tCO₂, while non-dogmatic SCCs fall in the range 27-126\$/tCO₂ when $x = 2.5\%/\text{yr}$, a 4.6-fold reduction in disagreement. For $x = 10\%/\text{yr}$, the range of SCCs shrinks to 46-96\$/tCO₂, a ninefold reduction in disagreement. These reductions in disagreement occur despite the fact that disagreements about the primitive welfare parameters ρ, η remain intact.

Although a lot of this reduction in disagreement comes from the planner with preference parameters $\rho = 0.4\%/\text{yr}$, $\eta = 0.4$, this planner represents the fourth largest cluster. While this planner’s dogmatic SCC value is an outlier, the preference parameters that underlie it are not. Indeed, if we exclude outliers the results become even more dramatic. To demonstrate this, let $\mathcal{I}_{90}(x)$ denote the smallest SCC interval that contains 90% of the

¹⁰To facilitate comparison to Nordhaus (2017) the units of our SCC are 2010\$/tCO₂. Multiply by 44/12 to convert to 2010\$/tC.

Figure 2: SCCs in the initial model year (2015) as a function of the degree of non-dogmatism. Marker sizes are proportional to cluster sizes.

sample.¹¹ This interval excludes the most extreme 10% of SCC values, which in practice means the very low SCC values that obtain due to very large values for ρ , η , or both (i.e., the yellow, dark blue, black, or light green clusters in Figure 1). Table 1 records the values of $\mathcal{I}_{90}(x)$. Excluding outliers, we find a 7.7-fold reduction in the range of SCCs when $x = 2.5\%/yr$, with substantially bigger reductions in disagreement as x increases. Although our results are not driven by extreme *preferences*, the fact that non-dogmatism has a very substantial effect on extreme *SCCs* illustrates the value of a little normative humility in the context of the climate debate, or conversely, how inflexible adherence to a dogmatic normative paradigm can hold up agreement.

Figure 3 illustrates the dynamics of non-dogmatic SCCs. Figure 3a plots the one standard deviation range of SCC values in future model years for $x = 2.5\%$, for each

¹¹In detail, let Ω be an arbitrary subset of cluster indices such that $\sum_{i \in \Omega} m_i \geq 0.9$, and let $SCC^i[x]$ be the initial SCC in cluster i when the non-dogmatism parameter is x . We define $\mathcal{I}_{90}(x) = \min_{\Omega}[\min\{SCC^i[x] | i \in \Omega\}, \max\{SCC^i[x] | i \in \Omega\}]$.

non-dogmatic planner. The figure shows that even a small possibility of future preference change gives rise to considerable uncertainty about future SCCs; this is a consequence of variations in the endogenous trajectories of the state variables across different planners, and different realisations of the stochastic process for preference change. Despite this new source of uncertainty, we must look ahead 25 years before the variation in non-dogmatic SCCs is comparable to the *current* variation in dogmatic SCCs. It is essential to emphasize that this figure represents the uncertainty about future non-dogmatic SCC values for each planner, and not the reduction in disagreement about SCCs that would occur in any future period. Reductions in disagreement in future periods could be at least as large as those depicted in Figure 2, since the uncertainty about the interim trajectories of the state variables will be resolved when SCCs are computed in those periods. We illustrate this in Figure 3b, which plots dogmatic and non-dogmatic SCCs along a fixed reference trajectory for the state variables, taken to be the optimal path according to a dogmatic planner whose preference parameters coincide with those used in Nordhaus (2017). This figure illustrates that reductions in disagreement could be substantially larger in the future, depending on the interim evolution of the climate-economy system.

4 Conclusion

This paper presented a normative model of climate policy in which devotees of diverse theories of intertemporal social welfare are non-dogmatic – they admit the possibility of a change in their normative views, and internalise the preferences of possible future selves. The model requires planners (or economists) to exhibit a little humility about their preferred framework for evaluating climate policies. Despite this, the model still allows analysts the freedom to advocate their preferred normative theory unequivocally. Although disagreements about contested welfare parameters – the pure rate of social time preference

Table 1: Reduction in disagreement excluding outlying 10% of sample

x (%/yr)	$\mathcal{I}_{90}(x)$ (2010\$/tCO ₂)	$ \mathcal{I}_{90}(0) / \mathcal{I}_{90}(x) $
0	11-459	1
2.5	68-126	7.7
5	72-105	13.6
10	76-96	22.4
20	79-92	34.5

(a) Shaded areas denote the one standard deviation range of future SCC values for each of the non-dogmatic planners ($x = 2.5\%$). Filled dots denote initial dogmatic SCCs.

(b) SCC values along a fixed trajectory for the state variables given by the optimal path according to a dogmatic planner with DICE preferences ($\rho = 1.5\%, \eta = 1.45$). Filled dots correspond to $x = 0$, open circles to $x = 2.5\%$, and stars to $x = 10\%$. The dashed line marks the DICE SCC.

Figure 3: Dynamics of disagreement about the SCC

and elasticity of marginal utility – remain intact, planners who embrace non-dogmatism will exhibit significantly less disagreement about the SCC. Disagreements reduce by almost a factor of five if planners admit the possibility of a change in views once every forty years, and substantially more if they are more non-dogmatic. While non-dogmatism cannot deliver a universally acknowledged ‘best’ value of the SCC, it can focus policy evaluation on a much narrower range of values, which nevertheless reflects a plurality of normative views. This can hopefully help to move the debate on optimal climate policy past ethics, and on to practicalities.

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Appendix

A Details of the numerical solution

We solve the model using numerical stochastic dynamic programming. The model's time step is 10 years, the initial model year is 2015, and the terminal period is taken to be $T = 50$, corresponding to the year 2515, at which point the economy comes to an end.¹² The final period value function for each type i is given by the utility of consuming all output plus any remaining undepreciated capital. By approximating the value functions at any $t \leq T$, we can solve the problem for each type at time $t - 1$. We iterate until $t = 0$.

Value functions are approximated by Chebyshev collocation. That is, we choose a degree of approximation (N_K, N_{CO_2}) and approximate each value function $V^{i,t}$ by $\tilde{V}^{i,t}(K, CO_2) \equiv \sum_{j=0}^{N_K-1} \sum_{k=0}^{N_{CO_2}-1} z_{jk}^{i,t} \zeta_j(K) \zeta_k(CO_2)$, where $z_{jk}^{i,t}$ is the set of $N_K N_{CO_2}$ coefficients for type i at time t , and $\zeta_j(\cdot)$ is the Chebyshev polynomial of degree j . The value function is approximated in $[\underline{K}, \overline{K}] \times [\underline{CO_2}, \overline{CO_2}]$ (with the state intervals normalised to $[-1, 1]$ for the Chebyshev approximation itself). We compute the set of Chebyshev nodes in this region, solve the optimisation problem of type i at time t at each node, and choose the coefficients such that the approximation holds exactly at these nodes (Judd, 1998).

We choose $N_K = 24$, $N_{CO_2} = 10$. The problem is set up in Julia, using JuMP and the solver IPOPT. We use tight tolerances and verify that the relative errors in the Bellman equation are small (typically of the order of 10^{-4}), despite the existence of a kink where the abatement rate reaches unity (the maximal degree of abatement). The algorithm is stable as long as the state space region is chosen large enough.

After solving for the value functions, simulation of time paths (given an initial state) is straightforward: given a realisation of the type sequence, the optimal decision can be calculated for each t . Social costs of carbon are calculated using the formula (10), given our approximations for the value functions.

¹²We could use an alternative terminal condition, for example that the economy is forced to reach a steady state at this point. Given the DICE assumptions about TFP growth, and conservatively using the preference parameter combination $\min_i \rho_i$, $\min_i \eta_i$, the effects due to the choice of terminal condition are small.