## On the Relationship Between Environmental and Macroeconomic Policy.

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### Abstract

This paper explores the relationship between environmental policy and macroeconomic policy. The link hinges on a redefinition of output that deducts pollution damage from Gross Domestic Product. The paper proposes a dual link through the object of stabilization policy, consumption volatility, and stabilization tools, interest rates. Volatility in pollution-adjusted consumption depends on the covariance of market goods and services and pollution damage. The nature of the covariance hinges on the stringency of pollution control. Pollution-adjusted interest rates depend on the intertemporal changes in pollution intensity. Economies on a cleaning-up path justify a higher natural rate. Societies growing more pollution intensive suggest a lower natural rate. In an empirical application to the U.S. economy, the natural rate inclusive of pollution damages differs significantly from the federal funds rate. The implementation of major federal air pollution legislation enacted in the 1970s significantly affected the covariance between damages and output. The effect of this on year-over-year variance in per capita consumption, net of pollution damage, is appreciable.

**Keywords:** Natural interest rate, stabilization, air pollution, greenhouse gases, environmental accounting.

JEL Codes: E43, E63, E21, Q53, Q54, Q56, Q58, Q51.

### I. Introduction.

Macroeconomic policymakers rely on the National Income and Product Accounts (NIPAs) for estimates of real output and growth, both of which are important determinants of efforts to stabilize, and more broadly, manage, economic and financial systems. Yet, the NIPAs are incomplete. The NIPAs omit three key contributors to national economic welfare: the value of leisure time, home production, and environmental goods and services (Nordhaus and Tobin, 1973; NAS NRC, 1999). The present paper demonstrates that the third omission has large and measureable consequences for metrics critical to macroeconomic policy: volatility in per capita consumption and the natural interest rate.

To show that extending the NIPAs to include the environment has repercussions for macroeconomic policy, the paper introduces an adjusted measure of consumption grounded in the national accounting literature (Nordhaus and Tobin, 1973; Nordhaus, 2006; Abraham and Mackie, 2006; Muller, 2014). In accord with this literature, pollution damage is deducted from Gross Domestic Product (GDP) to measure net or environmentally adjusted value-added (EVA) since emissions are an unpriced residual from market production and consumption1. 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 focus lies at the intersection

<sup>&</sup>lt;sup>1</sup> 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 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.

of environmental and macroeconomic stabilization policies. The paper proposes a dual link. One connection occurs through the object of stabilization: consumption volatility. The other relation manifests through tools to achieve stabilization: interest rates.

With pollution damage deducted from market consumption, volatility in EVA depends not just on the variance of its parts but also on their co-movements<sup>2</sup>. Positive covariance between damage and market consumption dampens volatility in EVA since the covariance term enters the expression for the variance of a difference of random variables negatively. However, negatively covariant damages and output accentuate volatility. Importantly, the sign of the covariance between market consumption and pollution damage hinges on environmental policy. Absent aggressive environmental policy, this covariance is likely positive. Greenhouse gases and most major air pollutants are produced from the combustion of fossil fuels from power production, manufacturing processes, transportation, and agriculture. Hence, more economic output, absent abatement, translates to more emissions. Upon implementation of binding environmental controls, the covariance term may attenuate or become negative. Environmental policy affects volatility in consumption through the sign of the relationship between market output and damage.

Using the redefinition of potential income (inclusive of pollution damages) proposed above, pollution damages also affect interest rates. This connection is most clearly evident if one considers a definition of the natural interest rate. 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

<sup>&</sup>lt;sup>2</sup> Recall that the variance of a difference of two random variables is: Var(X - Y) = var(X) + var(Y) - 2cov(X,Y)

potential output..." The contention herein is that "potential" or "full potential" income is fundamentally mis-measured without consideration of environmental pollution damage3. The empirical analysis conducted in this paper demonstrates that environmental policy affects pollution damages and, thus, the level of potential output. This forges the connection between natural interest rates and environmental policy.

The connection between environmental quality and full potential income, a key driver of the natural interest rate, may seem oblique. To concretize this mechanism, consider that since the 1970's, empirical research reports an association between exposure to environmental air pollutants and premature mortality (Lave and Seskin, 1970; Dockery et al., 1993; Krewski et al., 2009; Lepeule et al., 2012)4. Further, a range of morbidity (illness) states are also amplified by exposures to environmental pollutants (USEPA, 1999; 2010). Thus, both the size (through mortality risk) and the productivity (through illness and absenteeism) of the labor force are plausibly affected by environmental exposures. Hence the link between pollution exposure, damage, and potential output.

The empirical section of the paper employs carbon dioxide (CO<sub>2</sub>) and air pollution damage estimates spanning from 1957 to 2016 in the U.S. economy. The air pollution series (developed in Muller, 2019b), reports estimates of premature mortality risk from exposure to fine particulate matter (PM<sub>2.5</sub>) on an annual, aggregate (across the U.S.) basis. The CO<sub>2</sub> series uses U.S. Department of Energy emission estimates along with the social cost of carbon to tabulate greenhouse gas damage (USDOE, 2011; 2019; USFWG, 2016). The 60-year time horizon in this study encompasses years before and after the passage and implementation of landmark federal

<sup>&</sup>lt;sup>3</sup> The position that mis-measurement of potential income will yield mischaracterization of the natural interest rate is also noted in Laubach and Williams (2015), though not due to environmental hazards.

<sup>&</sup>lt;sup>4</sup> In addition to the epidemiological literature, recent research in environmental economics reports significant causal impacts of exposure to PM<sub>2.5</sub> on adult mortality rates (Jha and Muller, 2018; Deryugina et al., 2019).

legislation to control air pollution. (The Clean Air Act was passed in 1970, and implemented in the years following.) The period also includes several recessions and, hence, considerable variation in macroeconomic conditions. The empirical setting provides an excellent opportunity to test how pollution-adjusted measures of consumption volatility and natural interest rates change relative to environmental policy and the business cycle.

### a. Preview of Results.

The conceptual modeling confirms the links between environmental pollution damages (and hence, environmental policy) and macroeconomic policy proposed above. The first result pertains to volatility in the augmented measure of per capita consumption. The conceptual model introduces uncertainty in both future market consumption and pollution damage. Doing so confirms that volatility in EVA is the sum of the variances of consumption of market goods and services and pollution damage *less* their covariance. The empirical analysis shows that the variance of EVA was less than GDP prior to passage of the Clean Air Act. During this pre-policy period, GDP and pollution damages were positively correlated. Following enactment of the Act, volatility in EVA exceeded that of GDP because of the significant negative covariance between GDP and damages. Thus, the sign of the covariance hinges on the stringency of pollution control. This critically affects the relative volatility of EVA and GDP.

The second result pertains to the calibration of the natural interest rate. When potential income reflects the deduction of pollution damage, the pollution-adjusted rate (hereafter, the green interest rate) depends on the intertemporal changes in pollution intensity. Economies on a cleaning-up path justify a higher rate. Societies growing more pollution intensive suggest a lower rate. 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 so that it occurs when less environmental pollution damage is deducted from market consumption enhances welfare. Higher rates induce savings and investment, encouraging more future consumption relative to that in the present. Conversely, if an economy is degrading its environment, expectations for future consumption prospects become dimmer; consumption in the future suffers a greater implicit tax stemming from higher losses due to pollution damage. Under such conditions, the interest rate should fall, reducing the incentive to save. Consuming more in the present attenuates the effective penalty from pollution damage.

The paper empirically compares the green interest rate to the federal funds rate. On average, the green interest rate exceeded the federal funds rate by 50 basis points. However, the green interest rate was less than the federal funds rate from 1957 to 1970. This occurred because pollution intensity and damages were on the rise, dampening future consumption prospects. The lower green rate encourages more near-term consumption at the expense of future consumption when the pollution penalty (the deduction of damage from potential income) was higher. Following 1970, the green interest rate exceeded the federal funds rate because combined CO<sub>2</sub> and air pollution damage fell over the 1970 to 2016 time period. Hence, a relatively higher interest rate induces less near-term consumption and slightly more in the future when pollution damage is lower.

In a simulation exercise, the analysis models intertemporal changes to consumption and savings that would occur if households faced the green interest rate. In total, the intertemporal reallocation of consumption induced by the green interest rate would have prevented between 7,000 and 25,000 premature deaths from PM<sub>2.5</sub> exposure. Importantly, the vast majority of these benefits would have occurred immediately following passage and prior to full enactment of the Clean Air Act. While these reductions are a small fraction of total damages, and of the emission

changes induced by the Clean Air Act, this new environmental-macroeconomic policy dimension could have provided an important stopgap prior to the full enactment of the Clean Air Act. The remainder of the paper is structured as follows. Section II introduces the conceptual model and works through the alternative definitions of consumption, interest rates, the intertemporal consumption path, and volatility in consumption. Section III presents the data and methods. Section IV covers results and V concludes.

#### II. Model.

This section of the paper begins by laying out the basic conceptual modeling set up and establishing the alternative definitions of consumption. Next it derives expressions for the interest rates using each measure of consumption and the resulting intertemporal consumption paths. Finally, the conceptual model introduces uncertainty in labor productivity and pollution intensity.

#### a. Basic Set-Up

Assume the 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  $(c_i)$  is consumption of market-produced goods in period (t), and the pure rate of time preference is given by  $(\rho)$ . More specifically, let  $U(C_t) = \frac{c_t^{1-\eta}-1}{1-\eta}$ , denote utility from consumption in period (t)s. As is well-known, the present value of lifetime utility is maximized when the marginal utility from consumption, again in present value terms, is equated across time periods and

<sup>&</sup>lt;sup>5</sup> The appendix explores a constant elasticity of substitution utility function defined over environmental quality and market goods.

consumers utilize their entire budget. And, with power utility, because consumers can borrow and lend at (r), the extant real interest rate, this condition is shown in (1):

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

Hence, the marginal rate of substitution is equated to (one plus) the interest rate, discounted.

Following Goodfriend (2004; 2016), let  $\binom{Y_1}{1+\mu_1+\gamma_1}$ ,  $\binom{Y_2}{1+\mu_2+\gamma_2}$  reflect potential income in periods (1) and (2), respectively. The  $(\mu_t)$  term in the denominator reflects distortions that attenuate potential income such a taxes, regulations and the like. The  $(\gamma_t)$  term represents expenditures on environmental quality (i.e. pollution control). Plugging  $\left(\frac{Y_2}{1+\mu_2+\gamma_2}\right)$  in to (1), for  $(c_2)$ , and

rearranging yields an expression for current consumption:  $c_1 = \left( \left( \frac{1+\rho}{1+r} \right) \left( \left( \frac{Y_2}{1+\mu_2+\gamma_2} \right) \right)^{\eta} \right)^{1/\eta}$ .

The same notation for period (1) potential output obtains:

$$\left(\frac{Y_1}{1+\mu_1+\gamma_1}\right) = \left(\left(\frac{1+\rho}{1+r}\right)\left(\left(\frac{Y_2}{1+\mu_2+\gamma_2}\right)\right)^{\eta}\right)^{1/\eta}$$
(2)

Thus, consumption across the two periods equals potential income. Ultimately, (2) is solved for (r), the interest rate that maximizes two-period consumption. The next subsection introduces pollution into potential income.

#### a. Alternative definitions of potential income.

In addition to the market-centric definition of potential income above, this paper includes both investments in environmental quality (pollution control) and damages from pollution. As above, in period (t),  $\gamma_t$  depicts the fraction of income allocated to pollution control; investments in

abatement of environmental pollutants such as CO<sub>2</sub> or particulate matter. Next, let  $\alpha_t$  denote the pollution intensity of output, say CO<sub>2</sub> damage per unit GDP, and  $\beta_t$  shows the responsiveness of environmental pollution damage to abatement investment  $\gamma_t$ .

Therefore, maximum potential income in period (1) is redefined as shown in (3):

$$c_{1}^{e} = \left( \left( \frac{1+\rho}{1+r} \right) \left( \frac{Y_{2} \left( 1 - (\alpha_{2} - \beta_{2} \gamma_{2}) \right)}{1+\mu_{2} + \gamma_{2}} \right)^{\eta} \right)^{1/\eta}$$
(3)

Here, the superscript (e) denotes "environmentally-adjusted" consumption. Note that abatement expenditure ( $\gamma_2$ ) reduced damage through ( $\beta_t$ ) and it deducts from potential income through the denominator of (3).

### b. Interest Rates.

The analysis next turns to interest rates. The thrust of this section is to characterize differences in interest rates with and without acknowledgement of non-market pollution damages. This section solves for the two-period consumption maximizing interest rate beginning with deterministic consumption measures. Section II.d introduces uncertainty in productivity and pollution intensity and the implications of this for volatility in consumption as defined in (3).

To begin, (2) is solved for (r). This yields the natural interest rate; that which equates consumption in each period to maximum potential output. For simplicity, we assume  $\eta = 1$ . This yields (4):

$$r_1 = \frac{Y_2}{Y_1} (1+\rho) \left(\frac{1+\mu_1+\gamma_1}{1+\mu_2+\gamma_2}\right) - 1 \tag{4}$$

Hence, the natural rate of interest is increasing in the growth of potential income (labor productivity) and in households' rate of time preference and it is attenuated by income-reducing distortions.

Substituting (3), the pollution-adjusted measure of consumption into (2) and solving for (r) yields (5):

$$r_g = \frac{Y_2}{Y_1} (1+\rho) \left(\frac{1+\mu_1+\gamma_1}{1+\mu_2+\gamma_2}\right) \left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right) - 1$$
(5)

Expression (5) is the green interest rate.

Of particular interest is the final term:  $\left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right)$ . This is the ratio of pollution intensity across the two periods. That is,  $Y_1(\alpha_1 - \beta_1\gamma_1)$  characterizes period (1) monetary pollution damage, and  $Y_1(1 - (\alpha_1 - \beta_1\gamma_1))$  depicts period (1) *net* potential income. Hence,  $(1 - (\alpha_1 - \beta_1\gamma_1))$  conveys the pollution intensity of the economy in period 1; higher values of  $(1 - (\alpha_1 - \beta_1\gamma_1))$  indicate lower pollution density of output, given abatement. Thus, the ratio  $\left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right)$  shows how environmental pollution damage intensity changes across the two time periods.

As is clear in (5), the direction of change in pollution damage is crucial to determining the green interest rate. An economy on a "cleaning-up" trajectory features  $\left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right) > 1.$ 

Conversely, an economy with rising pollution intensity suggests:  $\left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right) < 1$ . If

 $\left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right) > 1$ , the reduction in future damages boosts consumption prospects in the future, and the interest rate in (5) will be higher than (4). As demonstrated below, the higher green

interest rate (when pollution damages are falling) induces more savings, less consumption today, and more consumption in the future. More consumption occurs when the economy is "cleaner", or pollution intensity is lower.

However, when  $\left(\frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))}\right) < 1$ , pollution intensity is rising; this dampens the green interest rate because rising damage implies more limited consumption opportunities (lower potential income) in the future. A lower green interest rate due to rising damages draws consumption from the future into the present when the drag due to pollution damage is lower.

Expression (5) and the subsequent discussion forge the first link between environmental policy and macroeconomic policy in this paper. Specifically, the stringency of environmental policy clearly influences the net intensity of pollution damage. Intertemporal changes in net pollution intensity are transmitted through the green interest rate to affect intertemporal consumption decisions.

Mismeasurement of income potential, and by extension income growth, results in mischaracterization of the natural interest rate (Laubach and Williams, 2015). In the present context, mismeasurement occurs by omission of non-market pollution damage and changes in pollution intensity over time. Expression (6) shows the measurement error implicit in the natural interest rate due to omitting environmental pollution damage.

$$\Delta_r = r_g - r_1 = \frac{Y_2}{Y_1} (1+\rho) \left( \frac{1+\mu_1+\gamma_1}{1+\mu_2+\gamma_2} \right) \left( \frac{((\alpha_1 - \beta_1 \gamma_1) - (\alpha_2 - \beta_2 \gamma_2))}{(1-(\alpha_1 - \beta_1 \gamma_1))} \right)$$
(6)

The difference in rates is positive if pollution intensity is falling. Conversely,  $(r_1)$  exceeds the green interest rate if damages are rising. There is no mismeasurement if pollution intensity is static between the two time periods. Expression (6) also reveals that the difference in rates is

increasing in the degree to which the economy is polluted in period 1; the difference becomes arbitrarily large as  $(\alpha_1 - \beta_1 \gamma_1) \rightarrow 1$ . In this extreme case, the (environmental, or social) penalty to consumption in the present becomes infinitely large.

## c. The Consumption Path.

The model next considers how the interest rates  $(r_1)$  and  $(r_g)$  affect environmentally-adjusted consumption in the two period model. To accomplish this, the expressions for  $(c_1^e, c_2^e)$  are evaluated at  $(r_1)$  and  $(r_g)$ , for the case of log utility.

Deducting  $c_1^e(r_1)$  from  $c_1^e(r_g)$  yields (7):

$$\Delta_{c,1} = c_1(r_g) - c_1(r_1) = \frac{Y_1((\alpha_2 - \beta_2 \gamma_2) - (\alpha_1 - \beta_1 \gamma_1))}{(1 + \mu_2 + \gamma_2)}$$
(7)

This expression indicates that the difference in period (1) consumption, according to whether households face  $(r_l)$  or  $(r_g)$ , hinges on whether pollution intensity of output is rising or falling. In an economy with rising pollution intensity,  $\Delta_{c,1} > 0$ . Consumption tilts to the present if households face  $(r_g)$  rather than  $(r_l)$ . This should be intuitive. An economy growing more polluted levies a larger effective tax on consumption in the future. That is, a greater share of consumption is lost to pollution damage in the future period relative to the present. Interest rates should convey these expected conditions to consumers. This is precisely the signal that  $(r_g)$  presents, relative to  $(r_l)$ .

In the opposite case, in which pollution intensity is falling,  $\Delta_{c,1} < 0$ . Consumption tilts to the future if consumers face the green interest rate relative to  $(r_l)$ . This occurs because with less distortion from pollution in period (2), it is preferred for households to consume less in the present and more in the less-polluted context of period (2). The higher green interest rate presents consumers with this incentive. And, trivially, if pollution intensity is constant:  $\Delta_{c,1} = 0$ . Repeating this experiment for period (2), produces the following expression for the difference in consumption given  $(r_1)$  and  $(r_g)$ :

$$\Delta_{c,2} = c_2(r_g) - c_2(r_1) = \frac{Y_2((\alpha_1 - \beta_1 \gamma_1 + \gamma_1) - (\alpha_2 - \beta_2 \gamma_2 + \gamma_2))}{(1 + \mu_1 + \gamma_1)}$$
(8)

Expression (8) presents the mirror image of (7). With rising (falling) pollution intensity, consumption in period (2) subject to  $(r_g)$  falls short of (exceeds) that conditional on  $(r_1)$ . The intuition of this permutation of consumption in period (2) given  $(r_g)$  relative to  $(r_1)$  is presented above.

Of course, whether or not policymakers target the natural rates defined by  $(r_1)$  or  $(r_g)$  also has implications for the consumption growth rate. Specifically, evaluating  $c_1^e$  and  $c_2^e$  according to  $(r_1)$ or  $(r_g)$ , then computing the proportional growth rates in consumption produces (9) and (10).

$$G_{r_1}^e = \frac{Y_2(1 - (\alpha_1 - \beta_1 \gamma_1))(1 + \mu_1 + \gamma_1)}{Y_1(1 - (\alpha_2 - \beta_2 \gamma_2))(1 + \mu_2 + \gamma_2)} - 1$$
(9)

$$G_{r_g}^e = \frac{Y_2(1 - (\alpha_2 - \beta_2 \gamma_2))(1 + \mu_1 + \gamma_1)}{Y_1(1 - (\alpha_1 - \beta_1 \gamma_1))(1 + \mu_2 + \gamma_2)} - 1$$
(10)

In (9), which relies on the natural rate of interest absent environmental damage, growth of consumption is increasing (decreasing) if pollution damage intensity is rising (falling). This suboptimal consumption path stems from the mismeasurement of consumption in the expression for  $(r_1)$ . In contrast, (10) shows that the green interest rate induces a higher growth rate when pollution damage is falling. This comports with the logic laid out above.

The consumption path induced by  $(r_l)$  is demonstrably sub-optimal. The first-order condition for optimal inter-temporal consumption equates the marginal rate of substitution between consumption in periods (1) and (2) to  $\left(\frac{1+r}{1+\rho}\right)$ . Evaluating marginal utilities at  $(c_1^e, c_2^e)$ , which follow

from the green interest rate  $(r_g)$ , and computing the ratio yields:  $\frac{Y_2}{Y_1} \left( \frac{1+\mu_1+\gamma_1}{1+\mu_2+\gamma_2} \right) \left( \frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))} \right)$ , or  $\left( \frac{1+r_g}{1+\rho} \right)$ . Conversely, computing marginal utilities at the levels of consumption induced by  $(r_l)$ , and computing the ratio yields:  $\frac{Y_2}{Y_1} \left( \frac{1+\mu_1+\gamma_1}{1+\mu_2+\gamma_2} \right) \left( \frac{(1-(\alpha_1-\beta_1\gamma_1))}{(1-(\alpha_2-\beta_2\gamma_2))} \right) \neq \left( \frac{1+r_g}{1+\rho} \right)$ . The key difference lies in the last terms:  $\left( \frac{(1-(\alpha_2-\beta_2\gamma_2))}{(1-(\alpha_1-\beta_1\gamma_1))} \right)$  and  $\left( \frac{(1-(\alpha_1-\beta_1\gamma_1))}{(1-(\alpha_2-\beta_2\gamma_2))} \right)$ .

Figure 1 shows these different paths. The two linear downward sloping lines represent budget constraints. The outer constraint corresponds to apparent feasible consumption paths. The inner constraint deducts environmental pollution damage. Note the difference in slopes. The slope of the outer constraint is  $(\frac{1+r_1}{1+\rho})$ , whereas the slope of the inner constraint is:  $(\frac{1+r_g}{1+\rho})$ . In this configuration,  $Y_1(\alpha_1 - \beta_1\gamma_1) > Y_2(\alpha_2 - \beta_2\gamma_2)$ . Damages are falling. As demonstrated above, when damages fall from period 1 to period 2, the consumption path incentivized by  $(\frac{1+r_1}{1+\rho})$  features more consumption in period 1 and less in period 2 than the path induced by  $(\frac{1+r_g}{1+\rho})$ . This is shown on figure 1 by the point B, relative to the tangency condition at  $(c_1^e, c_2^e)$ . At point B, consumers equate their MRS to  $(\frac{1+r_1}{1+\rho})$ , inducing a suboptimal intertemporal consumption path.

Summarizing this subsection, interest rates based on measures of output that omit damage yield suboptimal consumption paths. The orientation of this sub-optimality hinges on whether pollution intensity is rising or falling. An economy on a cleaning-up trajectory will feature too much near term consumption if interest rates are defined without consideration of pollution. Conversely, in an economy becoming dirtier, too much savings occurs.

#### d. Uncertainty in Productivity, Pollution, and Consumption.

While uncertainty is likely to permeate each aspect of this model, the focus is on uncertainty in productivity growth and pollution intensity growth. (One motivation for not exploring uncertainty in abatement intensity is that environmental policy targets are often pre-specified, or codified, in extant policies.) In accord with the notation above, let expected productivity in period (t) =  $(Y_t)$ , and the expected pollution intensity in period (t) =  $(\alpha_t)$ . Time period (t) additive shocks to these two rates are given by  $(\varepsilon_{c,t})$  and  $(\varepsilon_{d,t})$ . In terms of the distribution of these shocks, it is assumed that  $E(\varepsilon_c) = 0$ , and  $E(\varepsilon_d) = 0$ ;  $E(\varepsilon_c^2) = \sigma_c^2$ ;  $E(\varepsilon_d^2) = \sigma_d^2$ ;  $E(\varepsilon_c \ \varepsilon_d \ ) = \rho_{c,d}$ . Thus, the period (t) realization of productivity is:  $Y_2 + \varepsilon_{c,t}$ ; and that for pollution intensity is;  $\alpha_2 + \varepsilon_{d,t}$ . In this setting, the period (2) equivalent of (2) and (3) with uncertainty is given by (11) and (12):

$$c_2^p = \left( \left( \frac{1+\rho}{1+r} \right) \left( \frac{(Y_2 + \varepsilon_c)}{1+\mu_2 + \gamma_2} \right) \right) \tag{11}$$

$$c_2^e = \left( \left( \frac{1+\rho}{1+r} \right) \left( \frac{\left( Y_2 + \varepsilon_c \right) \left( 1 - \left( \left( \alpha_2 + \varepsilon_d \right) - \beta_2 \gamma_2 \right) \right)}{1 + \mu_2 + \gamma_2} \right) \right)$$
(12)

From an ex ante perspective, the policymaker is not equipped with sufficient information to set the optimal rate (either  $(r_1)$  or  $(r_g)$ ) conditional on realized productivity and pollution shocks. The policymaker's second best choice is to regulate according to their expectations over productivity and pollution shocks. According to this tack, and because of the mean-zero property of the distribution of pollution and productivity shocks, the regulator employs the deterministic characterizations of  $(r_1)$  or  $(r_g)$  shown in (4) and (5).

A primary goal of macroeconomic policy is limiting volatility in consumption. A key reason for this policy objective is that excessive variability in economic conditions is costly (Lucas, 1981). The analysis first characterizes the variance in future consumption for both (11) and (12). In examining the variance in future consumption, (11) and (12) are evaluated at  $(r_1)$  and  $(r_g)$ , respectively.

Expression (13) presents the variance in consumption absent pollution damage.

$$var(c_2^p) = \sigma_p^2 = \frac{\sigma_c^2}{(1+\mu_2+\gamma_2)^2}$$
(13)

Straightforwardly, the variance in future market consumption depends on the variation in future productivity shocks.

The value of expression (13) is in comparison with (14) below, which depicts the variance in augmented consumption.

$$var(c_{2}^{e}) = \sigma_{e}^{2} = \frac{1}{(1+\mu_{2}+\gamma_{2})^{2}} \Big( \sigma_{c}^{2} \Big( 1 - (\alpha_{2} - \beta_{2}\gamma_{2}) \Big)^{2} + \sigma_{d}^{2} (Y_{2}^{2} + \varepsilon_{c}^{2}) - 2\rho_{c,d} \Big( 1 - (\alpha_{2} - \beta_{2}\gamma_{2}) \Big) \Big)$$
(14)

While this expression may seem cumbersome, it is quite intuitive, given how augmented consumption is defined. The form in (14) stems from the fact that augmented consumption is market consumption less pollution damage. Hence, it is the variance of a difference of random variables. This structure yields a well-known general form: the sum of variances less the covariance of the random variables.

<sup>6</sup> Specifically: Var(X - Y) = var(x) + var(y) - 2cov(X,Y).

The first term (inside the parenthesis) indicates that the variance in productivity shocks affects the variance in this measure of consumption through (one minus) the damage intensity of output. Hence, it is the variance in productivity shocks times the marginal productivity net of damage. The second term is the variance in pollution intensity shocks. This term is scaled by period (2) productivity. This means that the contribution of variance in pollution shocks to variance in consumption is increasing in productivity. Finally, the covariance between pollution and productivity affects the variance of augmented consumption through marginal productivity net of damage, akin to the productivity shock. Whether (14) exceeds or is less than variance in market consumption (13) critically depends on the sign and the magnitude of the covariance term. If damage and market consumption are negatively correlated, then (14) likely exceeds the variance in market output. If damage and market consumption are positively correlated, then the magnitude of (14) relative to (13) is ambiguous.

Of central importance to the covariance between pollution and productivity shocks is abatement. That is, absent efforts to reduce emissions, one might conjecture that abnormally productive periods would occur together with high pollution episodes. However, pollution controls limiting particularly high realizations of ( $\varepsilon_d$ ), or even inducing predominantly negative pollution shocks, may result in negative covariance. Thus, variance in augmented consumption relative to that of market consumption depends heavily on the presence and stringency of pollution control policy.

#### **III.** Data and Methods.

The empirical analysis conducted in this paper relies on several sources of data. These data are subdivided into two groups: macroeconomic data and environmental data. Section III.a focuses on the environmental data while III.b discusses sources and methods 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 (2019b). These data correspond to a combination of satellite observations and modeled data from 1980 – 2016 provided by Meng et al., (2019), see figure A.1 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 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.2).

Conversion of ambient PM<sub>2.5</sub> 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). The damages are limited to premature mortality risk from exposure to PM<sub>2.5</sub> 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 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), location (i), 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<sub>2.5</sub> exposure is computed as shown in (15).

$$Mort_{a,i,t} = Pop_{a,i,t} M_{a,i,t} \left( 1 - \frac{1}{exp(\theta P M_{i,t})} \right)$$
(15)

The ( $\theta$ ) term, which controls the marginal effect on mortality risk from PM<sub>2.5</sub> 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 Clean Air Act (USEPA, 1999; 2010) and by numerous academic researchers (Levy, Baxter, Schwartz, 2009; Muller and Mendelsohn, 2009; Fann et al., 2009; Muller, 2014; 2019a; 2019b). 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 ( $V_t$ ).

$$D_t = \sum_{i=1}^{I} \sum_{a=1}^{A} Mort_{a,i,t} V_t \tag{16}$$

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 0.4 income elasticity (Kleckner and Neumann, 1999). This series was used in Muller (2019a). Figure A.3 in the appendix shows how the VSL changes from 1957 to 2016.

Emissions of greenhouse gases (expressed as CO<sub>2</sub> equivalents) are provided by the U.S. Department of Energy (DOE, 2011; 2019). These are economy-wide emission estimates. Monetization of the CO<sub>2</sub> emissions employs the social cost of carbon (SCC) metric. This is the dollar-per-ton marginal damage of CO<sub>2</sub> 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 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.4.

#### 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). The fraction of output allocated to abatement of air pollution is calculated from the USEPA's most recent benefit cost analysis of the Clean Air Act (USEPA, 2010). Conversion from nominal to real values relies on the USBEA's GDP deflator.

What is the appropriate interest rate to serve as the basis for comparison of the green interest rate? The empirical analysis begins by using the federal funds rate (FRED, 2019b). Kaplan (2018) refers to the natural interest rate as the "theoretical federal funds rate at which the stance of Federal Reserve policy is neither accommodative nor restrictive." Goodfriend (2016) similarly links policy rates to the natural interest rate: "Interest rate policy is...about shadowing the natural

interest rate." (Goodfriend, 2016 p.4). Finally, Laubach and Williams (2015) aver that the natural interest rate is "the real short-term interest rate consistent with the economy operating at its full potential". Thus, the empirical calibrations of the green interest rate begin with short term, year-over-year changes in pollution intensity and comparisons are made to the federal funds rate.

The conceptual model characterizes net, potential income in period (1) as:  $Y_1(1 - (\alpha_1 - \beta_1 \gamma_1))$ . In order to compute this environmentally-adjusted measure, the gross external damage (GED) from air pollution and CO<sub>2</sub> are computed and deducted from real GDP, by year, from 1957 to 2016. At the national, or economy-wide, scale, this adjusted measure is referred to as environmentally-adjusted value added (EVA), (Muller, 2014; 2019a). All macroeconomic aggregates (GDP, GED, and EVA) are expressed in real, per capita terms.

In the appendix section I. is a detailed description of the methods used to provide an assessment of the effect that the green interest rate would have on consumption/savings decisions by households. Briefly, this hinges on consumption responses (and, subsequently, damages) to the change in interest rates if households faced the green interest rate. The simulation recursively tracks the change in consumption and damages from 1957 to 2016. In doing so, it also estimates EVA and EVA growth rates to assess the effect of the green interest rate on adjusted growth.

## IV. Results.

The results section begins with a brief description of summary statistics and stylized facts that are relevant to the analysis that follows. Figure 2 depicts the real GDP, EVA, and GED series from 1957 to 2016. Real, per capita GDP increased from just under \$20,000 in the late 1950s to nearly \$60,000 in 2016. By definition, EVA is always less than GDP, as GED is deducted from GDP to estimate EVA. Fluctuations and the business cycle are evident in both series. From 1957 to 1970, GED increased in concert with GDP. EVA grew less rapidly that GDP over this decade (Muller, 2019a). However, figure 2 makes clear that since real GED fell from roughly 1970 to 2016, the gap between EVA and GDP narrowed over this 50 year period. Thus, since 1970, EVA growth seemingly outpaced real, per capita GDP growth.

Table 1 concretizes the results in figure 2. Prior to 1970, air pollution and climate damage averaged just under \$7,000 per capita or about 1/3 of per capita income. This figure (also reported in Muller, 2019a) reveals a stunningly large external cost burden. Just 7 percent of this damage was due to CO<sub>2</sub> emissions. Table 1 and the left panel of figure 3 reveals that CO<sub>2</sub> damage climbed throughout the sample, while air pollution GED started to fall in the 1970's. The shares of GED from air pollution and CO<sub>2</sub> changed considerably between 1970 and 2016; in the final decade of the analysis CO<sub>2</sub> damage comprises 13 percent of GED.

Table 2 focuses on annual growth rates. Column (1) reports the 60-year average growth rates for GED, GDP, and EVA. Over the entire period, air pollution damage fell by one half of a percentage point per year. In contrast, damages from CO<sub>2</sub> increased by two percent, annually. Real, per capita GDP increased by just under two percent per year. Deducting the GED enhances growth, relative to GDP. Specifically, when GED (including both air pollution damages and CO<sub>2</sub>) is deducted from GDP, the EVA growth rate was 2.40 percent, or about half of a percentage point more rapid than GDP. Table 2 reports considerable heterogeneity in growth of GED, EVA, and GDP by decade7. The central result from the comparison of growth rates over time in the U.S. economy is that before 1970, EVA growth fell short of GDP growth, because GED was growing. Whereas, after 1970 which featured the passage of the Clean Air Act, EVA

<sup>7</sup> While Muller (2019a) reported air pollution GED and relative growth metrics for this time period, the present study includes CO<sub>2</sub>.

growth outpaced GDP growth because the air pollution GED fell rapidly (Muller, 2019a). More specifically, prior to 1970 air pollution GED grew rapidly at about 4 percent annually.  $CO_2$ damage was also growing quickly: 3.4 percent per annum. After 1970, air pollution GED contracted because the local air pollutants comprising GED were regulated by the Clean Air Act. The maximum rate of decline (2.9 percent) occurred during the 2000's. In contrast,  $CO_2$ continued to expand. This growth in  $CO_2$  GED occurred because this pollutant was largely unregulated throughout the entire sample period.

The difference between EVA and GDP growth, while persistently positive after 1970, narrowed considerably. During the 1970s, the growth gap averaged about 150 basis points. During the 1980s the spread was roughly 100 basis points. By 2016, the divergence was just 15 basis points. The growth rate of CO<sub>2</sub> and air pollution damage, along with real GDP are shown in the right panel of figure 3. This graph makes clear the influence of environmental policy on the relative growth rates of CO<sub>2</sub> and air pollution damage. From 1957 to 1970, GED from these two pollutants increased. Then, upon passage of the Clean Air Act in 1970, the growth rates of GED from air pollution turned negative. Growth in CO<sub>2</sub> damage was typically positive and closely aligned with GDP. And both air pollution and CO<sub>2</sub> damages are clearly sensitive to the business cycle.

#### a. Interest rates.

Table 3 reports two different sets of interest rates. As a benchmark for comparison, table 3 reports the federal funds rate (FRED, 2019b). Over the entire sample, the federal funds rate averaged about 5 percent. As is well known, the federal funds rate fluctuated over this 60-year period. In the 1960s, the federal funds rate averaged less than four percent. The federal funds rate

increased in the 1970s, and peaked in the 1980s, during which time it averaged about 10 percent. From the 1990s through 2016, the federal funds rate fell. Table 3 also reports the green interest rate calculated using the expression in (5). Table 3 reports that on average the green rate exceeded the federal funds rate by about 50 basis points. Hence, the green interest rate suggests less current consumption and more savings relative to what the federal funds rate would produce. Why is this the case? The reason is that pollution damage (air pollution and CO<sub>2</sub> combined) has fallen in real terms from 1957 to 2016 as shown in table 1 and table 2. Recall from section II. that an economy on a cleaning up trajectory justifies a higher green interest rate because falling damages imply greater (net) consumption prospects (potential income) in the future. Higher rates induce such behavior.

However, table 3 also shows that, prior to 1970, the green interest rate fell short of the federal funds rate by 70 basis points. This difference manifests because per capita GED increased during this time (see table 1 and table 2). Pollution was not regulated. With rising damage, future potential income, net of damage, is attenuated. Rising damages necessitate a lower green interest rate because lower rates tilt consumption to the present.

Following enactment of the Clean Air Act in the early 1970s, the green interest rate exceeded the federal funds rate. 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. Recall that the growth rate differential between EVA and GDP reported in table 2 diminished from about 140 basis points during the 1970s down to just 15 points after 2010. A key driver in *both* the convergence in growth rates and the interest rates is the attenuation of the rate at which damages were falling late in the sample.

Figure 4 plots the federal funds rate and the green interest rate series. The vertical line demarcates passage of the Clean Air Act. First, prior to the Act, the green interest rate was more frequently lower than the federal funds rate. However, upon passage and implementation of the Act, the green interest rate exceeded the federal funds rate. Hence, the figure reinforces the decadal averages reported in table 3.

#### b. Interest Rates and the Business Cycle.

Table 4 compares the interest rates at different stages of the business cycle. Column (1), as in table 3, simply reports the averages across all 60 years. Column (2), however, reports averages during NBER recession years. During contractions, the federal funds rate averaged 6.5 percent while the green interest rate averaged 7.4 percent for a difference of 0.73 (p < 0.05). During expansionary periods, the difference attenuated, falling down to 0.44 percent (p < 0.05). Table 5 also separately compares the rates during expansions and contractionary periods before and after 1970. The sensitivity of the difference between the green interest rate and the federal funds rate to the business cycle is considerably greater before 1970 and the passage of the Clean Air Act.

Table A3 in the appendix provides some insights into this pattern. 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. In contrast, after 1970, GED fell in both recession and non-recession periods. The rapid growth of GED during expansions prior to 1970 drives the green interest rate lower than the federal funds rate by 120 basis points. Thus, the difference between the green interest rate and the federal funds rate, prior to the onset of federal air pollution policy, hinges on the business cycle because the rate of change in damage fluctuates in a strong pro-cyclical manner.

Generally, that the green interest rate exceeds bond yields by a larger spread during recessionary periods than while the economy expands runs counter to the typical conceptualization of interest rate or stabilization policy. That is, conventionally, lowering rates stimulates consumption, mitigating short run recessionary effects. However, inclusion of environmental damages in the green interest rate tempers this standard policy prescription. As stated above, when the economy is growing dirtier (more pollution intensive), more consumption should occur in the present. The penalty from pollution damages is greater in the future. Hence, tilting consumption to the present mitigates the implicit tax from pollution damage. The intertemporal reallocation of consumption *toward* the low damage period increases total consumption and welfare. The appropriate policy position to stimulate more consumption in the present is to lower rates. The converse argument holds when an economy is cleaning up. Delaying consumption raises welfare because households consume more during the period when the penalty from pollution damage is lower. And, raising interest rates (increasing the return to saving) induces just such a delay.

The critical second piece to the argument for the countercyclical effect of pollution damage on interest rates is the following: table 4 and figures 2 and 3 provide clear evidence that pollution intensity falls during recessions. Thus, delaying consumption as the economy cleans up during recessions reduces gross pollution damage. Importantly, a standard measure of within-market consumption (without pollution) overlooks the non-pecuniary benefits from holding back consumption as the economy cleans up. The measure of consumption proposed herein captures this benefit and results in the countercyclical modification to standard interest rate policy.

Table A3 emphasizes an additional critical finding: absent comprehensive policy, pollution damage is pro-cyclical (more so than when binding policies are in place). Thus, the effect of the

green rate on damages (and comprehensive consumption) is especially important for unregulated pollutants.

## c. Changes in Damages from the Green Interest Rate.

Together with estimates of the elasticity of consumption with respect to changes in interest ratess, and the green interest rate reported in table 3, the intertemporal reallocation of consumption and damage induced by the green interest rate is calculated. The details of the calculation are shown in the appendix. The changes in consumption and damage are used to compute EVA conditional on consumers facing the green interest rate. The resulting impacts on EVA growth are reported in table 5. Across the entire 60-year period, the green interest rate induces a modest 8 basis point increase in growth rates. However, this small boost to growth masks considerable temporal variability. The largest change to growth. Because the GED was rapidly changing through the 1950s and 1960s (recall from table 2 that GED grew at nearly 4 percent, annually before 1970) the reallocation of consumption due to the green interest rate has a large effect on GED levels and the EVA. Following the 1970 passage of the Clean Air Act, GED comprise a much smaller share of GDP and the effect of reallocation due to the green rate is much smaller.

The total reduction in premature mortalities from air pollution exposure due to the green interest rate ranges between 7,000 and 25,000 as shown in figure A.6. The range of total avoided deaths stems from the two elasticities used. Early in the sample, deaths rise due to the consumption reallocation. This occurs because damages increased at an increasing rate. Total avoided deaths

<sup>8</sup> Two values (0.25 and 0.75) from Elmendorf (1996) are used.

turn negative in 1970. Mortalities from air pollution continue to fall until about 1980. Hence, the majority of these reductions occurs immediately following passage and prior to full implementation of the Clean Air Act. While these reductions are a small fraction of total deaths from pollution, and of the emission changes induced by the Clean Air Act, this new environmental-macroeconomic policy dimension could have provided an important stopgap prior to the Clean Air Act.

Importantly, the conceptual model considers two time periods which need not be consecutive or adjacent. That is, the green interest rate could be computed over longer maturities. Figure A.7 models the case in which the green interest rate is modeled over a five-year maturity. Thus, consumers face longer consumption-savings tradeoffs than in the two period maturities modeled in figure A.6. The effect of this longer maturity on avoided mortalities is considerable. Rather than a range between 7,000 and 25,000 avoided deaths, figure A.7 reveals that the five-year maturity avoids nearly 60,000 deaths (assuming the 0.25 elasticity). This larger reduction in PM<sub>2.5</sub> deaths occurs because the term that drives the difference between the federal funds rate and the green interest rate  $\left(\frac{((\alpha_1 - \beta_1 \gamma_1) - (\alpha_2 - \beta_2 \gamma_2))}{(1 - (\alpha_1 - \beta_1 \gamma_1))}\right)$ , is much greater over five-year periods.

## d. Variance in Market and Adjusted Consumption.

The top panel of table 6 reports the partial correlation coefficients between GDP and air pollution, CO<sub>2</sub>, and combined GED. The 60-year sample is divided into the years prior to the passage of the CAA, 1970 to 2000, and 2000 to 2016. Column (1) of the top panel indicates that both combined damage and air pollution damage are negatively correlated with GDP in levels (p < 0.01). In contrast, CO<sub>2</sub> damages are nearly perfectly, positively correlated with GDP (p < 0.01). Columns (2) and (3) highlight the importance of environmental policy. Before passage of the CAA, air pollution *and* CO<sub>2</sub> damage were positively correlated with GDP (p < 0.01).

However, after the CAA became law, air pollution damage became negatively associated with GDP (p < 0.01), while CO<sub>2</sub> remained positively correlated with GDP (p < 0.01). And, after the year 2000, the sign of the correlations between local air pollution, CO<sub>2</sub>, and GDP remained as they were after 1970 (p < 0.01).

The second panel of table 6 explores correlations in growth rates. Across the full sample, GDP growth was positively correlated with air pollution, and  $CO_2$  damage growth (p < 0.01). The key insight here is that the correlation between GDP growth and air pollution damage growth weakened after the passage of the CAA both in magnitude of the correlation coefficient and in statistical significance. In contrast, the correlation between  $CO_2$  damage growth and GDP growth strengthened.

Figure 3 provides an alternative, supporting perspective on these results. In both panels, CO<sub>2</sub> moves in lock step with GDP. The left panel shows that both GDP and CO<sub>2</sub> damage roughly triple between 1957 and 2016. The right panel displays the strong positive correlation between CO<sub>2</sub> growth and GDP growth. However, air pollution damage, while rising with GDP through 1970, then fell to 75 percent of its real value in 1957. The right panel of figure 3 shows consistently negative growth in air pollution damage after 1970, while GDP growth remained mostly positive. In both panels, drawing on a theme from section IV.b above, the importance of the business cycle is clear.

The bottom portion of table 6 reports the variances of EVA, GDP, and GED (combined CO<sub>2</sub> and air pollution). In general, EVA levels and growth were more variable than GDP levels and growth over the 1957 to 2016 period. However, the relative degrees of volatility changed before and after the passage of the CAA. EVA was less variable than GDP before 1970 (in both levels and growth). This stems from the strong positive correlation between GDP and GED before

1970. In striking contrast, EVA was more variable than GDP between 1970 and 2000. Again, the top panel of table 6 conveys strong negative correlations between GDP and GED levels from 1970 to 2000. In light of expression (14), the negative correlation boosts the variance of EVA. Similarly, the positive correlation between GED growth and GDP was substantially weaker after 1970 than before. Thus, all else equal, EVA volatility was enhanced by this effect as shown in the bottom panel, column (3).

These empirical calculations show that, in levels, pollution damage was positively correlated with GDP prior to the enactment of the Clean Air Act, and negatively correlated afterwards. Further, growth rates in pollution damage began strongly, positively correlated and became weakly correlated after 1970. The effect of these changes in the relationships between damage and GDP is a reorientation of the variance of EVA and GDP. Prior to the passage of the Clean Air Act, EVA is less volatile than GDP. However, following passage and enactment, EVA is more variable both in levels and growth rates.

# V. Conclusions.

This paper proposes a novel intersection between environmental policy and two aspects of macroeconomic policy: volatility in per capita consumption and interest rates. This intersection fundamentally stems from a redefinition of consumption to include pollution damage that rests on a firm footing established in the environmental accounting literature (Nordhaus and Tobin, 1973). The paper shows that the covariance between productivity and pollution is the critical determinant of whether pollution-adjusted consumption is more or less variable than market consumption. And, the sign of this covariance term depends on whether pollution is regulated because in an unregulated setting, the covariance term would almost assuredly be positive. Further, by extending consumption beyond just market-produced goods and services to include

pollution damage, the paper develops an expression for natural interest rates that depends on the trajectory of pollution intensity of output. Economies on a cleaning up path should feature somewhat higher interest rates (relative to conventionally-defined rates) because future consumption incurs a smaller pollution penalty. Thus, the higher green interest rate delays consumption to the less pollution intensive state. In contrast, economies becoming more polluted should feature lower interest rates. This incentivizes more current consumption in the less polluted economy.

The empirical portion of the paper shows that the green interest rate exceeds the federal funds rate by about 50 basis points. However, prior to the passage of the Clean Air Act in 1970, the green interest rate fell short of the federal funds rate because pollution damages were rising. Once, the Act was passed, enacted, and implemented, damages from air pollution fell. This caused the orientation between market rates and the green interest rate to switch, with the green rate exceeding the federal funds rate in the post-1970 context of falling damage.

The passage of the Act also induced a reversal of the relative magnitudes of volatility in GDP and adjusted consumption. Prior to the Clean Air Act, the variance in adjusted consumption was less than that of GDP because positively correlated productivity and pollution shocks dampened the variance in EVA. After 1970, negatively correlated shocks amplified consumption volatility. The empirical analysis highlights two sources of environmental damage: CO<sub>2</sub> and local air pollutants. Recent research suggests that damages from these pollutants amount to a considerable share of GDP (Muller, 2019a; 2019b). The present paper demonstrates that the regulatory status of the two types of pollution dictates the nature of correlation between damage and productivity shocks. Unregulated CO<sub>2</sub> is positively correlated with GDP. Local air pollutants were regulated beginning in 1970. Prior to this date damages from these substances covaried positively with

GDP. After 1970, the covariance became negative. This result has broad implications for future research that may seek to incorporate additional pollutants, or sources of environmental goods and services, into the extended measure of consumption used herein. Namely, unregulated externalities driven by procyclical emissions will dampen volatility in consumption. Residual damages from managed emissions will, in contrast, accentuate variability provided regulation is stringent enough to induce negatively correlated damages and output.

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Figure 1: Inter-temporal Consumption Choices with Green Interest Rate.





Figure 2: GDP, Pollution Damage, and EVA.

Vertical lines demarcate NBER recessions.

Solid = GDP; Dash = EVA; Dash-dot = GED.

EVA = GDP - GED



Figure 3: GDP, Air Pollution and CO<sub>2</sub> Damage.

Solid = Real GDP

 $Dash = Real CO_2 GED$ 

Dash-dot = Real air pollution GED

Vertical lines demarcate NBER recessions.

Figure 4: Federal Funds Rate and Green Interest Rates.



Left panel LOWESS smooth: Solid = Federal Funds Rate; Dash = Green Interest Rate. Right panel: Green Interest Rate – Federal Funds Rate.

# Tables.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Total sample	1960s	1970s	1980s	1990s	2000s	2010s
GDP	35456.87 <sup>A</sup>	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

Table 1: Output and Damage per Capita.

A = (\$2012)

Standard deviations in parenthesis.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Total sample	1960s	1970s	1980s	1990s	2000s	2010s
GDP	1.90 <sup>A</sup>	2.56	2.07	2.10	1.97	0.93	1.51
	(2.105)	(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)
Climata	1.09	2 26	2.02	1.25	1.02	0.49	1 26
Climate	1.98	3.30	3.03	1.23	1.92	0.48	1.30
	(2.829)	(1./10)	(3.293)	(3.364)	(1.236)	(3.111)	(3.011)
N	59	12	10	10	10	10	7

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

A = all values are average growth in (%)

Standard deviations in parenthesis.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Total sample	1957 –	1970s	1980s	1990s	2000s	2010s
		1970					
Federal Funds	5.04	3.83	7.10	9.97	5.15	2.96	0.16
	(3.558)	(1.730)	(2.428)	(3.152)	(1.403)	(2.012)	(0.106)
Green Rate	5.60	3.19	8.62	11.06	5.84	3.45	0.32
	(4.252)	(2.711)	(3.143)	(3.601)	(1.589)	(2.039)	(0.429)
Green Rate-	0.52***	-0.72	1.52**	1.10**	0.70***	0.50**	0.16
Federal Funds	(1.495)	(2.041)	(1.738)	(1.321)	(0.534)	(0.699)	(0.366)
Ν	60	13	10	10	10	10	7

Table 3: Comparison of Federal Funds Rate and Green Interest Rate.

 $\overline{\text{mean coefficients; sd in parentheses}}^* p < 0.05, ** p < 0.01, *** p < 0.001 \text{ for t-test of rate difference H}_0 = 0.$ 

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Total	Recession	Expansion	Recession	Expansion	Recession	Expansion
	sample			Pre-1970	Pre-1970	Post-1970	Post-1970
Federal	5.04	6.50	4.42	3.61	3.97	7.62	4.52
Funds	(3.558)	(4.493)	(2.917)	(2.665)	(1.007)	(4.626)	(3.209)
Green	5.60	7.44	4.85	4.00	2.75	8.49	5.35
Rate	(4.254)	(5.150)	(3.645)	(3.456)	(2.438)	(5.219)	(3.731)
Green	0.52***	0.73***	0.43**	0.27	-1.22*	0.88**	0.82***
Rate -	(1.495)	(1.651)	(1.439)	(1.262)	(2.242)	(1.773)	(0.830)
Fed.							
Funds							
N	60	18	42	5	8	13	34

Table 4: Comparison of Federal Funds Rate and Green Interest Rate Across the Business Cycle.

mean coefficients; sd in parentheses \* p < 0.05, \*\* p < 0.01, \*\*\* p < 0.001 for t-test of rate difference H<sub>0</sub> = 0.

	(1)	(2)	(3)	(4)
	Total sample	1960s	1970 - 2000	2000 - 2016
EVA	2.395 <sup>A</sup>	1.859	3.104	1.523
	$(2.372)^{\rm B}$	(2.395)	(2.582)	(1.548)
EVA Green	2.478	2.316	3.071	1.479
Rate	(2.778)	(2.970)	(3.063)	(1.736)
$(e = 0.25)^{C}$			· · · ·	
EVA Green	2.468	2.157	3.109	1.479
Rate	(2.355)	(2.060)	(2.603)	(1.685)
(e = 0.75)				
N	59	12	30	17

Table 5: Effects of the Green Interest Rate on Growth Rates.

A = average growth rates (%).

B = sd in parentheses.C = elasticity estimates from Elmendorf (1996).

	(1)	(2)	(3)	(4)
Correlation	Total sample	1960s	1970 - 2000	2000 - 2016
Levels				
Air + Climate	-0.586 <sup>***A</sup>	$0.990^{***}$	-0.936***	-0.696**
Air	-0.649***	$0.990^{***}$	-0.944***	-0.724**
Climate	$0.990^{***}$	0.994***	$0.980^{***}$	0.831***
Growth				
Air + Climate	0.583***	0.753**	0.516**	0.570*
Air	0.567***	0.753**	0.498**	0.544*
Climate	0.661***	0.593*	0.642***	0.784***
Variance				
Levels				
GDP	1.40 <sup>B</sup>	6.44	36.5	6.49
EVA	1.63	1.13	50.7	8.49
Air + Climate	2.15	2.28	1.29	2.47
Growth				
GDP	4.43 <sup>°</sup>	6.37	4.52	2.57
EVA	5.63	5.74	6.67	2.40
Air + Climate	25.66	32.99	12.77	30.16
N	59	12	30	17

Table 6. Variance and Correlations between per Capita GDP and Pollution Damage.

\* p < 0.05, \*\* p < 0.01, \*\*\* p < 0.001

A = pairwise Pearson's correlation coefficient between each listed variable and GDP growth.

B = (\$2012) millions.

C =growth rates (%).

## Appendix

The supplementary appendix contains three sections. It begins with a discussion of the methods and results from a set of calculations that demonstrate how intertemporal consumption and damages would change if the green interest rate faced households, rather than actual market rates are approximated by the 10-year Treasury bond. The second and third subsections include additional figures and tables that support the main text.

## I. Substitution between environmental damage and consumption.

An important issue in the context of the present paper is substitution between consumption of market goods and environmental quality, or damage. The simple, univariate power utility function employed in section II. of the main body of the paper is easily augmented to include environmental quality in a separable fashion. For example, Hoel and Sterner (2007) propose a utility function of the form:

$$U_{t}(c_{t},e_{t}) = \frac{1}{1-\eta} \left( (1-\theta)c_{t}^{1-\frac{1}{\sigma}} + (\theta)(c_{t}(\alpha_{t}-\beta_{t}\gamma_{t}))e_{t}^{1-\frac{1}{\sigma}} \right)^{\frac{(1-\eta)\sigma}{\sigma-1}}$$
a.1

where:  $\sigma$  = constant elasticity of substitution between environmental quality (et) and market goods (ct).

 $\theta$  = scaling parameter proportional to consumption shares of environmental quality (et) and market goods (ct).

One central question is whether, conditional on the form shown in (a.1), the first order condition with respect to consumption of market goods is affected. Recall from section II., that this first order condition plays a key role in the conceptual analysis which solves for the green interest rate.

To explore this, the marginal utility from market consumption is derived for t = 1 and t = 2. Here the assumption of log utility is maintained for simplicity. This assumption yields (a.2).

$$U_t(c_t, e_t) = \frac{\sigma}{\sigma - 1} ln \left( (1 - \theta) c_t^{1 - \frac{1}{\sigma}} + (\theta) \left( c_t(\alpha_t - \beta_t \gamma_t) \right) e_t^{1 - \frac{1}{\sigma}} \right)$$
(a.2)

Setting marginal utilities from consumption of market goods in periods 1 and 2 equal and rearranging yields (a.3) which is identical to (2).

$$\frac{c_2}{c_1} = \frac{1+r}{1+\rho}$$
 (a.3)

Thus, with power utility and with  $\eta = 1$ , the key form used to derive interest rates is unaffected by allowing arbitrary substitution between market goods and environmental quality in the representative consumer's utility function.

It is important to note that environmental quality does not enter into the utility function as employed into the main body of the paper. Rather, environmental pollution damage is, in effect, deducted from *potential income*. This treatment reflects guidance from the environmental accounting literature (Nordhaus, 2006; Abraham and Mackie, 2006). This tack does imply substitution between damage and consumption (through the adjustment of potential income). This assumption that damages are deducted from potential income manifests through the intercepts of the intertemporal budget constraint as shown in figure 1.

### **II.** Damage change from green interest rates.

In order to (empirically) estimate the effect that implementation of the green interest rate would have on consumption and damages the following approach is used. First, it is assumed that consumers face a series of two period consumption-savings decisions in accord with the structure of the theoretical model used in the main body of the paper. Thus, in period (t), households decide how much to consume and save. In period (t+k), households face a new interest rate and

they repeat this process. The resulting change in consumption is translated to damages using the empirically estimated damage intensity of output (GED/GDP) in periods (t) and (t+k). The sum of damages over each pair of periods is computed from 1957 to 2016. These damage estimates are then deducted from the observed GED, matched to each pair of years. These calculations are shown in (a.4).

$$\Delta GED_t = (\Delta r_{t-k} \,\varepsilon_s GED_t - \Delta r_t \,\varepsilon_s (GED_t + (\Delta r_{t-k} \,\varepsilon_s GED_t))$$
(a.4)

In (a.4),  $\varepsilon_s$  denotes consumers' elasticity of savings with respect to the interest rate, and ( $\Delta r$ ) is the difference between market and the green interest rate (expression 6). Estimates of  $\varepsilon_s$ , 0.25 and 0.75, are drawn from the literature (Elmendorf, 1996).

In addition to modeling year-over-year consumption/savings tradeoffs induced by the green interest rate, the empirical analysis explores longer maturities. The basic structure of the simulation is identical to that described above except that k = 5 in (a.4) rather than k = 1. Figure A.7 shows that the avoided deaths due to the longer term (five-year) green interest rate are much higher than under the one-year maturity. Specifically, a total of 60,000 avoided mortalities accrue if households faced the 5-year green interest rate as opposed to just under 8,000 with the one-year rate.

Supplementary Figures.



Figure A.1: Annual Average PM<sub>2.5</sub> Concentrations: Satellite-Monitor Comparison.

Squares = USEPA AQS Monitor Data, Circles = PM<sub>2.5</sub> Data from Meng et al., (2019).

Source: Muller (2019b).

Figure A.2: TSP and PM<sub>2.5</sub> National Average Concentrations.



 $Dash = PM_{2.5}$  (95% Confidence intervals on predicted values prior to 1980); Solid = TSP Vertical lines demarcate NBER recessions. Source: Muller (2019b).

Figure A.3: VSL under various assumptions.



Source: Muller (2019a).

Solid: default VSL used in the present analysis.

Dash: VSL-income elasticity = 0.4

Dash-dot: VSL-income elasticity = 1.0



Figure A.4: U.S. Economy CO<sub>2</sub> Emissions and Social Cost of Carbon Estimates.

Solid line = CO<sub>2</sub> emission estimates.

Squares = SCC.



Figure A.5: Real, Per Capita Air Pollution and CO<sub>2</sub> GED.

Solid = air pollution; Dash = CO<sub>2</sub>.



Figure A.6: Change in PM<sub>2.5</sub> Deaths due to Households Facing Green Interest Rate.

Solid = assumes elasticity of savings of 0.25.

Dash = assumes elasticity of savings of 0.75.



Figure A.7: Change in GED due to Households Facing Green Interest Rate with 5-Year Maturity.

Solid = one year maturity.

Dash = five year maturity.

# Supplementary Tables.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Total	1960s	1970s	1980s	1990s	2000s	2010s
	sample						
Abatement	1.0001 <sup>A</sup>	1.0000	1.0005	0.9998	0.9998	1.0002	1.0000
	(0.00071)	(0)	(0.0016)	(0.00028)	(0.00002)	(0.0002)	(0.0001)
Green	$0.0052^{B}$	-0.0074	0.0146	0.0107	0.0068	0.0050	0.0016
Coefficient	(0.0146)	(0.0203)	(0.0171)	(0.0132)	(0.00517)	(0.00684)	(0.00357)
GED/GDP	$0.2088^{D}$	0.3235	0.3194	0.2200	0.1465	0.1016	0.0803
	(0.101)	(0.0312)	(0.0384)	(0.0294)	(0.0169)	(0.0110)	(0.00476)
N	59	12	10	10	10	10	7

# Table A1: Summary Statistics by Decade.

All statistics in table A1 are year over year ratios.

A = fraction of GDP spent on abatement of air pollution (USEPA, 2011).

$$\mathbf{B} = \left(\frac{\left((\alpha_1 - \beta_1 \gamma_1) - (\alpha_2 - \beta_2 \gamma_2)\right)}{\left(1 - (\alpha_1 - \beta_1 \gamma_1)\right)}\right)$$

C = Hours of all persons worked in non-farm business sector (FRED, 2019).

	(1)	(2)	(3)	(4)	(5)
	Total sample	Recession	Not Recession	Energy Crisis	Great Recession
Abatement	1.0001 <sup>A</sup>	1.0004	0.9999	1.0027	1.0003
	(0.000711)	(0.00125)	(0.000199)	(0.00326)	(0.000130)
Green	$0.0052^{\rm B}$	0.0089	0.0036	0.0223	0.0049
Coefficient	(0.0140)	(0.0109)	(0.0134)	(0.00140)	(0.00719)
GED/GDP	0 2088 <sup>D</sup>	0 2420	0 1942	0 3303	0 0903
	(0.101)	(0.0967)	(0.0999)	(0.0106)	(0.00776)
N	59	18	41	2	3

Table A2: Summary Statistics and the Business Cycle.

All statistics in table A2 are year over year ratios.

A = fraction of GDP spent on abatement of air pollution (USEPA, 2011).

$$\mathbf{B} = \left(\frac{\left((\alpha_1 - \beta_1 \gamma_1) - (\alpha_2 - \beta_2 \gamma_2)\right)}{\left(1 - (\alpha_1 - \beta_1 \gamma_1)\right)}\right)$$

C = Hours of all persons worked in non-farm business sector (FRED, 2019).

 Table A3: Growth Rates and the Business Cycle.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Total	Recession	Expansion	Recession	Expansion	Recession	Expansion
	sample			Pre-1970	Pre-1970	Post-1970	Post-1970
GDP	1.90	-0.35	2.81	0.06	3.81	-0.47	2.57
	(2.105)	(2.134)	(1.249)	(2.732)	(1.209)	(2.034)	(1.153)
EVA	2.39	0.36	3.21	0.36	2.65	0.37	3.34
	(2.346)	(2.497)	(1.723)	(2.133)	(2.189)	(2.678)	(1.606)
GED	-0.55	-3.20	0.53	-0.49	6.10	-4.03	-0.79
	(5.338)	(5.742)	(4.832)	(5.266)	(5.153)	(5.815)	(3.751)
N	59	17	42	4	8	13	34