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The derivation of discount rates with an augmented measure of income[☆]

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ABSTRACT

Most developed economies invest in public goods such as national defense, education, infrastructure, and the environment. Discount rates used to evaluate such projects should reflect the rate of return on the current mix of investment opportunities. Rates derived from the productivity of private capital neglect returns beyond the market boundary. The present paper derives discount rates using an augmented measure of national income inclusive of non-market goods. In an empirical application focusing on air pollution and climate damages in the United States economy, the paper reports that the difference between augmented and market discount rates averages 0.3 percentage points from 1999 to 2014.

1. Introduction

Most developed economies invest in public goods such as national defense, education, infrastructure, and the environment. Holding total investment fixed, expenditures on public projects entail a diversion of funds away from market consumption or investments in private capital. The appropriate discount rate with which to evaluate public projects must reflect the rate of return on social investment opportunities (Baumol, 1968). Comprehensively evaluating the return to such investments likely requires data that lie beyond the market boundary. For example, private investment that subsequently boosts output is likely to induce non-market external costs such as climate change and local pollution. Additionally, public goods investment may yield non-market returns through ecosystem services, domestic security, and human capital. Measuring only those returns that accrue within the market may produce biased estimates of the yield on investment. This bias would, in turn, manifest in social discount rates. In light of this, the present paper suggests using an augmented measure of income to evaluate both market and non-market returns. This facilitates estimation of an appropriate social discount rate used for Net Present Value (NPV) analysis of public projects.

Economists tend to base estimates of the discount rate used in NPV calculations on interest rates in financial markets, the rate of return on private capital, or the utility-neutral rate of savings (Gollier, 2011). Despite these rather crisp recommendations, estimating social discount rates has long-occupied economists (Steiner, 1959; Marglin, 1963a, 1963b; Baumol, 1968; Bradford, 1975; Mendelsohn, 1981; Weitzman, 1994). Recent debates concerning the economics of climate change centered

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on the appropriate discount rate (Stern, 2007; Nordhaus, 2007). Even more recently, papers have explored departures from conventional approaches to discounting including declining discount rates (Weitzman, 2001; Cropper et al., 2014), dual discounting for market and environmental goods (Drupp, 2018), and the role of relative prices and substitution between market and environmental goods (Hoel and Sterner, 2007; Traeger, 2011).

The present paper does not propose to settle ongoing discussions regarding the "right" social discount rate. Rather, the paper offers a different perspective on this topic by deriving discount rates for public projects using an augmented measure of national income inclusive of non-market goods. This tack permits expenditure on public goods to both (1) reduce the rate of return on saving by diverting funds away from private capital, and, critically, (2) to affect the level of public goods and services, which then, in turn, permutes augmented output. When calculated in such a framework, discount rates reflect three key factors: the productivity of private capital, the opportunity cost of direct expenditure on public projects, and the returns to public investment that accrete outside of the market boundary. This paper compares this augmented discount rate to market discount rates (the yield on relatively risk-free assets, like U.S. government bonds), showing under what conditions these rates differ and how.

The analytical modeling in this study builds on the approach to distilling discount rates from a National Income and Product Accounts (NIPA) framework developed by Weitzman (1994), who explored differences between market rates of discount and rates that reflect the diversion of some investment to pollution abatement expenditure.[1] Intuitively, expenditures on maintaining environmental quality necessitated by binding policy constraints effectively ratchet back gains from saving (and, hence, discount rates) because some of the returns from investment in private capital are diverted to abatement. This result is a clear elicitation of the need to employ an augmented measure of output in the presence of external economies; because a market-centered accounting framework does not allow environmental damage to directly affect income, abatement can only adversely affect the return to savings and lower the discount rate. Weitzman's tack assumes that abatement expenditure (investment in public goods) is less productive than investment in private capital simply because the returns to investment manifest outside the scope of income in the NIPAs.[2] More broadly, if the output measure does not include the services generated by a public good, then investments made by society in such a good will appear to be unproductive. In marked contrast, the present paper employs an income measure that includes non-market goods. This enables one to more comprehensively calculate the rate of return on investments in both private capital that may generate environmental externality and in public goods such as environmental quality.

Weitzman's model largely subsumed time (Weitzman, 1994). While savings decisions today affected consumption in a future period, the ramifications of savings in the present was ignored, and the responsiveness of environmental damage to abatement and damage were held fixed. This paper allows expenditure on abatement, the responsiveness of environmental damage to abatement, and the damage intensity of output to change over time. Further, this paper explicitly treats time. Abatement (and damage for that matter) inhibit growth in any period: when society saves in (t), it triggers less abatement (and damage), in (t), because current period consumption falls. Of course, the productivity of private capital increases output in period (t + 1) which increases abatement and damage. The time path of *both* abatement and damage are crucial to the augmented discount rate (Hoel and Sterner, 2007; Gollier, 2010). A model that subsumes time and holds damage fixed overlooks this effect.

The paper also empirically estimates damages from air pollution and greenhouse gas (GHG) emissions in the U.S. from 1999 to 2014. (This particular application is chosen because of well-developed empirical models and large damages, Muller, 2014a, 2014b.) Air pollutants included in the empirical analysis are fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and ammonia (NH_3). The air pollution damages are estimated using an integrated assessment model (IAM), the AP3 model that is calibrated to the U.S. economy over this 15-year period. AP3 and its predecessors have been widely applied in peer-reviewed studies (Holland et al., 2015; Muller, 2011, 2014a; 2014b; Muller et al., 2011; NAS NRC, 2010; Michalek et al., 2011; Clay et al., 2018). Additionally, estimates of the marginal damage from carbon dioxide emissions (CO_2) are drawn from recent estimates in the literature (IAWG, 2016). The damages for both air pollution and GHGs are computed by first estimating pollutant-and-source-specific marginal damages, and then multiplying these pollution "prices" times reported emission "quantities". Thus, Gross External Damages (GED), inclusive of both CO_2 and air pollution, are computed in a manner that is directly analogous to how market indices such as gross domestic product (GDP) are calculated (Nordhaus, 2006; Muller et al., 2011). Using estimates of damages, reported GDP, and abatement expenditure (USEPA, 2011a), the paper ties the conceptual modeling to the empirical estimates of three discount rates calibrated to the U.S. economy from 1999 to 2014.

1.1. Summary of key results

This paper derives expressions for three discount rates: market, environmental, and augmented discount rates. The market rate is simply the rate of return on private capital. The environmental discount rate (a term coined by Weitzman

[1] Though the tools developed in this paper apply to a range of non-market entities, because of the specific empirical application that zeroes-in on environmental externality, the discussion here focuses on this area. Broadly, the literature refers to environmental quality and natural resources as natural capital and it is straightforward to extend the concepts raised herein to investments in these other areas (see Heal, 2009, 2012; Maler et al., 2008).

[2] Weitzman recognized this and argued that both benefits (damages) and costs should be considered.

(1994) and maintained here) is derived by including an explicit characterization of abatement expenditure in the accounting identity (Weitzman, 1994). It is the rate of return on capital less the drag due to diversion of investment returns from output to abatement. This rate depends on the trajectory of abatement through time. Increasing (falling) allocations of resources to abatement reduces (boosts) the discount rate. The third discount rate is derived by including both abatement and environmental pollution damage into the national income identity.

The augmented rate is the rate of return on capital minus the current period partial effect of income on damages and abatement. This rate also depends on the trajectory of abatement and damages. This derivation shows that reallocating consumption across time (through savings and investment decisions) has an ambiguous effect on the return to savings and discount rates. The ramifications of investment depend on the relative intensities of abatement and damage across time. For example, savings withdrawn from consumption in a high damage economy and ultimately consumed in a low damage economy boosts the return to savings and discount rates. Contrarily, reallocating consumption from a low abatement economy to an economy featuring higher rates of investment in pollution control attenuates discount rates. The paper concludes by considering these results in the context of an environmental Kuznets curve.

The empirical section of the paper reports that GED from air pollution and greenhouse gases (GHGs) amounted to $1.1 trillion in 1999 and that this fell to $1.0 trillion in 2014, in real terms. Expressed relative to GDP, GED fell from 8.8 percent of output in 1999 to 6.1 percent in 2014. Thus, damages fell both in absolute and relative terms. The proposed measure of adjusted output (GDP less environmental pollution damage) grew by about 0.2 percentage points more rapidly than market GDP. And, over this 15-year time period, the augmented discount rate exceeded the yield on long-term U.S. Treasury bonds by about 34 basis points (0.34 percent). This stands in contrast to Baumgartner et al. (2015) who report social discount rates in excess of market rates estimated in contexts with deteriorating environmental quality.

1.2. Related literature

In addition to the early literature on the social discount rate (Steiner, 1959; Marglin, 1963a, 1963b; Baumol, 1968; Bradford, 1975; Mendelsohn, 1981), this paper builds on several strands of the more recent environmental economics literature. The basic approach relying on the NIPAs to derive discount rates inclusive of production of natural capital builds on Weitzman (1994). Prior research raised the issue of changing relative prices for market and environmental goods and the complications that this poses for standard uniform discounting (Weikard and Zhu, 2005; Sterner and Persson, 2008; Hoel and Sterner, 2007; Drupp, 2018). Another series of papers explore dual discounting as a means to address relative price changes (Hasselman et al., 1997; Yang, 2003; Tol, 2003; Weikard and Zhu, 2005; Heal, 2009; Gollier, 2010; Baumgartner et al., 2015; Drupp, 2018). The basic premise of dual discounting is that, if relative prices are ignored, environmental services should be discounted separately for market goods (Weikard and Zhu, 2005; Drupp, 2018).

One perspective on the approach to the deriving of discount rates proposed in this paper is that it embodies properties of dual discounting. The augmented discount rate combines market rates based on the opportunity cost of capital and changes in natural capital, ecosystem services, or environmental damage into one rate. This is akin to the literature that extends the Ramsey discounting equation to include separate terms for environmental services and market goods (Hoel and Sterner, 2007; Heal, 2009). Further, both the conceptual and empirical models in this paper reflect the role of relative prices. The characterization of environmental pollution damage in the augmented rate implicitly depends on the marginal values of pollution. Moreover, the empirical modeling that estimates the augmented rate demonstrates the role played by prices for environmental services (the marginal damages of pollution).

The paper also relates to work that demonstrate how social discount rates vary with the level of environmental services (or pollution damage) (see Epstein and Hynes, 1983; Das, 2003; Le Kama et al., 2007; Hoel and Sterner, 2007; Heal, 2009; Gollier, 2010; Baumgartner et al., 2015; Six and Wirl, 2015). One implication of incorporating environmental services into the formulation of discount rates is a variable term structure.

The present paper also relates to prior work featuring the calculation of air pollution and GHG damages (Muller and Mendelsohn, 2009; Levy et al., 2009). The inclusion of such damages into an augmented accounting system connects to earlier papers (Bartelmus, 2009; Muller et al., 2011; Muller, 2014a). Estimation of augmented growth rates links to Muller (2014a; 2014b). There is also a literature exploring the idea of inclusive wealth, which is basically defined to augment conventional notions of wealth with various measures of natural capital (Polasky et al., 2015).

The remaining sections of the paper include the following. Section 2 lays out the structure of the analytical model and derives various expressions for the discount rates. Section 3 introduces the empirical model and data sources. Section 4 reports empirical results and Section 5. concludes.

2. Analytical models

This section uses a national income accounting framework to derive discount rates using three definitions of income: (1) observed income that accrues within the market boundary, (2) observed income with an explicit treatment of investment in environmental public goods, or natural capital, and (3) augmented income that includes both of the above and consumption of natural capital.

In each of these frameworks, discount rates are derived by modeling consumption-investment tradeoffs with a known rate of return on private capital ($r \geq 0$) in a highly aggregated, one-commodity macro model a la Solow (1956). Like Weitzman (1994), the paper assumes that savings becomes part of planned investment and that the economy is at full employment.

Observed (produced and consumed within the market) production, (Y_t^m) is expressed in terms of the standard accounting identity[3] as shown in (1).

$$Y_t^m = C_t + I_t + G_t + X_t \tag{1}$$

where:

C_t = consumption of market goods during time (t).
$I_t = K_t - \lambda K_{t-1}$: net investment in physical capital, where λ is the depreciation of physical capital.
G_t = government expenditure.
X_t = net exports.

Next, the standard framework is modified to distinguish between investment in private capital I_t^p, and investment in pollution abatement, or natural capital, I_t^a. The present paper focuses on pollution and as such, let A_t represent expenditure on abatement of pollution: $I_t^a = A_t = \gamma_t Y_t^a$, where $(0 \leq \gamma_t \leq 1)$. This extension is shown in (2).

$$Y_t^a = C_t + I_t^p + I_t^a + G_t + X_t \tag{2}$$

Expression (3) proposes a third characterization of national income that distinguishes within-market consumption of private goods and services, C_t^p, from, C_t^e, the consumption of environmental services.[4]

$$Y_t^e = C_t^p + C_t^e + I_t^p + I_t^a + G_t + X_t \tag{3}$$

More concretely, let (C_t^e) reflect pollution damage,[5] or degradation of natural capital: $C_t^e = D_t = \alpha_t Y_t^e - \beta_t(\gamma_t Y_t^e)$. The pollution-intensity of output is given by (α), while (β) reflects the sensitivity of environmental damage to investment in abatement.

2.1. Savings, and changes to income, abatement, and damage

In period (t), suppose that consumption is reduced and savings increased by (ε_t). Savings is allocated to planned investment in productive capital that earns a rate of return (r), and, thus, boosts output in period (t+1) by $(1+r)\ \varepsilon_t$. In the context of market income, the resulting output level in period (t + 1) is shown in (4a).

$$Y_{t+1}^m + (1+r)\varepsilon_t = C_{t+1} + I_{t+1} + G_{t+1} + X_{t+1} \tag{4a}$$

In the context of Eq. (2), savings, as above, reduces consumption in period (t) while boosting output in (t + 1). Savings also reduces abatement in (t) and subsequently increases abatement in period (t + 1), relative to the case of no savings. Abatement declines by $\left(\frac{\partial A_t}{\partial Y_t^e}\right)\varepsilon_t$ and then increases by $\left(\frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)(1+r)\varepsilon_t$. Whether levels of abatement rise or fall over time depends on the relative size of $\left(\frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)$ and $\left(\frac{\partial A_t}{\partial Y_t^e}\right)$. Output in period (t + 1) with savings in period (t) is shown in (4b).

$$\left(Y_{t+1}^a + (1+r)\varepsilon_t\right) = C_{t+1} + I_{t+1}^p + I_{t+1}^a + G_{t+1} + X_{t+1} \tag{4b}$$

where: $I_{t+1}^a = (Y_{t+1}^a + (1+r)\varepsilon_t)\gamma_{t+1}$

Finally, employing income as defined in Eq. (3), savings has three effects: on consumption of market goods, abatement, and the consumption of environmental services: C_{t+1}^e.

[3] In a Solow (1956)-type framework, output at time (t), denoted Y_t, is expressed as a function of capital (K_t) and labor (L_t). Since this paper models output in a highly aggregated form, it does not require the use of a particular production function.

[4] As noted above, Weitzman (1994), in footnote 8, states that a more complete treatment of the discount rate would include the benefits of pollution abatement policy. Those benefits are captured here as reduced damages from abatement.

[5] There is precedent in the literature for how to incorporate pollution damage into the accounts; a measure of income that includes damages from remaining pollution is referred to as "comprehensive consumption" (NAS NRC, 1999 p. 147). Why consumption? Polluters effectively consume the waste-repository services provided by the natural environment. Whether long-term storage of heavy metals or greenhouse gases, or short-term transport of wastewater, the environment acts as a no-cost sink for residuals.

$$\left(Y^{e}_{t+1}+(1+r)\varepsilon_t\right)=C^{p}_{t+1}+C^{e}_{t+1}+I^{p}_{t+1}+I^{a}_{t+1}+G_{t+1}+X_{t+1} \tag{4c}$$

where: $C^{e}_{t+1} \;=\; (Y^{e}_{t+1}+(1+r)\varepsilon_t)(\alpha_{t+1}-\beta_{t+1}\gamma_{t+1})$

$$I^{a}_{t+1}=\left(Y^{e}_{t+1}+(1+r)\varepsilon_t\right)\gamma_{t+1}$$

As above, because savings is withdrawn from consumption in (t), investment in abatement falls, relative to the no savings case, as does damage. In period (t + 1), both abatement and damage rise, relative to the case without savings in (t). The intertemporal path of investments in abatement and consumption of environmental services depends on the relative magnitudes of $\left(\frac{\partial A_{t+1}}{\partial Y^{e}_{t+1}}\right)$ and $\left(\frac{\partial A_t}{\partial Y^{e}_t}\right)$ as well as $\left(\frac{\partial D_{t+1}}{\partial Y^{e}_{t+1}}\right)$ and $\left(\frac{\partial D_t}{\partial Y^{e}_t}\right)$. The analysis below will show that these rates of change in abatement and damage are critical determinants of the augmented discount rate and its magnitude relative to market rates.

2.2. Derivation of discount rates

In order to derive the discount rates, the analysis computes the rate of return on savings in the three different income formulations (the appendix shows this procedure step-by-step.). The basic idea is to solve for consumption in two states: one with productive savings and one without, in two time periods (t) and (t + 1). Then, the difference in consumption due to savings and the rate of return on savings is computed.

The rate of return on savings in the context of market income is given by (5a). Straightforwardly, it is the familiar rate of return on investment in private capital.

$$i^{m}=(1+r)-1=r. \tag{5a}$$

Repeating this procedure with the accounts that recognize pollution abatement (2) yields:

$$i^{a}=r\left(1-\frac{\partial A_{t+1}}{\partial Y^{a}_{t+1}}\right)+\left(\frac{\partial A_t}{\partial Y^{a}_t}-\frac{\partial A_{t+1}}{\partial Y^{a}_{t+1}}\right). \tag{5b}$$

Expression (5b) reveals that the rate of return on private capital has two effects on the environmental discount rate. First, (i^{a}) increases in (r) as it reflects the opportunity cost of capital. Additionally, the $-r\left(\frac{\partial A_{t+1}}{\partial Y^{a}_{t+1}}\right)$ term reflects the opportunity cost of investment in abatement during the period when the returns to investment are available for consumption (t + 1). This effect indicates that a higher return to private capital also reduces (i^{a}) because greater resources available for consumption in (t + 1) implies greater abatement. These foregone returns from investment in private capital lower the effective discount rate relative to the marginal product of capital. This is akin to the “drag” term identified by Weitzman (1994). The second term $\left(\frac{\partial A_t}{\partial Y^{a}_t}-\frac{\partial A_{t+1}}{\partial Y^{a}_{t+1}}\right)$ indicates that a path of falling abatement shares increases (i^{a}). This manifests because, if $\left(\frac{\partial A_t}{\partial Y^{a}_t}>\frac{\partial A_{t+1}}{\partial Y^{a}_{t+1}}\right)$, ($\varepsilon_t$) is reallocated from a period of high abatement to a period of lower abatement. Savings moves resources from a high-drag to a low-drag time period. This boosts returns to savings and the discount rate. Conversely, rising levels of abatement has just the opposite effect, accentuating the drag on investment and lowering (i^{a}), because (ε_t) is reallocated to a period of higher abatement.

Using the procedure above in the context of (3) produces (5c).

$$i^{e}=r\left(1-\left(\frac{\partial D_{t+1}}{\partial Y^{e}_{t+1}}+\frac{\partial A_{t+1}}{\partial Y^{e}_{t+1}}\right)\right)+\frac{\partial D_t}{\partial Y^{e}_t}-\frac{\partial D_{t+1}}{\partial Y^{e}_{t+1}}+\frac{\partial A_t}{\partial Y^{e}_t}-\frac{\partial A_{t+1}}{\partial Y^{e}_{t+1}} \tag{5c}$$

In (5c), (r) has a multifaceted effect. First, it directly increases (i^{e}) as in (5b). In addition, higher rates of return to private capital generate resistance in two ways. First, the $-r\left(\frac{\partial A_{t+1}}{\partial Y^{a}_{t+1}}\right)$ term attenuates (i^{e}) in the same manner as (i^{a}). In addition, through the $-r\left(\frac{\partial D_{t+1}}{\partial Y^{e}_{t+1}}\right)$ term, market returns to savings further saps (i^{e}). Higher values of (r) yield more output for consumption in period (t + 1), which produces higher damage, suppressing (i^{e}).

Expression (5c) also shows that the temporal change in pollution damage affects (i^{e}). Falling pollution intensity of output increases (i^{e}). The intuition for this effect is the following; by saving (ε_t) in period (t), and then consuming the resulting returns (net of abatement) in period (t + 1), consumption is occurring in a period characterized by lower pollution damage intensity. This differential boosts the returns to investment, ceteris paribus, because the drag on output due to pollution damage is lower in (t + 1). Conversely, growing pollution intensity attenuates (i^{e}). Rising damage intensity lowers (i^{e}) because savings in period (t) and consumption of the returns in (t + 1) reallocates consumption from a low damage to high damage economy. Greater damage shrinks the return to savings and (i^e). Crucially, these effects manifest if and only if the definition of income encompasses non-market damage, a result reported in different modeling contexts by earlier authors (Hoel and Sterner, 2007; Gollier, 2010; Baumgartner et al., 2015).

The derivations above concern an economy without explicitly binding policy constraints. Abatement and damage are free to change from period (t) to period (t + 1). The appendix treats two additional cases: when damages are held fixed from (t) to (t + 1), and the case of efficient pollution control.

The analysis next compares the market and the augmented discount rate. Other comparisons are found in appendix. Subtracting (5a) from (5c), yields:

$$i^e - i^m = \frac{\partial D_t}{\partial Y_t^e} - \frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_t}{\partial Y_t^e} - \frac{\partial A_{t+1}}{\partial Y_{t+1}^e} - r\left(\left(\frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)\right). \tag{6}$$

Rearranging (6) reveals that the market rate and the augmented rate are equal when:

$$r = \frac{\left(\frac{\partial D_t}{\partial Y_t^e} + \frac{\partial A_t}{\partial Y_t^e}\right)}{\left(\frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)} - 1.$$

Consider that the numerator of this expression reflects the benefits to savings in period (t); it is the avoided damage and abatement that would have occurred if the (ε_t) was consumed in (t). The denominator shows the cost of savings in period (t) that manifest in (t + 1): the additional damage and abatement from the growth in savings that manifests in period (t + 1). The two rates coincide when the market rate equals the relative benefits and costs of savings. Assuming positive market rates, (i^e) and (i^m) can only coincide when the combined drag imposed by damages and abatement fall over time. Conversely, if $\left(\frac{\partial D_t}{\partial Y_t^e} + \frac{\partial A_t}{\partial Y_t^e}\right) < \left(\frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)$, then $r > i^e$. Hence, in an economy in which the combined partial effects of output on abatement and damages rise over time, market rates will exceed the augmented rate. The expression in (6) further underscores the importance of the time path of abatement and damage to the relative magnitudes of the augmented and market discount rates.

3. Empirical model and calibration to U.S economy

The empirical modeling is ultimately intended to bring data to the conceptual model. To do so, the AP3 integrated assessment model is used to estimate GED and to empirically estimate through computational simulation, the expression: $\alpha_t - \beta_t\gamma_t$. The empirical exercises in this paper require several sources of data. Economy-wide Gross Domestic Product (GDP), and the accompanying GDP deflators are reported by the U.S. Bureau of Economic Analysis (USBEA, 2014). For environmental damage, empirical estimates of damages from local air pollutants (GED) are produced using the AP3 model (Clay et al., 2018). AP3 is an updated version of the AP2 and APEEP models (Muller and Mendelsohn, 2007, 2009; Muller et al., 2011; NAS NRC, 2010; Michalek et al., 2011; Holland et al., 2015; Muller, 2011, 2014a; 2014b; Jaramillo and Muller, 2016). The AP3 model is an integrated assessment model (IAM) for local air pollution that covers the following five pollutants: ammonia (NH_3), sulfur dioxide (SO_2), nitrogen oxide (NO_x), fine particulate matter ($PM_{2.5}$), and volatile organic compounds (VOC). The model tracks emissions of these pollution species that are reported by the U.S. Environmental Protection Agency (USEPA) for the following years: 1999, 2002, 2005, 2008, 2011, and 2014 (see USEPA, 2002, 2005; 2008, 2011b; 2014, 2017). Emissions are reported by species, year, and source type (mobile versus stationary, for instance) and by the county of release.

For each data year, an air quality model in AP3 converts reported emissions into annual average pollution concentration estimates of ambient fine particulate matter ($PM_{2.5}$) for each county in the contiguous U.S. Specifically, the model employs a series of source-receptor matrices that characterize the effect of an incremental emission (one ton, say) from source (j) on air quality in receptor county (k). There are distinct matrices for each emitted pollutant and for four different source classifications: ground-level emissions and point source emissions from three different effective height classes. Ground-level emissions encompass discharges from vehicles, households, and small commercial facilities without an individually monitored smokestack. Point sources are divided into those with an effective height of emissions of less than 250 m, 250–500 m, and those over 500 m. The last category consists of 656 of the largest industrial air pollution sources in the lower-48 states. Most of these are fossil fuel fired power plants. The predictions of the air quality model in AP3 have been tested against ambient pollution monitors maintained by the USEPA (See Sergi et al., 2018 for the most recent diagnostic tests of AP3.).

With predicted concentrations, the model computes population exposures in each county. This relies on population estimates provided by the U.S. Census Bureau (Census, 2015). Importantly, population data are sub-divided into roughly 20 age groups by county. This is a critical distinction because baseline incidence rates vary *across both space and age*. Baseline mortality incidence data is provided by the Centers for Disease Control and Prevention (CDC, 2018). Both population and mortality rate data are provided for each modeled year. Thus, as population size, spatial distribution, and vitals change, the model picks this evolution up.

Converting exposure into physical effects (premature mortality) relies on dose-response or concentration-response functions. Paramount among these are the functional relationships between adult mortality rates and exposure to $PM_{2.5}$. The adult mortality-$PM_{2.5}$ link is modeled using the function reported in Krewski et al. (2009), and Lepeule et al. (2012). The use of these functions is widespread in the academic literature, in regulatory impact analyses, and in benefit-cost analyses (USEPA, 1999, 2011a). Monetization of premature mortality risk uses the Value of a Statistical Life (VSL) approach (Viscusi and Aldy, 2003). The VSL is a common approach to monetize mortality risk from air pollution exposure (USEPA, 1999; 2011a). Further, AP3 uses a VSL of $7.4 million (in year-2006 USD) which is the USEPA's recommended value. For modeling impacts in different data-years, the analysis converts the VSL to current-year dollars using the consumer price index. To account for income effects, the results from Kleckner and Neumann (1999), who reports an income elasticity for the VSL of 0.4, are used. To summarize, in the default modeling approach, damages from both local air pollution and GHGs are computed and expressed in real terms. The VSL is adjusted for income, and the $PM_{2.5}$-adult mortality dose-response function from Krewski et al. (2009) is used.

3.1. Computing marginal damage and integration into the national accounts

Because the damages from air pollution are integrated into an augmented accounting system, the approach to estimating aggregate damages reflects the approach to tabulating the gross value of production embodied in GDP. That is, total damage is the product of emissions (quantity) times marginal damage (loosely, the price of emissions). The environmental accounting literature recommends this approach (Nordhaus, 2006).

Marginal damages are computed using the algorithm first developed and applied by Muller and Mendelsohn (2007, 2009). This entails the following steps. First, for a given time period (say, 2011) baseline emissions reported by the USEPA are processed through the AP3 model to compute concentrations, exposures, physical effects, and monetary damages. The baseline gross damage number is stored. Next, one ton of one pollutant, $PM_{2.5}$ for example, is added to baseline emissions from source (j). The AP3 model is re-run and new concentrations, exposures, physical effects, and money damages are tabulated. The difference between the new damage figure and the baseline gross damage constitutes the marginal ($/ton) damage for source (j) emissions of $PM_{2.5}$ in year (t). This is captured in (7).

$$MD_{j,t,s} = \sum_{k=1}^{K} D_{k,t,s}^{+1} - D_{k,t,s}^{b} \tag{7}$$

where: $D_{k,t,s}^{+1}$ = damage in county (k), time (t), exposure to pollutant (s) after adding one ton of pollutant (s) to baseline emissions produced by source (j).

$D_{k,t,s}^{b}$ = damage in county (k), time (t), exposure to pollutant (s), conditional on baseline emissions.
K = total number of receptor counties.

Note that the marginal damage is a spatial sum over receptor counties subsequent to the additional ton emitted by source (j). The AP3 model then cycles through the remaining (N = 9,983) sources and five pollutants to produce a total of 50,000 source-and-pollutant-specific marginal damage estimates for each of the six years covered in the analysis.

Total damages, or GED, are the product of emissions and marginal damages, matched by source and pollutant. This is depicted in (8) which shows that economy-wide GED is the sum across pollutants (S), sources (J), and sectors (I).

$$GED_t = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{s=1}^{S} E_{j,i,t,s} \times MD_{j,i,t,s} \tag{8}$$

In time period (t) the empirical estimate of the coefficient of pollution intensity net of abatement is: $\alpha_t - \beta_t \gamma_t = \frac{GED_t}{GDP_t}$. Market macroeconomic aggregates and the GED are deflated using the GDP deflators reported by the USBEA. The empirical analog to expression (3) is produced by subtracting the *GED* from *GDP* as shown in (9), where *EVA* denotes environmentally adjusted value added (Muller, 2014a, 2014b).

$$EVA_t = GDP_t - GED_t \tag{9}$$

3.2. Damages from greenhouse gas emissions

The damages from greenhouse gases are estimated using an analogous price times quantity approach. This involves the application of a Social Cost of Carbon (SCC) estimate, which is essentially the present value of damage caused by emitting one ton of carbon dioxide (CO_2). The AP3 model is not a device that can compute the SCC. As such, the analysis turns to recent meta-analyses for SCC estimates. In particular, the SCC value reported by the U.S. Federal Government's Inter-Agency Working

Group on the Social Cost of Carbon is used (IAWG, 2016). The SCC is reported to be \$36/metric ton CO_2 in 2015 and \$31/metric ton CO_2 in 2010 in (\$2007). The present analysis interpolates to match years covered in the present analysis. This SCC is multiplied times emission estimates for the entire U.S. economy, because, unlike emissions of local air pollutants, the damage from emissions of CO_2 is independent of the location of emission. Thus, one marginal damage is applied to all emissions in a given year.

4. Results

The results section proceeds as follows. Section 4.1 reports the levels and growth rates of the macroeconomic aggregates relevant to the study. These include GDP, the GED, and EVA. Section 4.2 focuses on the calibrated parameters. Next, section 4.3 explores the resulting empirically estimated discount rates.

4.1. Macroeconomic aggregate indices

Column (1) of Table 1 reports real GDP from 1999 to 2014. (GDP is reported in three-year increments because this comports with the years for which emission data are available and hence damage estimates are provided.) As is well known, real GDP increased from 1999 to 2014. Column (2) shows the GED estimates inclusive of both air pollution and greenhouse gases using the default modeling assumptions. It is important to recall that the default case adjusts the VSL according to income levels. Thus, as income grew throughout the study period, the marginal value of mortality risk reduction increased as well. Hence, although the results in Table 1 are expressed in real terms, the income effect induces an increase in the VSL from 1999 to 2014.

In 1999, GED amounted to \$1.1 trillion. Roughly, 85 percent of the GED in 1999 was due to local air pollution. Real GED increased to \$1.2 trillion in 2002 and it remained essentially unchanged between 2002 and 2008 before falling nearly 20% to 2014. Column (3) presents the augmented measure of output, which is defined as GDP less GED. The augmented output measure increased from \$11.5 trillion in 1999 to \$15.9 trillion in 2014.

Tables A.I and A.II in appendix report the (national average) marginal damage estimates for each of the local air pollutants and CO_2 for each year covered in the analysis. Marginal damages for CO_2 (the SCC) rises over time according to the trajectory reported in the literature (IAWG, 2016). The local air pollution marginal damage estimates also tend to increase through time, though not monotonically. The marginal effects from these pollutants increase with population growth and because of changes in atmospheric composition as emission levels for SO_2, NO_X, and $PM_{2.5}$ have changed considerably over the 1999 to 2014 time period. Additionally, for each time period, AP3's predicted ambient pollution levels are calibrated to match monitoring data reported by the USEPA (USEPA, 2018). This affects the spatially-averaged marginal damages reported in Tables A.I and A.II. One other important difference *between* the tables is the influence of the VSL-income elasticity. Table A.II shows that when the VSL is adjusted by real, per-capita income, the rate of change (across years) in the marginal damages increases. (This has no effect on the CO_2 damages because the VSL is not explicitly part of the SCC calculation.)

Table 2 reports annualized growth rates in the macroeconomic aggregates. GDP expanded over each three-year period. The lowest growth rate occurred between 2008 and 2011 as the economy went through the Great Recession. The most rapid period of growth was between 2002 and 2005. The average real GDP growth rate was just about 2 percent. Using the default modeling assumption, GED expanded by 3.4 percent (annually) from 1999 to 2002, it was essentially flat between 2002 and 2005, and then GED grew by about 1 percent, annually between 2005 and 2008. Over the remaining years, real GED fell. The most rapid rate of GED contraction (about 5.5 percent annually) occurred between 2008 and 2011. Over all 15 years, the average annual GED growth rate was −0.47 percent. The average EVA growth rate was 2.17 percent. Because GED was, on average, falling while GDP expanded, EVA growth exceeded GDP growth. This result confirms that reported in Muller (2014a; 2014b) and it extends those results to include 2011 and 2014.

Table 1
Empirical model calibration: GED inclusive of damage from greenhouse gas and local air pollution emissions.

Year	(1) $Y_t = (GDP)^A$	(2) $D_t = (GED)^B$	(3) $E_t = (Y_t - D_t)$	(4) $\alpha_t - \beta_t\gamma_t$ (GED/GDP)
1999	12,615	1,114	11,501	0.0883
2002	13,495	1,232	12,263	0.0913
2005	14,915	1,223	13,691	0.0820
2008	15,608	1,266	14,342	0.0811
2011	15,842	1,069	14,773	0.0675
2014	16,899	1,031	15,867	0.0610

A = All values expressed in billions of real \$2012.
B = GED includes damages from local air pollution and principal greenhouse gases.

Table 2
Empirical estimates of growth rates.

Year	GDP	GED (1)	EVA (1)	Δ (1)	Δ (2)	Δ (3)	Δ (4)	Δ (5)
1999–2002	2.28[A]	3.42	2.16	0.11	−0.05	0.07	0.25	0.00
2002–2005	3.39	−0.24	3.74	−0.35	−0.51	−0.38	−0.98	−0.20
2005–2008	1.53	1.14	1.56	−0.03	−0.16	−0.08	−0.14	−0.05
2008–2011	0.50	−5.47	0.99	−0.49	−0.52	−0.50	−1.32	−0.23
2011–2014	2.18	−1.19	2.41	−0.24	−0.28	−0.24	−0.59	−0.12
Avg. Growth	1.97	−0.47	2.17	−0.20	−0.30	−0.23	−0.55	−0.12

A = All growth rates are annualized and expressed in (%).
Δ = GDP − EVA growth.
(1) = GHGs and LAP Income Adjusted VSL.
(2) = GHGs and LAP No Income Adjustment to VSL.
(3) = GHGs and LAP Income Adjusted Low VSL.
(4) = GHGs and LAP Income Adjusted VSL, High D-R.
(5) = LAP Income Adjusted VSL.

The right-hand panel of Table 2 reports the differences between GDP and EVA growth rates. The numeric column labels correspond to the modeling assumptions, which are explained in the caption. Column (1) in the right-hand panel of Table 2 shows that, when using the default modeling assumptions, EVA growth lagged GDP growth by 0.11 percentage points from 1999 to 2002. For every other three-year interval, EVA outpaced GDP growth. The greatest difference was nearly 0.5 percent during the Great Recession years.

The bottom row reports the time-series averaged difference between GDP and EVA growth over five different modeling scenarios. The magnitude of the difference in growth rates between GDP and EVA is sensitive to the integrated assessment modeling assumptions. The sign is not. The difference ranges between −0.12 and −0.55 percent. Column (2) removes the income adjustment for the VSL. This enhances the difference between GDP and EVA growth from, on average −0.20 to −0.30. Since real per-capita income grew between 1999 and 2014, the income adjusted VSL rises over time. Removing this effect causes damage to fall more rapidly, which boosts EVA growth. Column (3) employs a VSL drawn from stated preference studies rather than the USEPA default estimate (Kochi et al., 2006). (This VSL is about one-third of the magnitude of the default VSL.) This permutation only modestly affects the spread between the GDP and EVA growth rates because the trajectory of GED is largely unaffected. Column (4) employs the alternative $PM_{2.5}$- adult mortality dose-response function that is two-and-one-half times larger than the default function. This scenario dramatically affects the GDP-EVA growth rate disparity; the average difference increases from −0.20 in the default case to −0.55 percent. Finally, column (5) excludes damages from CO_2. This reduces, in absolute value, the difference between GDP and EVA growth to −0.12. Table A.III reports the effects on the GDP-EVA growth rate spread when using a unit elastic value of the VSL-income elasticity parameter (Hammitt and Robinson, 2011).

4.2. Model parameters

This section focuses on the empirically estimated model parameters that are subsequently used to characterize the discount rates. Returning to Table 1, column (4) reports the pollution intensity of output. It is crucial to emphasize that the empirical GED includes abatement. The emission inventories that are fed into the AP3 model are what is discharged after firms do abatement. Hence, the reported GED in Table 1, when divided by GDP, reflects the $(\alpha_t - \beta_t\gamma_t)$ term from the analytical model. Table 1 indicates that this measure of pollution damage intensity fell from 0.088 in 1999 to 0.061 in 2014. In fact, over the six years covered in this analysis, only from 1999 to 2002 did pollution intensity increase. The largest decrease in pollution intensity followed the Great Recession; in 2011, the combined monetary value of air pollution and greenhouse gas damage amounted to 6.75 percent of total output, which was down from 8.1 percent in 2008 and 9.1 percent in 2002. Because the GED are sensitive to different ways of calculating impacts, the $(\alpha_t - \beta_t\gamma_t)$ term is also calculated using four alternative modeling approaches. Table 3 presents these results. Table A.III reports the effects on GED intensity when using a unit elastic value of the VSL-income elasticity parameter. The effect of this change is modest.

Column (2) in Table 3 removes the income adjustment for the VSL. The results in monotonically decreasing pollution intensity from 9.84 percent of output down to 5.73 percent in 2014. Using a lower VSL (as shown in column 3) yields considerably lower pollution intensity estimates: from 4.4 percent of GDP in 1999 down to 2.7 percent in 2014. Column (4) implements the higher $PM_{2.5}$-adult mortality concentration-response function reported in Lepeule et al. (2012). This has a marked effect on pollution damage intensity. In 1999, damages are estimated to be 19 percent of GDP. Akin to the other modeling approaches, pollution damage intensity fall appreciably, down to 12.6 percent in 2014. Finally, excluding GHGs has a modest effect on the estimates of pollution intensity.

Table 3
Estimates of national income accounting model parameters.

Year	$\alpha - \beta\gamma$ (1)	$\alpha - \beta\gamma$ (2)	$\alpha - \beta\gamma$ (3)	$\alpha - \beta\gamma$ (4)	$\alpha - \beta\gamma$ (5)	β	γ
1999	0.0883	0.0984	0.0438	0.1944	0.0770	39	0.0016
2002	0.0913	0.0970	0.0438	0.2003	0.0788	34	0.0021
2005	0.0820	0.0836	0.0383	0.1774	0.0687	30	0.0025
2008	0.0811	0.0793	0.0367	0.1741	0.0664	27	0.0032
2011	0.0675	0.0649	0.0301	0.1413	0.0524	26	0.0044
2014	0.0610	0.0573	0.0267	0.1262	0.0457	27	0.0056

(1) = GHGs and LAP Income Adjusted VSL.
(2) = GHGs and LAP No Income Adjustment to VSL.
(3) = GHGs and LAP Income Adjusted Low VSL.
(4) = GHGs and LAP Income Adjusted VSL, High D-R.
(5) = LAP Income Adjusted VSL.
$(\alpha - \beta\gamma)$ = pollution intensity less abatement intensity times responsiveness of environmental damage to abatement.

Table 4
Estimates of unobserved pollution intensity parameter (α).

Year	α (1)	α (2)	α (3)	α (4)	α (5)
1999	0.1617	0.1071	0.2577	0.1617	0.1403
2002	0.1683	0.1151	0.2716	0.1683	0.1500
2005	0.1597	0.1143	0.2535	0.1597	0.1447
2008	0.1659	0.1233	0.2607	0.1659	0.1530
2011	0.1784	0.1436	0.2548	0.1784	0.1659
2014	0.2094	0.1788	0.2784	0.2094	0.1978

(1) = GHGs and LAP Income Adjusted VSL.
(2) = GHGs and LAP No Income Adjustment to VSL.
(3) = GHGs and LAP Income Adjusted Low VSL.
(4) = GHGs and LAP Income Adjusted VSL, High D-R.
(5) = LAP Income Adjusted VSL.
(α) = pre-abatement pollution intensity or output.

Table 3 also reports empirical estimates of the β_t *and* γ_t terms. The analysis employs the USEPA's reported benefit-cost ratio from the Clean Air Act (USEPA, 2011a) and its reported expenditure on abatement to approximate β_t *and* γ_t, respectively. Table 3 reports that γ_t (the share of national income allocated to abatement) grew from about 0.2 percent in 1999 to 0.6 percent in 2014. (As a point of comparison, Pearce and Palmer (2001) report total expenditure on pollution control (air, water, and solid waste) in the 1980's and 1990's of 0.6% of GDP in the U.S.) USEPA reports that β_t fell from 39 in 1999 to 25 in 2010. Values of β_t for the other years are interpolated. The product of $\beta_t\gamma_t$ rises from about 0.06 in 1999 to 0.15 in 2014.

Table 4 reports the estimated values of (α_t). Note that (α_t) is the pollution intensity of output, *without abatement.* This is not an observable parameter because the emissions inventories that feed into the damage calculations are discharges after abatement. The parameter (α_t) is estimated by adding back the product of abatement expenditure and the sensitivity of damage to abatement $(\beta_t\gamma_t)$, to the GED estimates $(\alpha_t - \beta_t\gamma_t)$. This introduces some error into the estimate of (α_t), because any non-regulatory changes in this measure of pollution intensity are attributed to abatement. Nonetheless, the (α_t) trajectories are instructive. Using the default modeling assumptions (α_t) increased from 0.16 in 1999 to 0.21 in 2014. For all five modeling scenarios, the (α_t) parameter estimate increased from 1999 to 2014. However, this parameter is sensitive to assumptions as shown in Table 4.

4.3. Discount rates

Table 5 reports the market interest rate (yield on long-term U.S Treasury bonds), the discount rate that adjusts for abatement expenditure (i^a), and the augmented discount rates that encompass both abatement and damage (i^e). As is well-known, bond rates fell over the 1999 to 2014 time period, from 5.6 percent in 1999 down to 2.5 percent in 2014 (FRED, 2018). The extension proposed by Weitzman (1994), which reflects the drag from abatement, amounts to a very small reduction from the market rates.[6] This finding stems from the relatively small share of output allocated to abatement of air pollution

[6] Since the environmental and augmented discount rates depend on the change in abatement shares, Table 5 begins in 2002.

Table 5
Empirical estimates of discount rates.

Year	r	i^a	i^e (1)	i^e (2)	i^e (3)	i^e (4)	i^e (5)	Avg. Difference (i^e - r)
1999	5.637[A]	*	*	*	*	*	*	*
2002	4.611	4.556	3.835	4.244	4.347	3.049	4.611	−0.7131
2005	4.290	4.236	4.812	5.221	4.628	5.760	4.290	0.7844
2008	3.667	3.583	3.378	3.719	3.602	3.274	3.667	−0.1586
2011	2.786	2.658	3.831	3.917	3.233	5.553	2.786	1.3038
2014	2.541	2.404	2.896	3.017	2.680	3.584	2.541	0.4851
Avg. Difference (i^e − r)		−0.0914	0.1717	0.4450	0.1193	0.6651	0.3006	0.3403

A = All values expressed in (%).
(1) = GHGs and LAP Income Adjusted VSL.
(2) = GHGs and LAP No Income Adjustment to VSL.
(3) = GHGs and LAP Income Adjusted Low VSL.
(4) = GHGs and LAP Income Adjusted VSL, High D-R.
(5) = LAP Income Adjusted VSL.
r = market interest rate.
i^e = augmented discount rate inclusive of damage and abatement.
i^a = augmented discount rate inclusive of abatement.

reported by the USEPA and used in this study.[7] For example, in 2002 (i^a) is just five basis points less than the bond rates. In 2014 this spread amounts to 14 basis points. The spreads increase over time because the abatement share of income rises throughout the sample period.

The results are quite different for the augmented rate (i^e). The spreads are larger and they depend on both the model year and the modeling assumptions. Over all modeling assumptions and all years, the augmented discount rate exceeds the market rate by 34 basis points or about 0.34 percentage points. In contrast, Baumgartner et al. (2015) found that, accounting for a distinct set of ecosystem services (not pollution), the social discount rate exceeded the discount rate for consumption goods by about 0.9 percentage points. The bottom row of Table 5 conveys the average differences in rates across years for each set of modeling assumptions. The absolute differences range between 12 and 67 basis points. The largest differences in discount rates occurs when the alternative adult mortality $PM_{2.5}$ function is used (column 4). The smallest spread manifests with the low VSL (column 3). The rate spread averages 17 basis points using the default assumptions.

The rate spreads vary over time. In 2002, the market rate exceeds all of the estimated augmented rates by an average of 71 basis points. This occurs because abatement, damages, and the damage intensity of production increased from 1999 to 2002. In 2005, all of the augmented discount rates exceed the market rate. Damages fell slightly and the damage intensity of output fell considerably (see Table 1). In 2008, damages were essentially unchanged from 2005 as was pollution intensity. As such, the difference between the market and augmented discount rates was quite small, just 16 basis points, on average. Then, in 2011, following the Great Recession, the level of damage and the pollution density of output fell precipitously. Concomitantly, the augmented rates far exceeded the bond rates; the average spread between grew to 130 basis points, or 1.3 percentage points. In 2014, pollution damage did not deviate much from the 2011 level. Neither did pollution intensity. Hence, the rate spread narrowed to 49 basis points.

This table highlights the importance of year over year changes in dictating whether the augmented discount rate exceeds or falls short of market rates. The one time period (from 1999 to 2002) characterized by significantly rising damage is associated with bond rates that are substantially greater than the augmented discount rate (an average difference of 71 basis points). During the time-periods when damages fell (2002–2005 and after 2008), the bond rates are less than the augmented rate.

Decomposing the results in Table 5 according to expression (6) is instructive. Recall that the difference between the market rate and the augmented rate is: $i^e - i^m = \frac{\partial D_t}{\partial Y_t^e} - \frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_t}{\partial Y_t^e} - \frac{\partial A_{t+1}}{\partial Y_{t+1}^e} - r\left(\left(\frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)\right)$ Decomposing the difference in rates for the year 2002 (with the default modeling assumptions) indicates that the difference in pollution intensity is $\frac{\partial D_t}{\partial Y_t^e} - \frac{\partial D_{t+1}}{\partial Y_{t+1}^e} = -0.0030$, the difference in abatement shares is $\frac{\partial A_t}{\partial Y_t^e} - \frac{\partial A_{t+1}}{\partial Y_{t+1}^e} = -0.0004$, and $-r\left(\left(\frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)\right) = -0.0043$. These components sum to −0.0078. While all three terms induce a drag on the return to investment, the bulk of the rate spread stems from the period 2002 damage and abatement shares.

[7] However, it is not clear that including other pollutants would appreciably change the results. Keiser and Shapiro (2019) report that abatement expenditures in the Clean Water Act are between 6% and 27% higher than those on air pollution abatement.

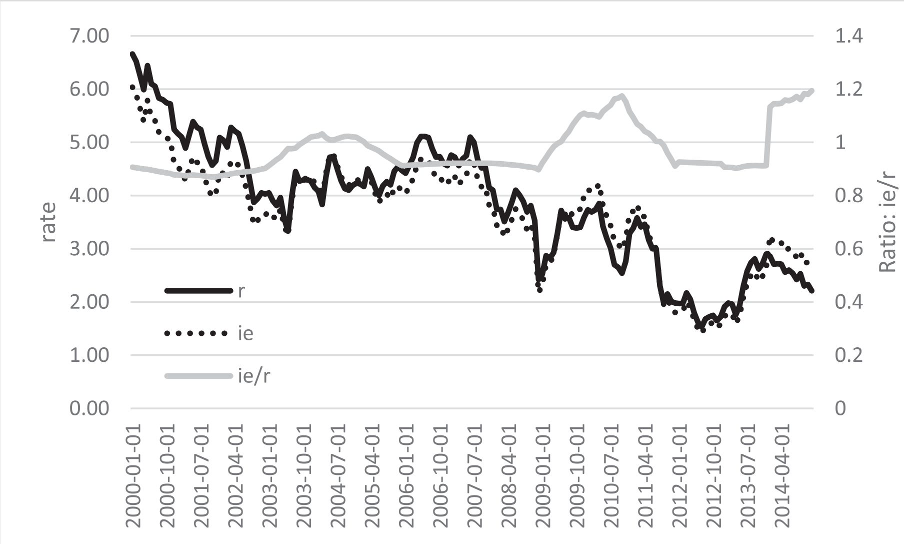

Fig. 1. Monthly time series of bond rates and augmented discount rate.

However, when applied to 2011, this decomposition demonstrates the importance of falling damage intensity. Again using the default modeling assumptions, $\frac{\partial D_t}{\partial Y_t^e} - \frac{\partial D_{t+1}}{\partial Y_{t+1}^e} = 0.0136$, $\frac{\partial A_t}{\partial Y_t^e} - \frac{\partial A_{t+1}}{\partial Y_{t+1}^e} = -0.0012$, and $-r\left(\left(\frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)\right) = -0.0020$. The reduction in damage overwhelms the drag on the augmented rate contributed by both the increase in abatement shares and the $-r\left(\left(\frac{\partial D_{t+1}}{\partial Y_{t+1}^e} + \frac{\partial A_{t+1}}{\partial Y_{t+1}^e}\right)\right)$ term.

Fig. 1 graphs monthly long bond yields and the augmented discount rate from 1999 to 2014. The left axis reports the rates (%) while the right axis shows that ratio of (i^e/r). While monthly bond yields are reported (FRED, 2018), values of model parameters are linearly interpolated, and 12-month changes in abatement expenditure and damage intensity are used to compute the augmented discount rate (i^e). Fig. 1 reinforces and concretizes the results in Table 5. That is, the augmented discount rate exceeds the bond rates during the periods from 2002 to 2005, 2008 to 2011, and at the end of the sample in 2014. Conversely, (i^e) lies consistently below bond rates from 1999 to 2002 and from 2005 to 2008.

4.4. *Returning to Weitzman*

Weitzman (1994) reported rough empirical estimates of the coefficient of environmental drag of between 4 and 6% of gross national product. Importantly, Weitzman's (1994) coefficient of drag assumed fixed damages from pollution and the calculation was made using essentially the definition of income given here as (2): market accounts with investment in abatement, without damage. In the present context, Weitzman's (1994) environmental rate with fixed damage is: $\overline{i^a} = r\left(1 - \left(\frac{\alpha_{t+1}}{\beta_{t+1}}\right)\right) + \frac{\partial A_t}{\partial Y_t^a} - \frac{\alpha_{t+1}}{\beta_{t+1}}$. If, however, all parameters in the model are fixed, except for the share of output allocated to abatement, the environmental rate is: $\overline{i_f^a} = r - (1+r)\frac{\alpha_{t+1}}{\beta_{t+1}}$. Therefore, the "drag" is: $r - \overline{i_f^a} = (1+r)\left(\frac{\alpha_{t+1}}{\beta_{t+1}}\right)$

Two inherent differences in the data are also critical to point out. First, Weitzman (1994) cited a USEPA report suggesting total abatement cost amounted to about 1% of GDP. In the present paper, USEPA's (2010) estimate of air pollution control cost is between 0.2% and 0.6% of GDP. Second, (β_t) here ranges between 39 and 25 whereas Weitzman (1994) had very little empirical evidence to base his estimate of this parameter on. This renders a direct comparison difficult. Using the empirical values for 1999 reported in Tables 3–5, the current estimate of "environmental drag" ($r - \overline{i_f^a}$) is about 0.9%. This is about five-times smaller than Weitzman's (1994) back-of-the-envelope estimate and it is largely driven by differences in (β_t).

This comparison highlights a crucial difference between the present paper and Weitzman (1994). This paper allows expenditure on abatement, the responsiveness of environmental damage to abatement, and the damage intensity of output to change over time. Further, this paper explicitly treats time. Savings withdrawn from consumption in period (t) *reduces* abatement in period (t). The productivity of private capital increases output in period (t + 1) which increases abatement. This induces the drag that Weitzman (1994) focused on, reducing the return to savings. However, abatement (and damage for that matter) inhibit growth in any period. As such, when society saves in (t), it triggers less abatement (and damage) which boosts output. By subsuming time, Weitzman (1994) overlooked this effect.

5. Conclusions

Many societies around the world invest in public goods. This necessitates a diversion of funds away from market consumption or investments in private capital. Evaluation of such projects often relies on NPV analysis. In principle, the appropriate discount rate in an NPV calculation should reflect the rate of return on the current mix of investment opportunities. Estimation of such a rate depends on market data (to compute the opportunity cost of capital) and it may also depend on data that lies beyond the market boundary if investments affect external costs or benefits. The present paper derives discount rates for public projects using an augmented measure of national income inclusive of non-market goods. The estimated discount rates reflect three key components: the productivity of private capital, the opportunity cost of direct expenditure on public projects, and the returns to public investment that accrete outside of the market boundary. Though the specific empirical application zeroes-in on environmental externality, the tools developed in this paper apply to a range of non-market entities.

The analytical modeling derives three discount rates: the market rate, an “environmental” rate, and an augmented rate. The analytical model yields the following expressions for the three discount rates discussed above. The market rate is simply the rate of return on private capital. The “environmental” rate is the rate of return on capital less the foregone returns due to the diversion of investment from capital to abatement. The augmented discount rate is the rate of return on private capital minus the partial effect of income on damages and abatement. Crucial to the environmental and augmented rates are the time paths of abatement and pollution intensity.

In an economy with rising investments in abatement, the environmental discount rate is less than the market rate, because rising abatement levels place a drag on the return to savings, and the discount rate. If rising abatement induces falling damage, the effect of damages counteracts the drag from abatement. Contrarily, damage intensity increasing over time attenuates the augmented discount rate.

Fig. 2 shows a plot of environmental damage relative to a conventional measure of income, GDP. The graph is divided into three regions that correspond to stages of development in which environmental damage is: increasing with income (I.), decreasing with greater income (II.), and fixed, perhaps reflecting binding policy constraints (III.). In regions I. and II., the graph assumes an inverted U-shape, which is just one of many possible forms to this relationship. This suggests the environmental Kuznets curve. In region I., an augmented discount rate is likely to be lower than the market rate. At early stages of development, investment in abatement is low and likely rising, while damages are rising. Here, the partial effect of income on both damages and abatement expenditure work in the same direction, dragging down the return to savings and, hence, the discount rate. Conversely, in region II., damages fall with income. Investments in abatement are likely substantial and rising. How augmented rates compare to market rates hinge on the relative rates of changes in damage and abatement. If damages fall more than abatement rises, the augmented rate will exceed the market rate. In region III., this hypothetical economy finds itself in the setting Weitzman (1994) modeled. Damages are fixed due, perhaps, to binding environmental policy constraints. The appendix demonstrates that drag in this context arises from the relative rates of (α_{t+1}) and (β_{t+1}).

The value in Fig. 2 is the ability to see how the magnitude of the augmented discount rate would change relative to the market rate as GDP (and the link between GDP and damage) changes. Lower augmented discount rates occur at levels of development characterized by rising damages *and* income. Higher rates occur in economies with damages that fall as income rises. In the context of climate policy (or any long run policy characterized by benefits that lag costs), the use of an augmented rate suggests more stringent policy in region I. and less stringent policy in region II. For the relationship between income and GDP shown in Fig. 2, this suggests a non-monotonic term structure in discount rates. This stems from the relative rates of abatement and damage implied by Fig. 2. When abatement intensity and damages increase, the augmented discount rate lies below the market rate. Conversely, when damages fall by more than abatement rises, the augmented rate exceeds the market

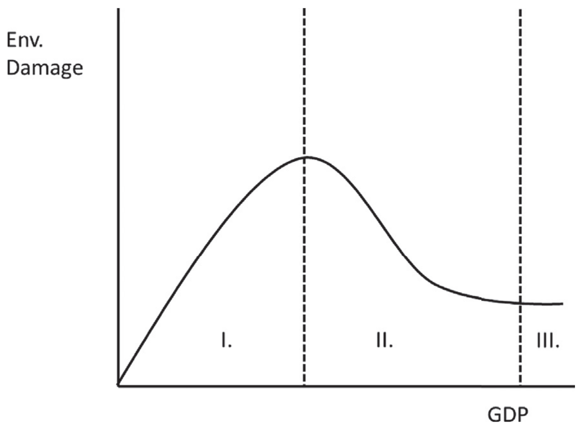

Fig. 2. Schematic of relationship between environmental pollution damage and national income.

rate. If an economy followed the trajectory shown in Fig. 2, augmented discount rates would fall and then rise. (Of course, many forms to the relationship shown in Fig. 2 are possible. This form may vary by country or pollutant.) This pattern is different than that suggested by the recent literature arguing for declining discount rates (Arrow et al., 2014). Importantly, the mechanisms are different. Here, changing intensities of abatement and damages yields the non-monotonic term structure. In contrast, Arrow et al. (2014) note that uncertainty in future discount rates yields a declining rate schedule (provided that the probabilities of possible realizations of future rates are known).

The framework developed herein is more general than merely applying to pollution damage, natural capital investment, or environmental accounting. In fact, this machinery is applicable to any context in which standard market measures of income are augmented to include non-market entities. Consider investment in national security; a society invests in physical capital and employs labor to reduce the risk of a terrorist attack or an invasion by another country. Such diversions of investment (from conventionally productive private capital investments to risk reduction measures) reduce the rate of return on savings when viewed through a market-centric measure of income. That is, if the return to such investments lies outside the scope of income, then the only dimension of this choice that manifests in the accounts is on the expenditure side – the opportunity cost of *not* investing in ordinary productive capital. By construction, the allocation of resources to national security places a drag on the yield of savings. In order to comprehensively capture the return to such expenditures, the definition of national income *must* include non-market measures of safety or risk. This paper shows how such investments affect comprehensive output and, in turn, discount rates whereas prior research explored these issues predominantly through via a consumption-side approach following the Ramsey Rule (Hoel and Sterner, 2007; Gollier, 2010).

This paper suggests research on a number of fronts. In no particular order, a logical empirical extension of this analysis is to apply the framework to different countries. That is, while the U.S. economy exhibits damages inversely related to output, other contexts such as rapidly growing developing countries likely feature damages that have increased with output (Baumgartner et al., 2015). Another area where the ideas set forth in this paper might be applied is by using a climate change IAM to characterize a dynamically efficient abatement policy with endogenous discount rates of the type proposed herein. Finally, the issue of uncertainty is not raised here. Of course, both market and augmented measures of output and therefore growth are not measured with certainty. This implies that the discount rates that depend on these aggregates are also estimated with some degree of imprecision. A thorough treatment of uncertainty would be a worthwhile extension. In any event, the proposed modification to more standard approaches to calibration of discount rates is likely to have pronounced effects on policy design for GHGs or other long-lived environmental challenges.

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Appendix A. Supplementary data

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