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ON THE GREEN INTEREST RATE.

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ABSTRACT

This paper demonstrates how a central bank might operationalize an expanded role inclusive of managing risks from environmental pollution. The analysis introduces the green interest rate (rg) which depends on temporal changes in the pollution intensity of output. This policy instrument reallocates consumption from periods when output is pollution intensive to when output is cleaner. In economies on a cleaning-up path, rg exceeds r*. For those growing more polluted, rg is less than r*. In the U.S. economy from 1957 to 2016, rg exceeded r* by 50 basis points. Federal environmental policy reversed the orientation between rg and r*.

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Appendices are available at http://www.nber.org/data-appendix/w28891

I. Introduction.

Central banks and financial regulators are increasingly focused on environmental risks to the financial system and the macroeconomy (The New York Times, 2020a; NGFS, 2020; Federal Reserve, 2020; White House, 2021). This paper demonstrates how a central bank could operationalize management of environmental pollution and climate risk through monetary policy. Specifically, the analysis proposes a green interest rate that transmits information on pollution damages to borrowers and lenders. This policy instrument mitigates damage to the economy by reallocating consumption from periods when output is more pollution intensive to when output is cleaner. Therefore, the largest potential impact of targeting the green interest rate occurs when pollution intensity changes rapidly: upon the introduction of binding environmental policy, during periods of rapid technological innovation, and over the business cycle (Muller, 2019a). These periods align with risks identified by the Federal Reserve in its 2020 Financial Stability Report (Federal Reserve, 2020, p. 58). This novel policy instrument also speaks directly to concerns articulated by central banks in a recent survey, namely ensuring that a transition to a low-carbon economy occurs in an orderly fashion (NGFS, 2020). Thus, the green interest rate may be an important tool for central banks to manage environmental risks to the economy during the transformation to a low-carbon economy.

The green interest rate (r_g) is a reconceptualization of the natural interest rate (or r*) that recognizes an expanded role for central banks inclusive of managing environmental risks. Two concepts underpinning r* prompt the inclusion of pollution damage in r_g: the notion of potential output and the measurement of trend growth in output. Each is explored briefly here. Laubach and Williams (2015) define the natural rate as "the real short-term interest rate consistent with the economy operating at its full potential." Similarly, Goodfriend (2016) states that "the natural interest rate is the interest rate that makes desired aggregate lifetime consumption plans conform to present and expected future potential output…" This paper contends that "potential", or "full potential", income is fundamentally mismeasured without consideration of environmental pollution damage. This argument stems from a literature dating back to the seminal work of Nordhaus and Tobin (1973) documenting that the National Income and Product Accounts (NIPAs) are incomplete (NAS NRC, 1999; Bartelmus, 2009; Muller, Mendelsohn, and Nordhaus, 2011; Mohan et al., 2020). Recent research suggests that this adjustment is currently about five percent of U.S. gross domestic product (GDP) for air pollution damages (Tschofen et al., 2019). In China and India pollution intensity is substantially higher (Mohan et al., 2020). Thus, the subtraction of pollution damage from output is not a trivial adjustment and inclusion of this information in r_g may appreciably shift central banks' policy rate target.

Second, a key driver of r^* is trend growth in potential GDP (Laubach and Williams, 2015; Lubik and Matthes, 2015; Kaplan, 2018). Building on the argument above, if output levels are mismeasured, estimates of trend growth may be inaccurate as well. Indeed, prior research reports differences between growth in GDP and in GDP less pollution damage of as much as 1.5 percent annually since the 1950s in the U.S. economy (Muller, 2014; Muller, 2019b). This growth rate differential varies considerably across countries (Mohan et al., 2020). Mismeasurement of growth due to the omission of pollution damage may effect empirical estimates of r^*. Specifying r_g corrects this bias by relying on growth in GDP less pollution damage.

To operationalize r_g, this paper deducts pollution damage from GDP to measure net output or environmentally adjusted value-added (EVA)[1]. This metric is grounded in the environmental

[1] The presence of environmental regulation may give one pause as to whether such costs are already in the accounts. Note, however, that what is subtracted are damages from *remaining emissions*, net of environmental policy. The only case in which double counting would occur is if

accounting literature (Nordhaus and Tobin, 1973; Nordhaus, 2006; Abraham and Mackie, 2006; Muller, Mendelsohn, Nordhaus, 2011; Tschofen et al., 2019; Mohan et al., 2020)[2]. The analysis deducts two types of pollution damage from GDP: premature mortality risk from exposure to fine particulate matter (or $PM_{2.5}$, a local air pollutant) and the present value of long-term damages from emissions of carbon dioxide (or CO_2, a long-lived greenhouse gas)[3]. The damages are estimated from 1957 to 2016 in the U.S. economy.

This 60-year period spans the passage and implementation of landmark federal legislation to control air pollution. (The Clean Air Act (CAA) was passed in 1970, and implemented in the following years.) This empirical setting stands to inform macroeconomic policymakers concerned about managing an orderly transition to a low-carbon economy. The CAA initiated a transformation of the U.S. economy from a state of rising pollution levels to an economy cleaning up. This significantly altered production processes in power generation, heavy manufacturing, and the light duty vehicle fleet. These industries are also likely to incur (or are already experiencing) disruptive technological change as the economy decarbonizes. The ramifications for pollution damage and r_g observed around the CAA's passage may shed light on how using r_g to set policy targets will affect environmental risks and stability as the economy decarbonizes.

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emissions are taxed according to their marginal damages (or if firms, subject to a system of tradable permits, had to purchase all allowances in an auction format). U.S. environmental regulations take the form of standards as well as a collection of small-scale or regional cap-and-trade programs that, for the most part, grant allowances for free.

[2] In contrast to prior analyses of environmentally-adjusted accounts that focus on sectoral decompositions (Muller, Mendelsohn, and Nordhaus, 2011; Tschofen et al., 2019), growth (Muller, 2014; 2019b), or discounting (Muller, 2019a), the present paper focuses on a recalibration of the natural interest rate to include pollution damage.

[3] These pollutants contribute the largest share of measurable damages from pollution across media (USEPA, 1999; 2011; Muller, Mendelsohn, and Nordhaus, 2011; Keiser, Kling, and Shapiro, 2019).

a. Preview of Results.

Pollution is introduced into a New Keynesian model of the economy on the supply side by specifying the pollution intensity of technology employed with labor to produce output. On the demand side, households face a neoclassical intertemporal consumption-savings problem. The optimal consumption path is characterized by the Euler equation. Solving for the interest rate that aligns consumption with full potential output yields r*. Doing so with pollution damage deducted from output yields r_g. This exercise reveals that r_g depends on the intertemporal changes in pollution intensity. When pollution intensity falls, r_g rises relative to r*. Conversely, if pollution intensity rises, r_g falls in comparison to r*. The intuition for this orientation is the following. In economies becoming cleaner or less pollution intensive, current prospects for future consumption brighten. Thus, delaying present consumption, as incentivized by a higher r_g, so that consumption occurs when less value is lost to environmental pollution, damage enhances welfare. In an economy degrading its environment, expectations for future consumption prospects diminish. Consumption in the future suffers greater losses due to pollution damage. Under such conditions, r_g is less than r*. This shifts consumption to the present and attenuates the effective penalty from pollution damage.

Empirically, the paper estimates air pollution and CO_2 damages and deducts these costs from GDP to estimate environmentally adjusted value added, or EVA, from 1957 to 2016 in the U.S. economy. Damages fell at an annual rate of 0.35 percent over this 60-year period. EVA growth outpaced GDP growth by an average of about 50 basis points. The paper empirically compares r_g to estimates of r* from the literature (Laubach and Williams, 2015). On average, r_g exceeded r* by 50 basis points. However, the orientation between r_g and r* changed around 1970 when the CAA was passed. From 1957 to 1970, pollution intensity increased rapidly and r_g was less than r* by about 150 basis points. During the 1970s, pollution intensity fell and r_g exceeded r*, by 150 basis points. After the 1970s, r_g consistently exceeded r* though the difference attenuated to just 15 basis points after 2010. The passage and enactment of the CAA initiated a transition in the U.S. economy to a lower level of pollution damage intensity. The position of r_g relative to r* reflects this transition.

The business cycle is also an important determinant of the position of r_g relative to r*; during recessions, the r_g exceeds r* by about two-times more than during expansions because of the pro-cyclical nature of pollution damage. This effect is largest prior to the enactment of the CAA. Finally, a series of simulations demonstrates the attenuation of pollution damage from the reallocation of consumption induced by r_g. The effects are largest prior to the enactment of the CAA, and during the energy crisis, the recessions of the early 1980s, and the Great Recession. These exercises show how the central bank targeting r_g would transmit information on changes in pollution damages to borrowers and lenders, and how the resulting reallocation of consumption to low damage intensity periods reduces total damage.

The remainder of the paper is structured as follows. Section II. introduces the conceptual model and derives the interest rates, the effects of r_g on damages and net output, and the interaction between conventional environmental policy and r_g. Section III. presents the data and methods. Section IV. covers results and V. concludes.

II. Model.

The theoretical set up is a standard New Keynesian model (Goodfriend, 2004; 2016; Gali, 2008). The model introduces pollution intensity to the production technology in order to define potential output as net of pollution damage. The model then solves for r* and r_g by equating intertemporal consumption to potential output without and then with pollution damage. The analysis then explores the effect of r_g on damages and consumption net of pollution, the transmission of r_g through economy, and the interaction between environmental policy and r_g.

a. Households.

Assume an economy is comprised of identical consumers that seek to maximize lifetime utility derived from consumption in a two period model: $U(c_1, c_2) = u(c_1) + \frac{1}{1+\rho} u(c_2)$, where ($c_t$) is consumption of market-produced goods in period (t), and the pure rate of time preference is given by (ρ). More specifically, let $U(c_t) = \frac{{c_t}^{1-\eta}-1}{1-\eta}$, denote utility from consumption in period (t)[4]. The intertemporal budget constraint is given by $(c_1) + \frac{1}{1+r}(c_2) = W_1$, where (r) denotes the real interest rate, and W_1 is period (1) wealth defined as the present value of current and future income. Solving the budget constraint for (c_2), substituting into the utility function, taking the partial derivative with respect to (c_1) and rearranging yields the familiar Euler equation, which is shown in (1):

$$\frac{{c_2}^{\eta}}{{c_1}^{\eta}} = \frac{1+r}{1+\rho} \tag{1}$$

The present value of lifetime utility is maximized when the marginal utility from consumption, in present value terms, is equated across time periods and consumers utilize their entire budget. As in Goodfriend (2004; 2016) the equilibrium outcome features the representative household being neither a net borrower nor a net saver.

[4] The appendix explores a constant elasticity of substitution utility function defined over environmental quality and market goods.

The appendix derives households' labor supply function, which assumes that utility derived from leisure is logarithmic. This is shown in (2), where n_t^s = hours worked in period (t), and ω_t = the real wage which households take as exogenous.

$$n_t^s = 1 - \frac{c_t}{\omega_t} \tag{2}$$

b. Firms and Output.

The supply side of the economy is characterized by *J* (many) firms that make differentiated products. Output (Y_t) is comprised solely of consumption goods produced by the *J* firms with technology (a_t) and labor (n_t) through a production function with diminishing returns to labor.

$$Y_t = a_t(n_t)^{1-\varphi} \tag{3}$$

where: $0 \leq \varphi \leq 1$.

Firms' marginal cost is the wage over the marginal productivity of labor: $MC_t = {}^{w_t}\!/_{\partial Y_t / \partial n_t} = \frac{w_t n^{\varphi}}{a_t(1-\varphi)}$. Because of product differentiation, firms can maintain a price in excess of marginal cost. The mark-up over marginal cost in period (t) is denoted $\mu_t = {}^{P_t}\!/_{MC_t} > 1$. Combining ($MC_t$) together with the markup, $\mu_t = \frac{P_t}{MC_t}$, and rearranging provides an expression for the real wage in terms of productivity and the markup: $\frac{w_t}{P_t} = \frac{a_t(1-\varphi)}{\mu_t n^{\varphi}}$. Equilibrium employment is determined by assuming that the market for goods clears ($Y_t = c_t$) and substituting (3) and the real wage into households' labor supply function (2), which yields $n_t^s = 1 - \frac{c_t}{\omega_t} = \frac{1}{1+\mu_t-\varphi}$. As Goodfriend (2004) pointed out, productivity does not affect equilibrium employment.

Productivity affects both consumption and wages proportionally. Thus, period (t) market-clearing output is given by (4):

$$Y_t = \frac{a_t}{1+\mu_t-\varphi} \tag{4}$$

Output varies in direct proportion to productivity and inversely with the markup.

c. Pollution in production.

This section introduces pollution intensity to the production technology. The motivation for this exercise is to recast potential output net of pollution damage for the derivation of r_g. By assumption, all firms exhibit identical degrees of pollution intensity. When adjusted for pollution damage, the production function is:

$$Y_t^e = a_t(1-\alpha_t-\beta_t\gamma_t){n_t}^{(1-\varphi)}. \tag{5}$$

Expression (5) includes three new terms to capture the dynamics between pollution from production, attempts to mitigate pollution through investment in abatement, and the responsiveness of damage to abatement. In period (t), γ_t depicts the fraction of income allocated to pollution control, investments in abatement of environmental pollutants such as CO_2 or particulate matter. Next, let α_t denote the pollution intensity of output, say CO_2 damage per unit GDP, prior to abatement. So this parameter captures the differences between a coal-powered economy, a petroleum powered economy, and an economy based on renewables. β_t shows the responsiveness of environmental pollution damage to abatement investment γ_t. Large values of (α_t) attenuate output. In contrast, greater values of abatement expenditure (γ_t) and (β_t) increase (Y_t^e) by reducing damage. The specification of damage is multiplicative: $D_t = \frac{a_t(\alpha_t-\beta_t\gamma_t)}{1+\mu_t-\varphi}$ characterizes period (t) monetary pollution damage. This implies that $Y_t^e = a_t\left(\frac{1-(\alpha_t-\beta_t\gamma_t)}{1+\mu_t-\varphi}\right)$

depicts period (t) *net* output, the production of consumption goods, less environmental pollution damage.

d. Interest Rates.

This sub-section derives the real[5] interest rate that equates consumption to full potential output. When aggregate demand aligns with potential output, where output consists of goods and services traded in markets, the market clearing interest rate is r* (Goodfriend, 2016). When potential output is defined as net of pollution damage, the market clearing interest rate is r_g. This rate compels borrowers and lenders to consider the relative pollution intensity of output in the present and the future. As shown in subsection e. below, r_g raises social welfare by increasing total net consumption. By targeting r_g in setting its short-term policy rate, the role of the central bank expands from sustaining full employment and price stability to managing environmental pollution risk.

To begin, periods (1) and (2) potential output $\left(\frac{a_1}{1+\mu_1-\varphi}\right), \left(\frac{a_2}{1+\mu_2-\varphi}\right)$ are substituted into (1) for (c_1) and (c_2). Then, the Euler equation is solved for (r). This yields r^* as shown in (6) for the case of logarithmic utility.

$$r^* = \frac{a_2}{a_1}(1+\rho)\left(\frac{1+\mu_1-\varphi}{1+\mu_2-\varphi}\right)^{1-\varphi} - 1 \tag{6}$$

The natural rate of interest is increasing in productivity growth and in households' rate of time preference and it is attenuated by growth in firms' markup.

[5] Recall from section b. that the labor supply decision by households depends on the real wage. Because the price level is factored into the model, the interest rates derived here are real rates.

Next, pollution-adjusted potential output in periods (1) and (2),

$\left(\frac{a_1\left(1-(\alpha_1-\beta_1\gamma_1)\right)}{1+\mu_1-\varphi}\right), \left(\frac{a_2\left(1-(\alpha_2-\beta_2\gamma_2)\right)}{1+\mu_2-\varphi}\right)$, is substituted into (1) and solved for (r) yielding (7):

$$r_g = \frac{a_2}{a_1}(1+\rho)\left(\frac{1+\mu_1^e-\varphi}{1+\mu_2^e-\varphi}\right)^{1-\varphi}\left(\frac{\left(1-(\alpha_2-\beta_2\gamma_2)\right)}{\left(1-(\alpha_1-\beta_1\gamma_1)\right)}\right)-1 \tag{7}$$

Expression (7) is r_g. The key difference between (6) and (7) is that r_g depends on the change in pollution intensity across the two periods: $\left(\frac{\left(1-(\alpha_2-\beta_2\gamma_2)\right)}{\left(1-(\alpha_1-\beta_1\gamma_1)\right)}\right)$. Through this term, r_g transmits information on changing pollution conditions in the economy to borrowers and lenders. If pollution intensity is constant, $r_g = r^*$.

Expression (8) characterizes the ratio of (6) to (7), assuming the markups are equivalent with and without pollution damage[6].

$$\Delta_r = \frac{r_g+1}{r^*+1} = \left(\frac{\left(1-(\alpha_2-\beta_2\gamma_2)\right)}{\left(1-(\alpha_1-\beta_1\gamma_1)\right)}\right) \tag{8}$$

An economy on a “cleaning-up” trajectory features $\left(\frac{\left(1-(\alpha_2-\beta_2\gamma_2)\right)}{\left(1-(\alpha_1-\beta_1\gamma_1)\right)}\right) > 1$. Under these conditions, r_g will exceed r^*. The reduction in future damages boosts consumption prospects in the future because proportionately less output is lost to pollution damage than in the present. With falling damages, the higher r_g induces more current savings and more consumption in the future.

Conversely, $\left(\frac{\left(1-(\alpha_2-\beta_2\gamma_2)\right)}{\left(1-(\alpha_1-\beta_1\gamma_1)\right)}\right) < 1$ holds in an economy with rising pollution intensity. In this case, r^* exceeds r_g. Rising damage limits net consumption opportunities in the future. Greater losses to

[6] Note that this does not imply the markups are fixed over time. Rather, including damage does not alter the markup in any given period. This assumption holds in a real business cycle context in which firms can flexibly permute prices to maintain their profit maximizing markup.

future net consumption are reflected in a lower r_g. This draws consumption from the future into the present when the drag due to pollution damage is lower.

Figure 1 depicts consumers' intertemporal choice problem. Both panels compare optimal consumption decisions when households face (r^*) and (r_g). The two solid downward sloping lines are the representative household's budget constraints. The outer constraint embodies consumption possibilities without consideration of pollution damage. The inner constraint deducts environmental pollution damage; it represents consumption possibilities if the economy were subject to Pigouvian taxation that efficiently subtracts pollution damage from output. The slope of the outer constraint is $-\left(\frac{1+r^*}{1+\rho}\right)$, whereas the slope of the inner constraint is $-\left(\frac{1+r_g}{1+\rho}\right)$. In this configuration, $Y_1(\alpha_1 - \beta_1\gamma_1) > Y_2(\alpha_2 - \beta_2\gamma_2)$. Damages are falling.

The left-hand panel compares household intertemporal choice in an economy without environmental policy with an interest rate of r^* to choices in an economy that is subject to binding environmental policy with an interest rate of r_g. Without binding environmental policy and with r^*, households have no incentive to consider pollution damage. They optimize by equating their marginal rate of substitution (MRS) to $\left(\frac{1+r^*}{1+\rho}\right)$. This is shown at point A and it is denoted ($c_1(r^*)$, $c_2(r^*)$). With environmental policy, and facing r_g, households optimize by harmonizing their MRS to $\left(\frac{1+r_g}{1+\rho}\right)$. This is shown at point B, which is denoted ($c_1(r_g)$, $c_2(r_g)$).

The reliance on r_g coupled with binding environmental policy affects consumption behavior through two channels. First, the change from point A to point C reflects a substitution effect, based on the new intertemporal terms of trade embodied in r_g. This is found at the point of tangency between the initial indifference curve and the compensated budget constraint with the slope of $-\left(\frac{1+r_g}{1+\rho}\right)$, shown by the dashed line. The remaining change in consumption, from C to B, is an income effect. It stems from the reduction in potential income from internalization of pollution damage.

The right-hand panel of figure 1 presents the representative household's intertemporal choice in an economy without binding environmental regulation. Here, point A is still the representative household's optimal bundle when facing r*. When consumers face r_g, the feasible consumption set changes as do the intertemporal terms of trade, as depicted by the dashed line. Since households are neither borrowers nor lenders in equilibrium, the new budget constraint passes through point A. By changing the intertemporal terms of trade, r_g encourages consumers to equate their MRS to $\left(\frac{1+r_g}{1+\rho}\right)$, at point D. The tangency at D represents a welfare improving reallocation of consumption from period 1 to period 2. That is, the new consumption locus lies on an indifference curve associated with higher total utility than A. This buttresses the conclusions from above; when damages fall over time, utility maximizing households facing r_g increase their savings and consume more in the future when damages are lower[7].

The right-hand panel of figure 1 embodies extant limitations to a central bank's policy portfolio. Setting short run policy rates is well within a central bank's authority, whether based on r_g or r*. Implementing binding environmental policy to limit consumption and damage is not; policy interventions of this sort are more often the purview of an environmental regulator. A central bank cannot induce consumers to relocate from A to B in the left-hand panel of figure 1. That would require both r_g and binding environmental policy. However, with the standard toolkit of

[7] The direction of the reallocation from A to D occurs because damages are falling in this example. Had figure 1 featured rising damage, consumption would move from period 2 to period 1.

setting short-term policy rates, macroeconomic policymakers can affect intertemporal consumption decisions of the sort embodied in the shift from A to D.

e. Damages and Net Consumption.

Figure A.1 in the appendix facilitates an analysis of how r_g affects damages and net consumption. The figure adopts the notation from figure 1 in terms of defining points A and D. The left-hand panel of figure A.1, the focus of the discussion here, corresponds directly to figure 1 in that damages are falling. Let $\Delta c_1 = c_{g,1} - c_1^*$ and $\Delta c_2 = c_{g,2} - c_2^*$, denote the change in the representative household's consumption (due to facing r_g rather than r*) in periods 1 and 2, respectively. In the left-hand panel, damage intensity is falling so $\Delta c_2 > 0$ and $\Delta c_1 < 0$. In moving from A to D, consumption is reallocated according to the following rate: $\frac{\Delta c_2}{\Delta c_1} = -\left(\frac{1+r_g}{1+\rho}\right)$. This is just the slope of the new budget constraint, shown as I in figure A.1.

The intertemporal rate of exchange in damages is: $\frac{\Delta c_2}{\Delta c_1}\frac{(\alpha_2-\beta_2\gamma_2)}{(\alpha_1-\beta_1\gamma_1)}$. This is the slope of II. Because damage intensity is falling $(\alpha_1 - \beta_1\gamma_1) > (\alpha_2 - \beta_2\gamma_2)$. The slope of II. is less than (closer to zero than) the rate of change in consumption, or the slope of I. Thus, for every unit of consumption moved from the present to the future, avoided damages from less present consumption exceeds additional damage from more future consumption in absolute value.

Because the rate of change in consumption of market goods exceeds the rate of change in damage, the rate of change in net consumption (net of pollution damage) exceeds that of gross consumption. Specifically, the intertemporal rate of exchange in net consumption is the slope of

III, which is equal to $\frac{\Delta c_2}{\Delta c_1}\left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right)$. This is greater than (farther from zero than) the slope of I, or $\frac{\Delta c_2}{\Delta c_1}$.

The incentives embedded in r_g result in a welfare improving adjustment of the representative household's intertemporal consumption path. This is evident in figure 1 in that D lies on a "higher" indifference curve than A. The argument in this section provides an alternative perspective on the representative household's response to r_g that confirms this result. The reallocation of household consumption from the present to the future at the rate of $-\left(\frac{1+r_g}{1+\rho}\right)$ results in an increase in total net consumption because the intertemporal rate of exchange in damages is less than that of market consumption. Crucially, if *net consumption* is what dictates social welfare, then society is made better off when households face r_g.

The right hand panel of figure A.1 reflects an economy growing more pollution intensive. Note, first, that the slope of I. is less (in absolute value) than I. in the left hand panel. Since damage is rising, $r_g < r^*$, and the absolute value of $\left(\frac{1+r_g}{1+\rho}\right) < \left(\frac{1+r^*}{1+\rho}\right)$. Thus, D implies more current and less future consumption. In this context of rising damage, II. is steeper than I. Damage falls from less future consumption by more than it rises when current consumption increases. In addition, III. is less steep than I. because present net consumption rises more than future net consumption falls. Hence, D lies on a "higher" indifference curve and welfare increases.

f. Interactions Between Investment in Pollution Control and r_g.

The thrust of this subsection is not to suggest that environmental policy should be designed according to how it alters r_g. Rather, the goal here is to discuss how environmental policy affects r_g because this, in turn, may permute monetary policy targeting r_g. That is, if central banks adopt an r_g-based target, policy makers could anticipate how r_g would change in a setting with dynamic environmental policy.

Pollution control, or abatement, conducted in period (t) reduces damage through the $(\beta_t \gamma_t)$ term, where (γ_t) denotes the fraction of output allocated to abatement and (β_t) represents the sensitivity, or responsiveness, of the environment to abatement. Because the $(\beta_t \gamma_t)$ term enters (7), abatement affects r_g. Inspection of (7) reveals that *how* investment in pollution control affects r_g depends on *when* the investment occurs. The basic intuition is the following. More pollution removal today raises the growth rate of damages, ceteris paribus. This lowers r_g. More abatement in the future, holding other factors fixed, lowers the growth rate of damages. This raises r_g. To more precisely characterize the effect of pollution control on r_g, expressions (9a) and (9b) calculate the partial effect of (γ_1) and (γ_2) on r_g.

$$\frac{\partial r_g}{\partial \gamma_1} = -\beta_1 \frac{Y_2}{Y_1}(1+\rho)\left(\frac{1+\mu_1^e-\varphi}{1+\mu_2^e-\varphi}\right)^{1-\alpha} \frac{\left(1-(\alpha_2-\beta_2\gamma_2)\right)}{\left(1-(\alpha_1-\beta_1\gamma_1)\right)^2} \tag{9a}$$

$$\frac{\partial r_g}{\partial \gamma_2} = \beta_2 \frac{Y_2}{Y_1}(1+\rho)\left(\frac{1+\mu_1^e-\varphi}{1+\mu_2^e-\varphi}\right)^{1-\alpha} \frac{1}{\left(1-(\alpha_1-\beta_1\gamma_1)\right)} \tag{9b}$$

Hence, (9a) is negative while (9b) is positive, supporting the intuition above. Increasingly stringent environmental policy will raise r_g, because policies that prescribe higher levels of abatement in the future boost growth in net output by reducing damage over time[8]. This case is also instructive for economies that have not yet instituted binding environmental policies, but will do so in the future. Such a situation is broadly relevant. Some large developing economies (such as India) currently lack binding pollution control policies. Were such nations to enact such

[8] Looking back at environmental policy in the U.S., the CAA featured limits to ambient pollution that have gradually become more stringent since 1970. Thus, one of the landmark pieces of environmental legislation exemplifies this pattern of increasingly binding regulation.

rules in the future, r_g would rise. Developed economies like the U.S. lack comprehensive, binding climate change policy. Upon implementation of such policies, r_g would increase.

Conversely, a policy that sets an ambitious near term abatement target that then relaxes over time will result lower r_g. The idea is that if policies allow pollution intensity to rise, r_g will decline. A lower r_g also occurs when governments allow existing rules to lapse, or terminate policies, as was the case in the U.S. between 2017 and 2020 (New York Times, 2020b).

This section underscores that central banks considering an r_g target must be mindful of extant environmental policy and expectations over future environmental policy. Since such regulations appreciably affect pollution intensity, they will modify r_g. Upon the introduction of rules or regulations intended to induce significant decarbonization, the interplay between pollution intensity and r_g may be a critical consideration for central banks in managing this risk.

III. Data and Methods.

The empirical analysis conducted in this paper relies on several sources of data. Section III.a focuses on the environmental data while III.b discusses sources for the macroeconomic data.

a. Environmental pollution data.

The local air pollution series covers annual average fine particulate matter ($PM_{2.5}$) estimates reported in Muller (2019a). These data correspond to a combination of satellite observations and modeled data from 1980 – 2016 provided by Meng et al., (2019), see figure A.2 in the appendix. For the earlier data, the analysis relies on imputed $PM_{2.5}$ from total suspended particulate matter (TSP) data gathered from the early air pollution monitoring networks. The TSP data are provided by Clay et al., (2016). The imputation, discussed at length in Muller (2019a), regresses observed $PM_{2.5}$ in the U.S. Environmental Protection Agency's (USEPA) AQS monitor network from

1999 to 2016 on matching (spatially and temporally) TSP data. Predictions of $PM_{2.5}$ are made from 1979 back to 1957 and this series is spliced with the 1980-2016 satellite series to produce a continuous $PM_{2.5}$ series from 1957 to 2016 (see figure A.3).

Conversion of ambient $PM_{2.5}$ estimates into monetary damage relies on an approach that is standard in policy analyses (USEPA, 1999; 2010) and in the academic literature (Levy, Baxter, Schwartz, 2009; Muller, Mendelsohn, Nordhaus, 2011; Muller, 2014; Tschofen et al., 2019). The damages are limited to premature mortality risk from exposure to $PM_{2.5}$ both because of historic data constraints and because prior research in this area has repeatedly demonstrated that this category of damage accounts for the majority of all air pollution damage (USEPA, 1999; 2010).

Calculation of mortality damage requires vital statistics going back to 1957. The methods and data are discussed in Muller (2019a). The Centers for Disease Control and Prevention (CDC) provide population and mortality rate data used in this analysis. These data are reported by age group. This is an essential component of the empirical analysis because baseline mortality rates vary considerably over the life cycle and the functions that link exposure to mortality risk are multiplicative in nature (Krewski et al., 2009).

Using population by age cohort (a), and time (t), denoted ($Pop_{a,t}$), and baseline (reported) mortality rates, by (a) and (t), denoted ($M_{a,t}$), (CDC, various) premature mortality due to $PM_{2.5}$ exposure is computed as shown in (10).

$$Mort_{a,i,t} = Pop_{a,i,t} M_{a,i,t} \left(1 - {}^{1}\!/_{exp\left(\theta PM_{i,t}\right)} \right) \tag{10}$$

The (θ) term, which controls the marginal effect on mortality risk from $PM_{2.5}$ exposure, is reported in the epidemiological literature (Krewski et al., 2009). Aggregating over age groups and locations yields an estimate of national premature mortality.

In the air pollution context, mortality risk is commonly monetized using the Value of Statistical Life (VSL) approach. The VSL is the marginal rate of substitution between money (income) and mortality risk (Hammit and Robinson, 2011). This tack is used by the USEPA in its benefit-cost analyses of the CAA (USEPA, 1999; 2010) and by numerous academic researchers (Levy, Baxter, Schwartz, 2009; Muller and Mendelsohn, 2009; Fann et al., 2009; Muller, 2014; 2019a; 2019b; Tschofen et al., 2019). It is typical to apply the VSL to all populations *within a given time period* uniformly, regardless of income. Thus, monetary damages (D) in period (t) are calculated by simply multiplying premature mortalities times the VSL, shown as (V_t), in (11).

$$D_t = \sum_{i=1}^{I} \sum_{a=1}^{A} Mort_{a,i,t} V_t \qquad (11)$$

A crucial concern in the relatively long-run context of the present paper is that the VSL (V_t) varies by year according to the reported per capita income. To construct the VSL series over the 60-year span of the present study depends on estimates of the VSL-income elasticity reported in the literature (Kleckner and Neumann, 1999; Costa, Kahn, 2004; Hammitt, Robinson, 2011). The present analysis employs the VSLs by decade reported in Costa and Kahn (2004) from 1957 to 1980. For the 1980 to 2016 period, the paper begins with the USEPA's recommended VSL of $7.4 million ($2006). This VSL is adjusted according to changes in real income using the USEPA's income elasticity of 0.4 (Kleckner and Neumann, 1999). This series was used in Muller (2019a). Figure A.4 in the appendix shows how the VSL changes from 1957 to 2016.

Emissions of greenhouse gases (expressed as CO_2 equivalents) are provided by the U.S. Department of Energy (DOE, 2011; 2019). These are economy-wide emission estimates. Monetization of the CO_2 emissions employs the social cost of carbon (SCC) metric. This is the present value of damages from one U.S. short ton of CO_2 emissions. This study uses the updated SCC from the U.S. Federal Inter-Agency Working Group report from 2016 (USFWG, 2016). The annual real rate of change in the SCC reported in USFWG (2016) is used to estimate the SCC back to 1957. Both the emissions and the SCC estimates are depicted in figure A.5.

It is of interest to characterize how pollution damages change if households face r_g rather than r*. The difference in damage in period 1, between consumption levels with r*, denoted (c_1(r*)), and consumption levels with r_g, $c_1(r_g)$) is:

$$\Delta D_1 = \frac{a_1(\alpha_1 - \beta_1\gamma_1)}{(1-(\alpha_2-\beta_2\gamma_2))}\left(\frac{1-\varphi}{1+\mu_1^e-\varphi}\right)^{1-\varphi}(\alpha_1-\beta_1\gamma_1)-(\alpha_2-\beta_2\gamma_2) \quad (12)$$

The difference in damage in period 2 is shown in (13):

$$\Delta D_2 = \frac{a_1(\alpha_2 - \beta_2\gamma_2)}{((\alpha_1-\beta_1\gamma_1)-1)}\left(\frac{1-\varphi}{1+\mu_2^e-\varphi}\right)^{1-\varphi}(\alpha_1-\beta_1\gamma_1)-(\alpha_2-\beta_2\gamma_2) \quad (13)$$

For any given period (t) in the data, the sum of (12) and (13) is computed. The two year sum of the change in damages is reported because r_g induces an intertemporal reallocation, with consumption and damage either rising or falling in each period. Thus, it is the total change in damage that matters for social welfare.

In light of the standard view that monetary policy actions affecting short term rates also affect medium and longer term rates, the analysis also computes (12) and (13) over longer maturities[9].

[9] Roley and Sellon (1995) report mixed results of the relationship between short term policy actions and 30-year rates. The medium term maturities (three and five years) that are the focus here are significantly affected by short term policy actions (Roley and Sellon, 1995).

Specifically, the change in consumption over three and five year maturities are computed and reported.

b. Macroeconomic data.

In order to calculate the interest rate specifications derived in section II., several macroeconomic datasets are required. National GDP is provided by the U.S. Bureau of Economic Analysis (USBEA, 2019). Conversion from nominal to real values relies on the USBEA's GDP deflator. Pollution intensity is defined as empirically estimated GED over GDP. Net potential output (or EVA) is computed by deducting the gross external damage (GED) from air pollution and CO_2 from real GDP, by year, from 1957 to 2016. All macroeconomic aggregates (GDP, GED, and EVA) are expressed in real, per capita terms.

IV. Results.

The results section begins with a brief description of summary statistics and stylized facts. There are four patterns in the summary statistics that are most relevant to the subsequent analysis of interest rates. First, the U.S. economy exhibited falling damages, combined, from air pollution and CO_2, between 1957 and 2016. Regarding the analytical results derived above, this implies that, in general, r_g will exceed r^*. Second, the passage of the CAA reversed the trend in damage from rising prior to 1970 to falling thereafter. This trend break due to regulation reversed the orientation between r_g and r^*. Third, the CAA only affected emissions of local air pollution. Damages from CO_2 continued to rise after 1970 while damages from regulated pollutants fell. The importance of public policy in dictating the trajectory of damage speaks to the effects of future climate policy on r_g relative to r*. And, fourth, as reported in prior research, the combined damages are large relative to per capita income (Muller, 2019a; Tschofen et al., 2019).

Figure 2 depicts the real GDP, EVA, and GED series from 1957 to 2016. Table 1 reports that real, per capita GDP increased from just under $20,000 in the late 1950s to nearly $60,000 in 2016. This is an increase of about 2 percent per year (see table 2). Despite this growth in national income, table 1 shows that per capita GED fell by about 30 percent over this time from an average of $6,800 in the 1960s down to just under $4,900 after 2010. Combined GED decreased by 0.35 percent, annually (see table 2). EVA growth outpaced GDP growth by about 50 basis points. Real EVA growth in excess of GDP stems from falling pollution intensity. Table 1 reveals that, in the 1960s, GED amounted to about one-third of per capita income. After 2010, this damage burden dropped to under 10 percent. In light of analytical results in section II., such conditions suggest that r_g exceeded r* in the U.S. economy over this period. The statistical comparisons r_g and r* are presented below.

Though generally pollution intensity of the U.S. economy declined from 1957 to 2016, this reduction was non-monotonic (Muller, 2019a). These decadal results are shown in tables 1 and 2. From 1957 to 1970, the GED grew at just under 4 percent, annually, while real GDP expanded at about 2.5 percent per year. Increasing damage intensity in this pre-regulatory period suppressed EVA growth. Specifically, EVA growth averaged about 1.9 percent, annually, or roughly 60 basis points slower than real GDP. After 1970 and the passage of the CAA, GED began to fall. During the decade of the 1970s, combined GED shrank by about 1 percent per year. GDP growth, while slower than during the 1960s, was on average positive, at 2 percent. With falling pollution intensity, EVA growth exceeded GDP growth. The EVA – GDP growth gap was at its widest margins during the 1970s (150 basis points). The difference in growth rates generally attenuated until the 2010s.

The reversal in the direction of change in pollution intensity, and the orientation of EVA and GDP growth has intuitive ramifications for the relative magnitudes of r_g and r*. Namely, in the period of rising pollution intensity, section II. suggests that r* exceeded r_g. And, after 1970, when pollution intensity began to fall, section II. suggests the orientation of these two rates reversed. The statistical comparison of r_g and r* before and after 1970 is reported and discussed below.

Tables 1, 2, and figure 3 decompose the GED into air pollution and CO_2 damages. The left-hand panel of figure 3 shows the indexed levels of GDP and GED. The right-hand panel shows growth rates. Over the entire sample, CO_2 damages increased at roughly 2 percent annually whereas air pollution damage declined by 0.5 percent. Targeted regulation of local air pollution played a critical role in determining the relative rates of damage growth. Air pollution GED started to fall in the 1970s, after the passage of the CAA. The annual growth rate of air pollution GED before 1970 was 3.9 percent. In the 1970s it was -1.1 percent. In contrast, CO_2 damage growth was effectively unchanged from the 1960s (3.4 percent) to the 1970s (3.0 percent). Crucially, while the CAA specifically targets local air pollutants, it does not regulate CO_2. Because of this, CO_2 growth rates closely match GDP, as shown in figure 3.

The differential growth rates of CO_2 and air pollution damage translate into considerable changes in damage shares. Prior to 1970, air pollution damage averaged 96 percent of the GED. In the final decade of the analysis, CO_2 damage comprised 13 percent of GED. The pattern of falling air pollution damage and rising climate damage has implications for r_g. Extant constraints in the CAA are likely to keep air pollution damages low and on a downward trajectory. Continued regulatory omission of CO_2 will result in an ever-larger share of the GED stemming from this pollutant. If, as a result of rising CO_2 damage, GED eventually increases, the orientation between r* and r_g would reverse.

a. Interest rates.

Table 3 reports three different sets of interest rates: the real federal funds rate (FRED, 2019b), estimates of r* (Laubach and Williams, 2015), and r_g. Over the entire sample, the real federal funds rate (RFFR) averaged about 1.4 percent. As is well known, the RFFR fluctuated over this 60-year period. In the 1960s, the RFFR averaged less than two percent. High inflation reduced the RFFR to near zero in the 1970s. In the 1980s, the RFFR averaged about four percent. From the 1990s through 2016, the RFFR fell from an average of about two percent to negative 1.5 percent after 2010.

The second row of table 3 reports Laubach and Williams' (2015) updated estimates of r*. The sample average is about three percent, or about 160 basis points higher than the RFFR. As is well known, the r* estimate exhibits a strong downward trend from over five percent during the 1960s to effectively zero after 2010.

The bottom two rows of table 3 report r_g and the r_g - r* differential. r_g is calculated by differencing (6) from (7), as shown in (14) and then adding the empirical estimate of (14) back to r* as reported by Laubach and Williams (2015).

$$r_{g,t} - r_t^* = (1+\rho)\frac{a_t}{a_{t-1}}\left(\frac{1+\mu_{t-1}^e-\varphi}{1+\mu_t^e-\varphi}\right)^{1-\varphi}\left(\frac{((\alpha_{t-1}-\beta_{t-1}\gamma_{t-1})-(\alpha_t-\beta_t\gamma_t))}{(1-(\alpha_{t-1}-\beta_{t-1}\gamma_{t-1}))}\right) \quad (14)$$

For the purposes of the provisional calculations reported here, $\left(\frac{1+\mu_{t-1}^{e}-\varphi}{1+\mu_{t}^{e}-\varphi}\right)^{1-\varphi}$ is set to unity, and ρ is set to 0.01.

With this approach, table 3 reports that, on average, r_g exceeded r* by 50 basis points ($p < 0.01$). The reason for this difference is the large and significant reduction in the pollution intensity of output discussed above. Recall from section II. that an economy on a cleaning up trajectory justifies a higher green interest rate because falling damage intensity implies greater net consumption prospects in the future. In a broad sense, the data for the U.S. economy over the last 60 years exemplify such conditions and the result is r_g exceeding r* by about 50 basis points. However, as shown above, GED did not change monotonically.

Commensurate with the pattern of rising and then falling damage intensity reported above, figure 4 shows the reorientation of r_g and r* before and after the passage of the CAA. (The vertical line demarcates passage of the CAA.) Table 3 reports that prior to 1970, r_g fell short of r* by 150 basis points ($p < 0.05$). This difference manifests because per capita GED increased more rapidly than GDP during this time. Pollution intensity increased because neither air pollution nor CO_2 were regulated comprehensively at the federal level. Expressions (8) and (14) show mathematically that when pollution intensity rises, r_g is less than r*. Intuitively, with rising damage intensity, future potential income, net of damage, is attenuated. Under these conditions r_g falls relative to r* which encourages more consumption in the present when the effective penalty from pollution damage is lower.

Following enactment of the CAA in the early 1970s, r_g exceeded r*. The difference between the two rates was largest in absolute terms during the 1970s (150 basis points, $p < 0.01$). This rate spread steadily attenuated to just 15 basis points in the 2010s. With falling damage intensity, future net potential income was augmented. The higher r_g induces more future consumption when the loss from pollution damage is lower.

Figure A.7 in the appendix shows both the relative (year-over-year) changes in pollution intensity and the $\left(\frac{((\alpha_{t-1}-\beta_{t-1}\gamma_{t-1})-(\alpha_t-\beta_t\gamma_t))}{(1-(\alpha_{t-1}-\beta_{t-1}\gamma_{t-1}))}\right)$ term from (14). Prior to 1970 damage intensity increased. The rate of change fell from a 6 percent annual increase at the end of the 1950s down to zero in 1970. From the middle 1970s damage intensity declined by about 3 percent per year until fluctuating but remaining negative in the 2000s. The $\left(\frac{((\alpha_{t-1}-\beta_{t-1}\gamma_{t-1})-(\alpha_t-\beta_t\gamma_t))}{(1-(\alpha_{t-1}-\beta_{t-1}\gamma_{t-1}))}\right)$ term varies inversely with intertemporal changes in pollution intensity. This term is the key driver in the empirical difference between r_g and r*, as shown in (14), and it increased from the late 1950s until the early 1970s. Just like annual changes in pollution intensity, the sign changed in 1970 upon passage of the CAA. This term gradually attenuated, remaining positive, from the middle 1970s to 2016. As this term approached zero toward the end of the sample period, it diminished the difference between r_g and r*.

b. Interest Rates and the Business Cycle.

Table 4 compares the interest rates at different stages of the business cycle. Column (1) simply reports the averages across all 60 years for ease of comparison. Column (2) reports averages during NBER recession years. During contractions, r_g averaged 4.4 percent, a difference from r* of 0.86 ($p < 0.05$). During expansionary periods, the spread between r_g and r* fell to 0.38 percent ($p < 0.05$). In general, one would expect larger increases in GED during expansions. This would suppress r_g relative to r*. The smaller r_g to r* spread embodies this effect. Table 4 also separately compares the rates during expansions and contractionary periods before and after 1970. The sensitivity of the difference between r_g and r^* to the business cycle is considerably greater before 1970 and the passage of the Clean Air Act.

Table A.1 in the appendix demonstrates the procyclical nature of the GED. In column (2), real GED fell by over 3 percent during recessions. Column (3) shows that GED increased by 0.5 percent during expansions. The cyclical nature of GED changed fundamentally with the passage of the CAA. Prior to 1970, and absent federal air pollution regulation, GED fell slightly in recessionary periods, while during expansions, GED grew by more than 6 percent annually. The rapid growth of GED during expansions prior to 1970 drives r_g below r^* by 180 basis points ($p < 0.05$), as shown in column (5) of table 4. In contrast, after 1970, GED fell in both recession and non-recession periods (see table A.1. Thus, the difference between the r_g and r^*, prior to the onset of federal air pollution policy, hinges on the business cycle. After the CAA, the $r_g - r^*$ spread is essentially constant over the business cycle.

That r_g exceeds r^* by a larger spread during recessionary periods than during expansions runs counter to the typical conceptualization of interest rate or stabilization policy. Conventionally, accommodative policy stimulates consumption, mitigating short run recessionary effects. Inclusion of environmental damages in r_g tempers this standard policy prescription. Crucially, figures 2 and 3 show that pollution damages exhibit a strong pro-cyclical pattern, *especially prior to comprehensive regulation*. When the economy becomes dirtier over time more consumption should occur in the present because the penalty from pollution damages is greater in the future. More accommodative policy stimulates more consumption in the present.

The converse argument holds when an economy is cleaning up. Figures 2 and 3 show large and enduring reductions in pollution intensity during recessions. In such instances, delaying consumption raises welfare because households consume more during the period when the penalty from pollution damage is lower. Tighter monetary policy induces just such a delay.

c. The Change in Damage from r_g.

Figure 5 displays the percentage change in damage due to consumers facing r_g rather than r*. To construct the figure, the sum of (12) and (13) over one, three, and five-year maturities is calculated. The resulting sum is divided by the damage in period (t). So, for a one-year response to r_g in 1960, the change in damage in 1960 and 1961 is calculated and displayed as a percentage of observed damages in 1960. For a change in consumption over three years, the reallocation of damage between 1960 and 1963 is calculated. The figure shows that the impact of r_g, in percentage terms, is largest prior to the enactment of the CAA in 1970. Specifically, depending on the time period over which consumption responds to r_g, the reallocation of damage reaches as much as 3 percent of damages in early and middle 1960s. At this time, during the 1960s, the GED was rising more rapidly (4 percent) than GDP (2.5) percent. In this period of rapidly rising pollution intensity, r* exceeded r_g by about 150 basis points. Had optimizing households faced this lower rate, figure 5 demonstrates that the result would have been a significant adjustment of consumption *toward the present* when pollution intensity was lower than during the later 1960s. With more consumption in the less pollution intensive present, damages fall by between 1 and 3 percent. Figure A.7 reinforces why this reallocation occurs. Pollution intensity was rising by as much as 6 percent per year prior to the CAA. The lower r_g encourages more consumption in the significantly less polluted present. Figure 5 shows two additional periods when reallocated damages amount to as much as 0.5 percent of total damages. The first such episode occurs just prior to the recessions of the early 1980s, when both CO_2 and air pollution damages fell rapidly (see the right hand panel of figure 3 and figure A.7). At this time, r_g exceeded r* by about 100 basis points. The higher r_g would have delayed consumption until after the recessions when pollution intensity was much lower. The second period when r_g appreciably affected damages was in the late 1980s, just prior to the enactment of the CAA amendments of 1990 and the recession of 1991. During this period, local air pollution damages fell by as much as 5 percent annually (see the right hand panel of figure 3). Again, r_g was larger than r*, inducing a delay in consumption to the less pollution-intensive future.

Figure 6 plots the cumulative benefits of households facing r_g. The essential point of this figure reinforces that from figure 5. It is during the pre-regulatory period, that is, prior to the enactment of the CAA, when the benefits from r_g accrue rapidly. After the passage of the CAA benefits continue to accumulate, but at a much slower rate. Through the 1960s, benefits amount to between $15 billion (one year maturity) up to as much as $175 billion (for the five year maturity).

d. Sensitivity Analysis.

Table 6 reports the results of a sensitivity analysis in which the difference between r* and r_g is recomputed using alternative assumptions on key parameters in the damage calculation. The first row repeats the bottom row of table 3 for comparison purposes. The second row employs an alternative functional relationship between exposure to $PM_{2.5}$ and adult mortality rates (Lepeule et al., 2012). The coefficient in the alternative study is roughly 2.5 times larger than the default approach (Krewski et al., 2009). Accordingly, the average difference between r_g and r* is approximately 2.5 times larger than when using the default approach: 118 basis points ($p < 0.05$) rather than 50 basis points in the default approach. This alternative assumption also results in significantly larger spreads earlier in the sample. For example, prior to 1970, r_g is less than r* by more than 450 basis points ($p < 0.05$) while in the 1970s, r_g *exceeds* r* by more than 450 basis points. Note that the reversal of sign and the very similar absolute magnitude of the $r_g - r^*$ difference in the 1960s and 1970s is consistent with the default approach. Also robust to the alternative $PM_{2.5}$ mortality function is the considerable narrowing of the r_g to r^* spread between 1970 and 2016. By the end of the sample, r_g exceeds r^* by about 30 basis points (again, roughly two times the default estimate).

The second alternative strategy employs a different VSL-income elasticity. Recall that the default tack employs early estimates of the VSL from the literature (Costa and Kahn, 2004) which imply a higher VSL-income elasticity combined with the USEPA's value of 0.4 after 1980. The sensitivity analysis uses a unit elastic VSL-income elasticity. As figure A.4 shows, the unit-elastic VSL increases from 1957 to 1970 much more slowly than the default approach. Then, after 1980, the unit-elastic VSL appreciates much more rapidly. The average difference across all years is, like the default case, 52 basis points ($p < 0.01$). However, the GED growth rates are quite different compared to the default approach, and this, in turn, affects the $r_g - r^*$ difference across decades. Prior to 1970, $r_g - r^*$ is just 0.45 which is not statistically significant at conventional levels. During the 1970s, $r_g - r^*$ is 117 basis points ($p < 0.01$). Like the default approach, the difference in rates attenuates significantly throughout the remaining decades, though using the unit elastic VSL results in non-monotonic attenuation of $r_g - r^*$.

Finally, table 5 reports the $r_g - r^*$ difference when employing a considerably higher SCC (the marginal damage of CO_2 emissions). This strategy has very little effect on the $r_g - r^*$ spread. The sample average difference is 51 basis points ($p < 0.01$). Prior to 1970, r^* exceeds r_g by about 150 basis points ($p < 0.05$) and this orientation reverses during the 1970s with a very similar absolute magnitude. Then, the $r_g - r^*$ difference diminishes to just 14 basis points (compared to 16 basis points in the default scenario). The higher SCC has a limited effect on the r_g – r* spread because GHG damages throughout much of the sample comprise a small share of the total GED.

V. Conclusions.

Central banks and financial regulators now recognize the risks to the financial system and the economy posed by environmental pollution and climate change (The New York Times, 2020a; NGFS, 2020; Federal Reserve, 2020; White House, 2021). This paper proposes a novel policy instrument that central banks could use to mitigate risks from environmental pollution damage. The green interest rate, or r_g, is a reconfiguration of the natural interest rate (r*). The difference between r_g and r* is the inclusion of pollution damage into an economy's potential output, in both the present and the future. By building pollution damage into r_g, borrowers and lenders are compelled to consider intertemporal changes in pollution intensity of the goods they consume in determining their optimal consumption plans. Implicit consideration of pollution damage is a form of internalization of the pollution externality. Rather than affecting the relative prices of pollution-rich and green goods, as a Pigouvian tax would, r_g affects the intertemporal terms of trade according to the pollution intensity of aggregate output. The paper demonstrates that targeting r_g raises social welfare, relative to a policy rate targeting r*, by reallocating consumption to less pollution intensive periods.

This study models the case in which a central bank targets r_g without concomitantly binding environmental policy. This situation is explored in detail for two reasons. First, most pressing for central banks is the onset of climate policy and the associated transition risks to a low carbon economy. The Federal Reserve notes that these risks include devaluation of assets due to newly binding policy constraints, as well as damage to assets from changing climate conditions

(Federal Reserve, 2020). Given the absence of coherent federal climate policy in the U.S., an examination of r_g without environmental policy seems most relevant to practitioners.

Second, the goal of this paper is to demonstrate how a central bank could apply r_g autonomously; that is, without coordinating with an environmental regulator charged with enactment of traditional environmental policy (such as a Pigouvian tax). Political and social obstacles to meaningful climate policy in the near term render this context most broadly relevant.

Because r_g depends on the trajectory of pollution intensity of output, this policy instrument reallocates consumption to periods characterized by less pollution intensive output. Specifically, for economies on a cleaning up path, r_g exceeds r* because the higher rate delays consumption to the less pollution intensive future. In contrast, in economies becoming more polluted, r_g is less than r*. This incentivizes more current consumption in the less polluted present economy at the expense of consumption in the more polluted future. The analysis also explores the interaction between environmental policy design and r_g. Policy that grows more stringent over time will increase r_g, ceteris paribus. In contrast, relaxation or removal of existing rules lowers r_g.

The empirical portion of the paper estimates r_g from 1957 to 2016 in the U.S. economy. These calculations show that r_g exceeds estimates of r* from the literature by about 50 basis points. However, prior to the passage of the CAA in 1970, r_g fell short of r* because pollution damages were rising. After 1970, damages fell. This caused the orientation between r* and r_g to switch, with r_g exceeding r* in the post-1970 context of falling damage. The empirical analysis also reveals that the difference between r_g and r* is sensitive to the business cycle; r_g exceeds r* by nearly two-times more during recessions than expansions. This divergence is especially stark prior to the enactment of the CAA because, absent policy, pollution was strongly procyclical.

In a set of provisional calculations, the paper reports that targeting r_g rather than r* would have reduced damages by as much as 3 percent annually. These benefits were concentrated in the years leading up to the passage of the CAA. Cumulative benefits *prior to the enactment of the CAA* amounted to as much as $175 billion. Simply redefining the intertemporal terms of trade and therefore reallocating consumption to low damage periods would yield large benefits.

These results, while only provisional, are strongly suggestive of the important role that r_g may play in managing the transition to a low-carbon economy. Today, in the absence of meaningful federal climate policy, is analogous to the 1960s, prior to the deployment of the CAA. At that time, strongly pro-cyclical air pollution damage was rising rapidly. Today, damages from CO_2 emissions continue to rise, comprising an ever larger share of the total GED. During such periods, the simulations conducted herein show that monetary policy can play an important role in mitigating environmental pollution damage. However, this requires the central bank to target a rate that recognizes the trajectory of pollution intensity. This paper demonstrates that the data and modeling tools are available to support such an undertaking.

This analysis suggests future research on a number of fronts. While the focus on the present paper lies on the U.S., applications to other economies comprise important extensions of the concepts introduced herein. Recent work demonstrates that the pollution intensity of output varies considerably across countries over the past few decades (Mohan et al., 2020). In particular, China and India exhibit starkly different paths, with respect to pollution intensity, than observed in the U.S. Given the sheer size of these economies, an exploration of the potential role of monetary policy in managing environmental pollution risks may have global implications. Next, the present paper adopts a simple, parsimonious two period model to elucidate the central concepts underpinning r_g. Future work could employ an overlapping generations model to explore the ramifications of policies targeting r_g for savings and consumption decisions across agents' life cycles. Finally, the monetary policy position adopted by central banks affects exchange rates and trade flows. Recent research demonstrates that trade affects the pollution intensity of goods (Shapiro, 2020). Thus, if a central bank adopts r_g this is likely to permute trade flows and, in turn, pollution intensity. This nexus is an important subject for future inquiry.

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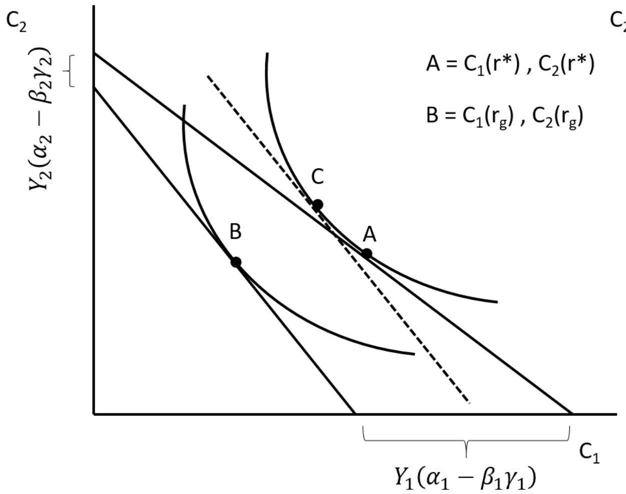
Figure 1: Comparison of Inter-temporal Consumption Choices with r_g and r^*.



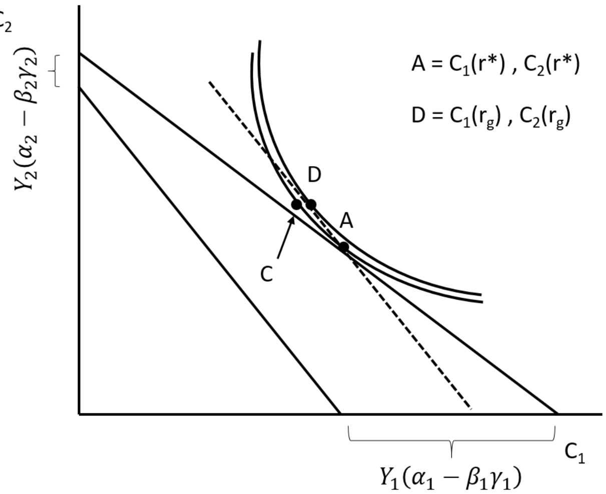
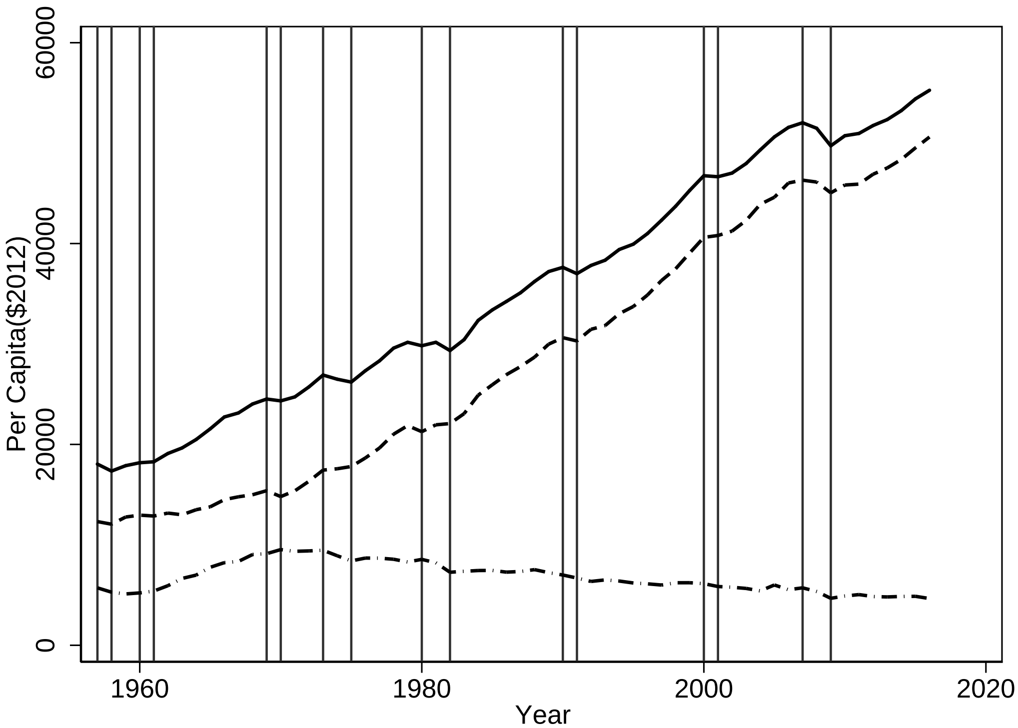
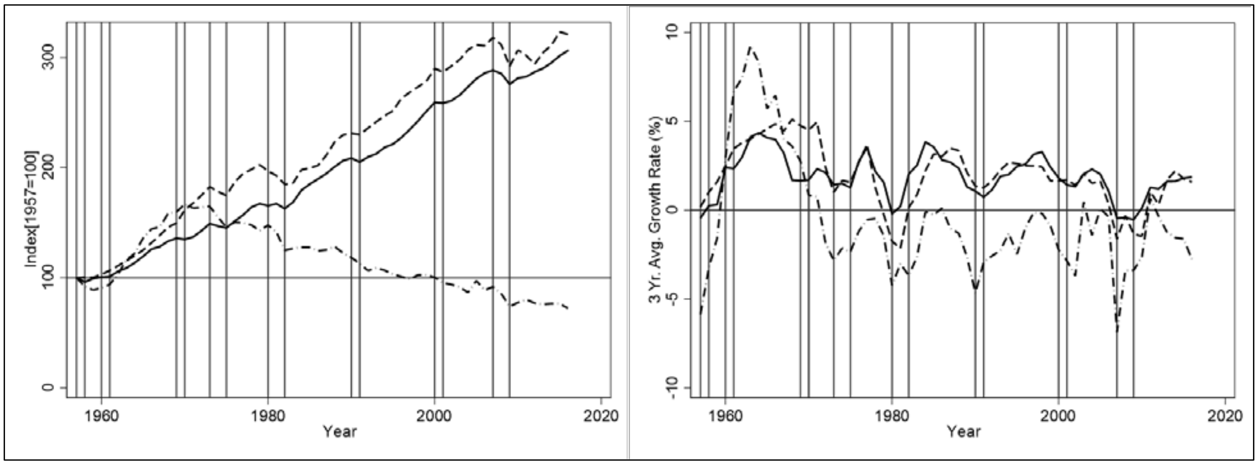


Figure 2: GDP, Pollution Damage, and EVA.



Vertical lines demarcate NBER recessions.
Solid = GDP; Dash = EVA; Dash-dot = GED.
EVA = GDP – GED
Source: USBEA, 2019, Muller, 2019a, and author's calculations.

Figure 3: GDP, Air Pollution and CO_2 Damage.



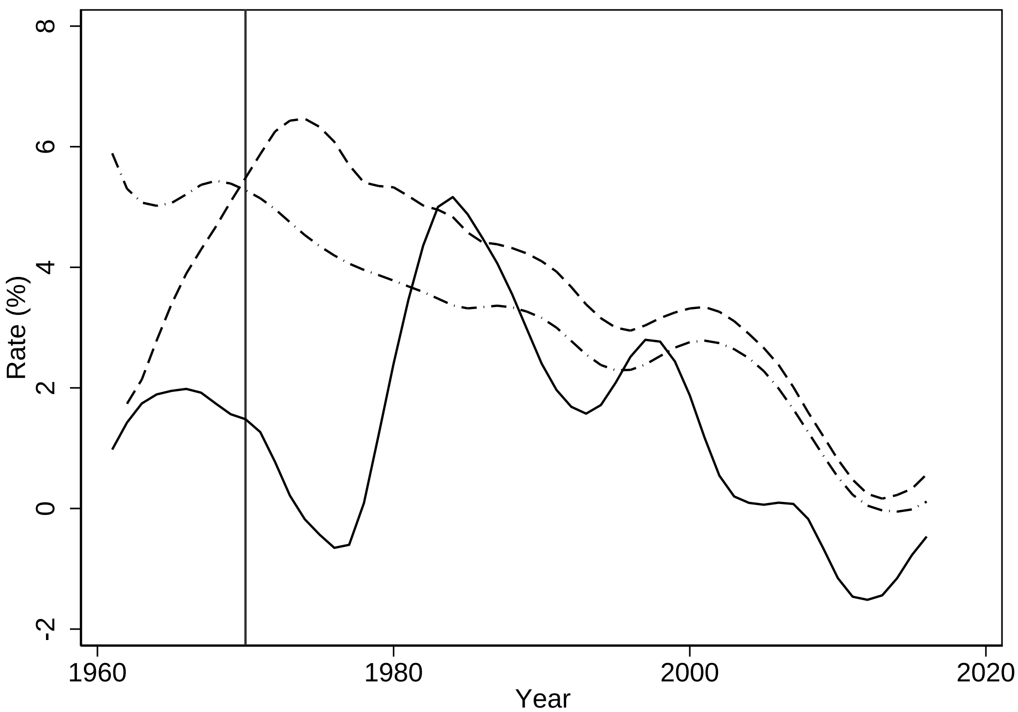
Solid = Real GDP

Dash = Real CO_2 GED

Dash-dot = Real air pollution GED

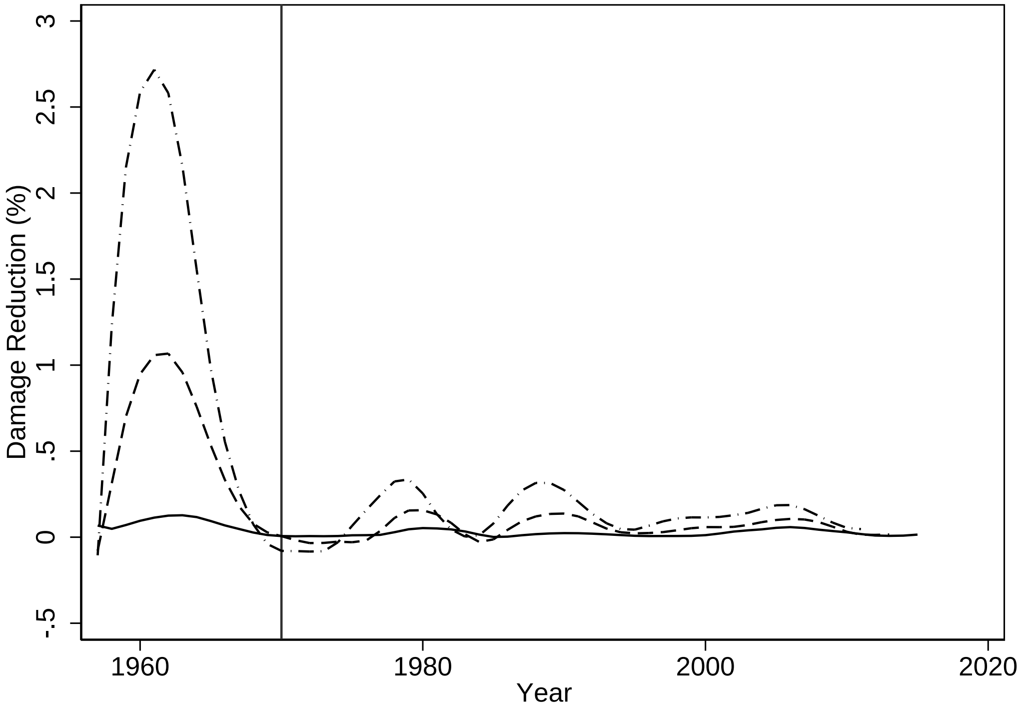
Vertical lines demarcate NBER recessions.

Figure 4: Interest Rate Comparison.



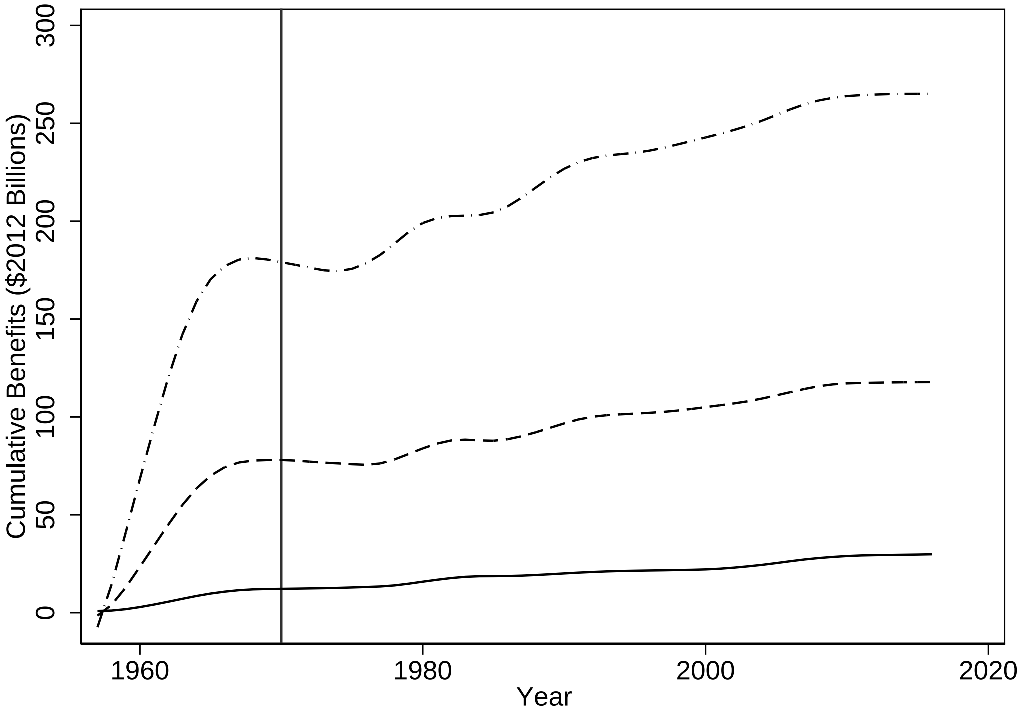
Solid = Real Federal Funds Rate; Dash = r_g; Dash-dot = r*.
Source: Federal Funds (FRED, 2019); r* Laubach and Williams (2015); r_g author's calculations.

Figure 5: Change in Damage Due to r_g.



Solid: change in consumption occurs in consecutive years.
Dash: change in consumption occurs in three years.
Dash-dot: change in consumption occurs in five years.

Figure 6: Total Benefits due to r_g.



Solid: change in consumption occurs in consecutive years.
Dash: change in consumption occurs in three years.
Dash-dot: change in consumption occurs in five years.

Tables.

Table 1: Output and Damage per Capita.

	(1) Total sample	(2) 1960s	(3) 1970s	(4) 1980s	(5) 1990s	(6) 2000s	(7) 2010s
GDP	35456.87[A]	20379.25	26983.46	32830.41	40247.88	49315.88	52672.27
	(11844.9)	(2538.2)	(1924.6)	(2837.3)	(2790.2)	(2101.2)	(1715.5)
EVA	28661.08	13546.24	18053.70	25259.12	33873.43	43700.98	47813.06
	(12760.0)	(1064.1)	(2300.0)	(3084.0)	(3000.7)	(2279.2)	(1803.8)
Air	6795.79	6833.00	8929.76	7571.29	6374.45	5614.90	4859.21
+ Climate	(1467.4)	(1509.0)	(469.1)	(446.5)	(297.0)	(410.3)	(117.2)
Air	6347.24	6588.28	8555.26	7155.21	5856.45	4994.69	4224.37
	(1545.5)	(1473.2)	(489.3)	(454.8)	(326.5)	(411.4)	(128.4)
Climate	448.55	244.72	374.50	416.09	517.99	620.21	634.84
	(145.1)	(36.51)	(27.49)	(30.58)	(36.52)	(23.02)	(21.53)
N	60	13	10	10	10	10	7

A = ($2012)

Standard deviations in parenthesis.

Table 2: Growth Rates of Per Capita Output and Damage.

	(1) Total sample	(2) 1960s	(3) 1970s	(4) 1980s	(5) 1990s	(6) 2000s	(7) 2010s
GDP	1.90[A]	2.56	2.07	2.10	1.97	0.93	1.51
	(2.105)[B]	(2.524)	(2.421)	(2.506)	(1.550)	(2.048)	(0.575)
EVA	2.40	1.86	3.51	3.15	2.65	1.43	1.66
	(2.372)	(2.395)	(3.309)	(2.732)	(1.628)	(1.968)	(0.733)
Air + Climate	-0.35	3.89	-0.95	-1.37	-1.49	-2.87	-0.08
	(5.065)	(5.743)	(3.467)	(4.577)	(2.832)	(6.498)	(3.426)
Air	-0.55	3.90	-1.12	-1.53	-1.78	-3.28	-0.30
	(5.338)	(5.914)	(3.485)	(4.721)	(3.040)	(7.084)	(3.709)
Climate	1.98	3.36	3.03	1.25	1.92	0.48	1.36
	(2.829)	(1.710)	(3.293)	(3.564)	(1.256)	(3.111)	(3.011)
N	59	12	10	10	10	10	7

A = all values are average growth in (%)

B = Standard deviations in parenthesis.

Table 3: Interest Rate Comparison.

	(1) Total sample	(2) 1960s	(3) 1970s	(4) 1980s	(5) 1990s	(6) 2000s	(7) 2010s
Federal Funds Rate[A]	1.36[B]	1.86	0.01	4.41	2.14	0.39	-1.46
	(2.278)[C]	(0.595)	(1.585)	(1.954)	(1.205)	(1.583)	(0.940)
r*	3.14	5.31	4.48	3.49	2.57	2.25	0.00
	(1.691)	(0.653)	(0.593)	(0.376)	(0.478)	(0.799)	(0.195)
r_g	3.58	3.69	6.00	4.59	3.28	2.75	0.16
	(2.115)	(2.108)	(1.640)	(1.214)	(0.770)	(0.963)	(0.406)
r_g – r*	0.50***	-1.49**	1.52**	1.10**	0.70***	0.50**	0.16
	(1.486)	(1.764)	(1.738)	(1.321)	(0.534)	(0.699)	(0.366)
N	56	9	10	10	10	10	7

A = real federal funds rate
B = mean coefficients
C = sd in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ for t-test of rate difference $H_0 = 0$.

Table 4: Interest Rate Comparison and the Business Cycle.

	(1) Total sample	(2) Recession	(3) Expansion	(4) Recession Pre-1970	(5) Expansion Pre-1970	(6) Recession Post-1970	(7) Expansion Post-1970
Fed.[A] Funds Rate	1.36[B]	1.44	1.33	1.81	1.87	1.38	1.22
	(2.278)[C]	(2.536)	(2.209)	(1.313)	(0.429)	(2.708)	(2.409)
r*	3.14	3.76	2.91	6.05	5.09	3.40	2.46
	(1.691)	(1.639)	(1.672)	(0.405)	(0.550)	(1.451)	(1.455)
$\mathbf{r_g}$	3.58	4.44	3.29	6.45	3.30	4.28	3.28
	(2.115)	(2.217)	(2.024)	(.)	(1.932)	(2.227)	(2.071)
$\mathbf{r_g - r^*}$	0.50***	0.86**	0.38**	0.68	-1.80**	0.88**	0.82***
	(1.486)	(1.704)	(1.405)	(.)	(1.654)	(1.773)	(0.830)
N	56	15	41	2	7	13	34

A = real federal funds rate
B = mean coefficients
C = sd in parentheses
$^{*}\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$ for t-test of rate difference $H_0 = 0$.

Table 5: Sensitivity Analysis: $r_g - r^*$.

	(1) Total sample	(2) 1960s	(3) 1970s	(4) 1980s	(5) 1990s	(6) 2000s	(7) 2010s
Default	0.50***[A]	-1.49**	1.52**	1.10**	0.70***	0.50**	0.16
	(1.486)[B]	(1.764)	(1.738)	(1.321)	(0.534)	(0.699)	(0.366)
$PM_{2.5}$ DR	1.18**	-4.89**	4.60**	2.79**	1.64***	1.11**	0.34
	(4.510)	(5.112)	(5.925)	(3.586)	(1.266)	(1.521)	(0.770)
VSL	0.52***	0.45	1.17***	0.48	0.36**	0.47*	0.04
	(1.002)	(1.457)	(0.880)	(1.172)	(0.560)	(0.995)	(0.592)
SCC	0.51***	-1.55**	1.54**	1.15**	0.72***	0.52**	0.14
	(1.548)	(1.801)	(1.872)	(1.365)	(0.543)	(0.728)	(0.414)
N	56	9	10	10	10	10	7

$PM_{2.5}$ DR employs the alternative $PM_{2.5}$ mortality dose-response function reported in Lepeule et al., (2012).
VSL employs a consistent unit-elastic VSL-income elasticity.
SCC employs the 95% SCC reported in the U.S. Federal Inter-Agency Working Group report (2016).
A = mean $r_g - r^*$
B = sd in parentheses
$H_0 = 0$; $H_A \neq 0$: $^{*}\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$