Draft
05/14/02

AAEA Annual Meeting
Long Beach, California
26-31 July 2002

Conservation Capital and Sustainable Economic Growth

JEL Code: O00, O41, Q2

Donna Theresa J. Ramirez (Presenter)
Graduate Student
University of Illinois at Urbana Champaign
405 Mumford Hall
1301 W. Gregory Drive MC-710
Urbana, IL 61801
Tel: 217-333-2657
Fax: 217-333-5538
Email: dtramire@uiuc.edu

Madhu Khanna
Associate Professor
University of Illinois at Urbana Champaign
431 Mumford Hall
1301 W. Gregory Drive MC-710
Urbana, IL 61801
Tel: 217-333-8089
Fax: 217-333-5538
Email: khanna1@uiuc.edu

David Zilberman
Professor
Department of Agricultural and Resource Economics
337 Giannini Hall
University of California
Berkeley, CA 94720
Tel: 510-642-6570
Fax: 510-643-8911
Email: zilber@are.berkeley.edu

Conservation Capital and Sustainable Economic Growth

This paper develops an endogenous growth model which links pollution to ineffective input-use, which can be reduced through conservation capital investment. It derives the conditions under which individual preferences for environmental quality and private investment in conservation capital can lead to non-decreasing environmental quality and balanced growth in an unregulated and in a regulated regime. In the absence of regulation, balanced growth can lead to improvement in environmental quality as long as the rate of growth is low. The extent to which the growth rate is low depends upon preference for environmental quality, interest and discount rates, productivity of conservation capital, and price of the polluting input. Under an emissions tax regime, sustainable balanced growth requires the interest rate to lie between the amenity value derived by consumers from environmental improvement and the marginal return to the firm due to the regenerative capacity of the environment. This implies that interest rate must be high enough to encourage consumers to forego consumption but low enough to constrain the productivity of conservation capital and restrain usage of the polluting input. The emissions tax is also shown to be equivalent to a pollution permit system or to a two-instrument scheme composed of a tax on polluting input and a subsidy on conservation capital investment.

Key Words: Balanced growth, conservation, environment, sustainable, effective input-use.

1. Introduction

The growing recognition of the value of preserving environmental assets because of their ability to provide critical support for human life, bio-diversity, non-use benefits and waste absorption services calls for regulations to protect the environment which in turn, provokes debates about its impact on economic growth. The conventional view maintains that environmental regulation impedes economic growth, while recent research argue that investment in specific efficiency-enhancing technologies can benefit both the firm and the environment, suggesting the consistency of economic and environmental objectives. This policy debate on the implications of environmental concerns and regulations for economic growth has made the objective of sustainable growth, defined as one that keeps the stock of natural environmental assets constant (Pearce et al., 1990), a controversial one. Does sustainable growth inevitably imply lower long run economic growth? Can stronger preferences for environmental quality and conservation-oriented technological innovation lead to improvements in environmental quality in the absence of environmental regulation? If not, can environmental regulation stimulate technological change and preserve environmental quality without adversely impacting long run economic growth?

This debate has motivated numerous studies that incorporate the economy-environment interaction in an endogenous growth framework. Like these existing literature, this study develops a model that recognizes the economy-environment link by incorporating various ways in which environmental quality and economic activity interact with each other and the linkages between environmental policy and the endogenously determined long-run rate of economic growth. The framework recognizes that the environment provides two types of benefits: first, it provides an amenity value which arises because environmental quality affects utility, and second, the stock of environmental quality determines its capacity to assimilate pollution and to regenerate itself. Economic activity also affects the environment in two ways: ineffective use of inputs increases pollution that degrades the environment, while investment in capital goods that augment input-productivity and lower the pollution intensity of inputs enables the prevention of environmental degradation associated with economic activity. We refer to this capital as *conservation capital* which plays a dual role in the production process. It is both *resource-conserving* (input-productivity enhancing) and *pollution-reducing* (input-waste reducing). Conservation capital is differentiated from other capital used for production, called *production capital*, which does not lower the pollution intensity of inputs[1] and serves as the key feature of the model that allows for the attainment of both economic and environmental goals.

However, the framework developed here differs from existing studies in several ways. First, in contrast to the common premise that pollution is a direct input to production[2], this study recognizes that the origins of pollution lie in the waste generated when inputs are not used effectively. The Law of Conservation of Mass[3] implies that inputs that are not embodied in the final output are wasted as residues that cause pollution. Technological changes in the last century have led to considerable increases in the productivity with which resources, such as fossil fuel energy, water and materials, are used and in our ability to recycle and reuse waste, leading to lower carbon intensity per unit of energy used and lower material intensity of production (see Ausubel, 1996; Khanna and Zilberman, 1997). For example, technological change has reduced the tin and aluminum requirements for manufacturing tinplate and cans and the silver content of film rolls and led to miniaturization of equipment. There are also several technologies for recycling and recovering inputs such as aluminum, mercury and sulfur for re-use as inputs in production. Proponents of environmental regulation stress that these regulations can stimulate technological innovation which increases the input productivity or the efficiency of resource use and can lead to higher rates of economic growth (Porter, 1990).

Second, we consider conservation capital to be rival and excludable, embodied in equipment or human skills and a private good (like production capital) acquired through investment by producers. The rival nature of conservation capital implies that acquisition of conservation capital is consistent with the assumption of perfectly competitive firms operating under constant returns to scale production technology and with real-world observations of private investment in such technologies (see Porter and van der Linde, 1995). The input-productivity enhancing effects of conservation capital imply that firms have incentives to undertake investment in it voluntarily (even in the absence of environmental policy), suggesting that to a limited extent, environmental-quality improving investment is privately determined, and not publicly provided by the government (as in Smulders 1995 and Bovenberg and Smulders 1995).

Third, the mechanism through which environmental regulations impact growth rates in this paper differs from that in Smulders (1995) and Bovenberg and Smulders (1995) which model the stock of environmental quality as an input in production. They find that while a reduction in pollution implies a reduction in input-use and thus in the productivity of capital and in the growth rate, it also improves the regenerative capacity of the environment and raises the stock of environmental quality which boosts productivity. The net impact of a policy to control pollution on growth in those papers can be positive if the impact of pollution reduction on environmental quality and regenerative capacity is large and positive. The model used in this paper, on the other hand, highlights the trade-off between the productivity and the crowding out effects that arises when environmental regulations are imposed. The trade-off arises when a chosen level of environmental quality requires more productive use of conservation capital which raises the productivity of both polluting inputs and production capital, but on the other hand, crowds out investment in production capital. Including the positive productivity effect of a higher stock of environmental quality on the production process would further enhance the potential for a positive impact of environmental regulations on growth in this paper.

Fourth, by allowing for endogenously determined allocation of savings between conservation capital and production capital and rate of economic growth, the framework enables us to examine how consumer preferences for consumption and the environment, and the impact on growth of policies operate to internalize environmental externalities. In investigating these consumer and firm choices, this paper provides the conditions under which private incentives from both consumers and firms are sufficient to prevent environmental degradation in the long run. In the absence of such incentives, environmental policy is needed to induce investment levels that can achieve sustainable balanced growth. We then examine the impact of the emissions tax on sustainable balanced growth rate. This comparison sheds light on the role of regulation and the design of environmental policy for achieving both environmental preservation and economic growth.

Our analysis demonstrates that an unregulated economy can achieve non-decreasing environmental quality together with balanced growth if there exists strong preferences for environmental quality, a low discount rate, a low interest rate, a high output elasticity of conservation capital and a high price of the variable polluting input. The first two conditions ensure that consumers are willing to forego present consumption, while the latter ensure that producers are willing to invest in environmental improvements. A high price of the variable input and high productivity of conservation capital provide private incentives to invest in conservation capital and together this can lead to a growing stock of environmental quality in the long run. The condition that the interest rate must be low also indicates that growth rate is low, suggesting that in an unregulated economy, achieving sustainable balanced growth involves sacrificing some economic growth objectives.

However, if these conditions are not met, then government intervention is needed to preserve environmental quality in a regulated economy that experiences balanced growth. In this case, we find that a low social rate of discount, and a high output elasticity of conservation capital can enable an economy to be on a balanced growth equilibrium in the long run, while simultaneously preserving the environment. These conditions ensure a strong productivity effect, and a weak crowding-out effect. In addition, the interest rate must be bounded not just from above but also from below to ensure willingness to forego consumption. The upper bound is meant to constrain the productivity effect of conservation capital on input use, and the magnitude is dictated by the social discount rate and natural rate of regeneration. The lower bound is intended to ensure sufficient savings and is influenced by the output elasticity of effective input and shadow value of environmental quality.

The paper proceeds as follows. Section 2 presents the technology and preference structure of the underlying model as well as a comparison of optimal decisions in a socially planned and an unregulated economy. Section 3 discusses the economic instruments that are consistent with sustainable balanced growth if an effluent tax is infeasible or if the conditions for sustainable balanced growth cannot be met in an unregulated economy. Section 4 investigates the conditions under which these economic instruments result in growth rates that are higher than in a deregulated setting. Section 5 concludes the paper.

2. Theoretical model

2.1. Production and preference structure in the economy

We consider an economy that produces a final output, Y, using a variable input, X, physical capital, K, and conservation capital, H. We abstract from the use of any labor input in production. The variable input X is assumed to represent endowed assets provided by households and converted to productive inputs by firms at a fixed per unit cost w. The effectiveness with which X is used in production (measured by the productivity coefficient of X, $a(H)$) depends upon the stock of conservation capital in the economy. Define $E=a(H)X$ as the "effective" variable input, with $a_H>0$ and $a_{HH}<0$. The production function is then specified as: $Y=F(a(H)X, K)$ where $F_X>0$, $F_K>0$ and $F_{XX}<0$, $F_{KK}<0$ (2.1)

As the stock of conservation capital increases, and the effective use of input X increases, input-waste per unit input is assumed to decrease. The pollution coefficient of the variable input (pollution generated per unit input), $g(H)$, is thus an inverse function of the stock of conservation capital. The flow of pollution, P, at any point of time is represented as: $P = g(H)X$ with $g_H<0$ and $g_{HH}>0$. (2.2)

The flow of pollution, accumulates over time and decreases the stock of environmental quality, N. Environmental quality is considered to be a renewable resource with a fixed rate of regeneration, R_N, at any instant. The net change in the stock of environmental quality is $\dot{N} = R_N N - g(H)X$ (2.3)

An investment, M, has to be undertaken over time to increase the stock of conservation capital and production capital. Hence, the rate of change of conservation capital is equal to M, $\dot{H} = M$ (2.4)

Investment in production capital $\dot{K}$ is obtained after deducting expenditures on consumption, the variable polluting input, and investment on conservation capital from total income, $\dot{K} = Y - C - wX - M$ (2.5)

Infinitely lived, identical individuals earn income from rental of both types of capital and derive utility from consumption goods, C, and environmental quality, N. A representative agent's time invariant utility function is indicated as: $U(C, N)$ with $U_c>0$, $U_{cc}<0$, $U_N>0$ and $U_{NN}<0$. (2.6)

Balanced growth is defined as a situation in which all economic variables grow at a constant rate of growth $g_J = \dot{J} / J = g$ for $J=C,H,K,M,X,Y$. This implies that the allocative variables $s_M=M/Y$, $s_C=C/Y$, and $s_X = wX/Y$ are constant. *Sustainable growth*, on the other hand, is defined as one where the level of environmental quality is maintained fixed at all points in time, implying $g_N=0$ and $\dot{g}_N = 0$. *Sustainable balanced growth* is, therefore, defined as one with: $g_N=0$, $\dot{g}_N = 0$ and $g_J = g \quad \forall J \neq N$.

2.2 The socially optimal solution

A social planner's optimization problem, with r as the rate of time preference can be represented as:

$$Max\, U = \int_0^{\infty} e^{-rt} U(C,N)\, dt \qquad (2.7)$$

subject to: i) $\dot{K} = Y - wX - M - C$, (ii) $\dot{H} = M$ (iii) $\dot{N} = R_N N - g(H)X$ (2.8)

This is expressed as a current value Hamiltonian using q_1, q_2 and q_3 as the multipliers for the three constraints. The first order conditions show that the optimal level of consumption at any point in time is determined such that the marginal utility of consumption is equated to its price, q_1, measured in terms of utility. At any point in time, output is allocated between consumption and investment in capital such that the marginal utility of consumption is equal to the marginal utility of investment, $q_2 = q_1 = U_c$ (2.9)

The optimal allocation of resources between consumption and investment is determined by condition (2.10), which is similar to the well-known Ramsey rule. The right-hand side, r, denotes the social rate of return on a unit of output invested in capital (in terms of consumption forgone). The Ramsey rule equates this to the cost of forgoing the consumption of that unit of output (on the left-hand side):

$$s\frac{\dot{C}}{C} - s_{cN}\frac{\dot{N}}{N} + r = \frac{e_K Y}{K} = r \tag{2.10}$$

where $e_K = F_K K/Y$ is the output elasticity of production capital, $s=(-U_{cc}C/U_c)$ is the inter-temporal elasticity of substitution of future for present consumption and $s_{cN} = (U_{cN}N/U_c)$ is the elasticity of marginal utility of consumption with respect to N which could be positive or negative. The first two terms on the left-hand side indicate the premium required over the rate of time preference, r, to induce individuals to forego a unit of consumption. This premium arises because as the rate of growth of consumption (first term on the left) increases, marginal utility falls and the value of future returns to savings decreases. Secondly changes in the stock of N affect marginal utility of consumption (second term on the left) and the costs of forgoing current consumption.

The socially optimal level of input-use is determined by equating the marginal product of X to its per unit social cost, which includes its market price, w, and its pollution costs. The latter depends upon its pollution coefficient, g, and the shadow price of environmental quality, $q_3=q_3/q_1$ relative to that of consumption goods. This is represented as

$$e_X - s_X = q_3 g X/Y \tag{2.11}$$

where $e_X = F_X aX/Y$ is the output elasticity of the variable input X. The shadow price of environmental quality, q_3, represents the pollution tax needed to achieve a socially optimal allocation of resources in a decentralized economy. The smaller the stock of conservation capital, the greater the pollution coefficient of X and the higher its social costs.

The optimal dynamic allocation of investment between K and H is determined such that the rate of return from both are equal to r:

$$r = e_K\frac{Y}{K} = e_E y\frac{Y}{H} + q_3 x g\frac{X}{H} \tag{2.12}$$

where $y = a_H H/a > 0$ is a measure of the conservation-effect of investment in conservation capital, e_E is the elasticity of output with respect to the effectively used input *E*, and $x = -g_H H/g > 0$ is a measure of the pollution-reducing-effect of that investment and $q_2 = q_2/q_1$. Since the price of conservation capital and production capital must be equal, the capital gains due to changes in the relative price of the two types of capital must also be equal. The net social return from investing in conservation capital arises from two sources. A marginal increase in the stock of conservation capital increases the productivity of *X* and increases the use of *X* at a given price *w*. It also reduces,*g*, the pollution coefficient of *X* and lowers the social costs of *X* (given by $q_3 g$) and this further increases the use of *X*. For both these reasons, investment in conservation capital increases the amount of effective *X* used at a given *w* and this increases the marginal productivity of *K*.

The desired level of environmental quality is chosen such that the marginal benefits from improving environmental quality normalized by its price plus the absorption capacity and rate of growth of its price, are equal to the rate of return on capital,

$$U_N / q_3 U_C + R_N + \frac{\dot{q}_3}{q_3} = r \qquad (2.13)$$

The marginal relative shadow value of environmental quality, q_3, measures the gains in utility to individuals from a marginal increase in *N*. This shadow value decreases as utility from environmental quality relative to utility from consumption goods decreases. Thus the optimal shadow value of environmental quality is:

$$q_3 = \frac{U_N}{U_C r} + \frac{R_N q_3}{r} \qquad (2.14)$$

such that the marginal cost of pollution reduction, q_3, is just equivalent to its marginal benefit (right hand side). In a regulated economy, q_3 represents the tax on pollution that achieves the socially optimal level of environmental quality. The first term on the right hand side represents the value to the individual of improved environmental quality measured by the elasticity of substitution between produced consumption and environmental quality, discounted by the time rate of preference. The second term represents the value of pollution reduction in terms of increased regenerative capacity of the environment, also discounted by the rate of time preference.

2.3 Feasibility of Sustainable Balanced Growth

We first examine the constraints for an unregulated economy, i.e., with $q_3=0$. Changes in the rates of growth of production and conservation capital can be specified as $\dot{g}_H / g_H = [g_M - g_H]$ (2.15)

and

$$\dot{g}_K / g_K = e_X g_X + y e_E g_H + (e_K - 1) g_K \tag{2.16}$$

Balanced growth requires $\dot{g}_H = \dot{g}_K = 0$ and that $g_X = g_H = g_K = g_M$, which implies that

$$e_X + e_H + e_K = 1 \text{ where } e_H = y e_E \tag{2.17}$$

Thus, as in most endogenous growth models, balanced growth is feasible if the production function displays constant returns to scale in X, H and K and the output elasticities e_X, e_H and e_K are constant over time. Balanced growth in the stocks of production and conservation capital and in the use of variable input X then leads to growth in output at the same rate. These restrictions on the production function also ensure that $r = e_K Y/K = e_H Y/H$ is constant under balanced growth.

Additionally, constancy of the balanced rate of growth of consumption, in (2.10), requires that the inter-temporal elasticity of substitution, s, the elasticity of marginal utility of consumption with respect to environmental quality, s_{cN}, and the rate of growth (decline) in the stock of environmental quality, g_N, be constant. These conditions on the production and preference functions ensure that a constant rate of growth in any endogenous variable, J ($\neq N$) is feasible and consistent with growth, at the same rate, in any other endogenous variable (other than N).

In addition to the restrictions above, we also want to derive the conditions that ensure sustainability which requires g_N to be constant and equal to zero such that $\frac{\dot{g}_N}{g_N} = \frac{\ddot{N}}{\dot{N}} - \frac{\dot{N}}{N} = 0$ (2.18)

implying that

$$g(H)X/N = R_N \tag{2.19}$$

Given the assumed pollution generation process, we can write (2.18) as

$$\frac{\dot{g}_N}{g_N} = (R_N - g_N)[1 - \frac{1}{g_N}(-x g_H + g_X)] \,. \tag{2.20}$$

On a balanced growth path, $g_H = g_X = g$ and $\frac{\dot{g}_N}{g_N} = (R_N - g_N)[\frac{g_N - g}{g_N}(1-x)]$. Thus, balanced growth in economic variables is by itself not technically sufficient to achieve $\dot{g}_N = 0$ For $\dot{g}_N = 0$ we require either $[g_N - g(1-x)] = 0$ or $g_N = R_N$. Since $g_N = R_N$ is not consistent with sustainability, $x = 1$ is needed to ensure that $\dot{g}_N = 0$ when $g_N = 0$.

We also need certain restrictions in preferences that would ensure that the growth rate implied by (2.10) and (2.11) is constant and equal to g. The socially optimal balanced growth requirement indicated in (2.11) as $q_3 = e_X Y/X - w/g$ and the restriction that $x = 1$, imply[4] that $\dot{q}_3 / q_3$ is constant and equal to g. We then solve for q_3 as in (2.14) and substituting for r from (2.10), we obtain:

$$q_3 = \frac{U_N}{[r - sg + s_{CN} g_N - R_N] U_C} \tag{2.21}$$

For this optimal level of q_3 to grow at the constant rate g, while being consistent with a constant N and with C growing at rate g, it is necessary that U_N/U_c increases at rate g when N is constant and that preferences be such that $U_N N/U_c C$ remain constant under balanced growth. As shown by Bovenberg and Smulders (1995) and King, Plosser and Rebelo (1988), this occurs if the elasticity of substitution between C and N is unity. This occurs because under balanced growth, with C growing and N becoming scarce, the price of C tends to fall relative to that of N creating a substitution effect towards C. But an elasticity of substitution of one between C and N ensures that the substitution towards C from N is exactly offset by the income-effect created by the increase in output under balanced growth, making $\dot{N} = 0$ consistent with balanced growth. We also assume $s_{CN} = 1$ so that balanced growth is feasible even in the absence of a non-constant g_N. These show that production and preference relations must satisfy specific restrictions to make balanced growth feasible and sustainable. The following discussion and the rest of the paper focus on the conditions that ensure the optimality of sustainable balanced growth.

In order to examine the relationship between environmental quality and balanced growth rate under social optimality (with $g_N = 0$), we choose production and preference relations that are consistent with balanced growth. We, therefore, make the following assumptions about the production and pollution functions: $a(H) = H^{(1-m)}$; $Y = (H^{(1-m)} X^m)^c K^{1-c}$; $g(H) = \frac{1}{H}$ (2.22)

These functions imply that an increase in the stock of conservation capital increases the productivity of input X and lowers its pollution coefficient and that there are constant returns to scale between effective input-use and production capital. Additionally, the specifications above allow us to assume a constant intertemporal elasticity of substitution between present and future consumption, s, an elasticity of substitution between N and C equal to one, and $s_{CN} = 1$. The utility function is

$$U(C,N) = ln\ C + f_N\ ln\ N \tag{2.23}$$

with f_N assumed constant and representing the weight attached to environmental quality. Assumptions (2.22) and (2.23) imply that:

$$e_K = (1-c); e_X = mc; y = (1-m); e_E = c;\ x = 1; s = 1; \frac{U_N N}{U_c C} = f_N; s_{cN} = 0 \tag{2.24}$$

which satisfy the conditions derived above. We now derive the socially optimal choices using the specifications assumed here and compare them to those made in an unregulated economy. We derive conditions under which private optimizing behavior can lead to balanced growth without degrading environmental quality even in the absence of regulation. In the absence of these conditions, we examine the environmental regulations needed to ensure sustainable balanced growth and analyze the effects of sustaining a higher level of environmental quality on the balanced growth rate.

2.3.1. Social Planner's Problem

The socially optimal choices can be obtained by replacing the elasticities and parameters in (2.10) to (2.12) by the notation assumed in (2.24) and with $P=X/H$ we obtain the following derivations from the first order conditions in the steady state:

$r = r + g$ (2.25) $s_X = mc - t$ (2.26) $r = (1-c)\frac{Y}{K}$ (2.27)

$r = [(1-m)c + t]\frac{Y}{H}$ (2.28) $r = \frac{f_N C}{N q_3} + R_N + g$ (2.29)

where $t = q_3 P/Y$ is the share of pollution tax revenues to total output in a regulated economy, $s_c = C/Y$ is the share of consumption in total output, $s_M = M/Y$ is the share of total conservation capital investment to total output, and $s_X = wX/Y$ is the share of expenditures on the variable input X in total output. These conditions imply that the rate of interest must be such that it is equivalent to the social discount rate plus the growth rate (2.25), and that it is equivalent to the marginal benefit from investing in production capital (2.27) and conservation capital (2.28). Further, the rate of return, r also governs the optimal choice of environmental quality (2.29) such that it is equivalent to the elasticity of the marginal utility of consumption with respect to environmental quality plus the rate of regeneration and the economic growth rate. The pollution tax plays a dual role in this model. It penalizes the use of the pollution-generating input X and raises the social cost of using X (2.26). It also enhances the social marginal benefit of investing in H due to its pollution-reducing effect and thus induces greater investment in H than would occur in the absence of the tax (2.28).

The expressions for the socially optimal shares of X, C and M can also be derived from the first-order conditions (2.25 to 2.29). The share of investment in H to total output is denoted as s_M and is derived from (2.28) by multiplying the right hand-side by M/M and solving for s_M using (2.25).

$$s_M = \frac{r - r}{r}\left((1-m)c + t\right) \qquad (2.30a)$$

We see that the output share of foregone consumption falls with the rate of time preference and increases with the marginal productivity of conservation capital, $(1-m)c$. These imply that as consumers are willing to forego present for future consumption, and as conservation capital becomes very productive, the output share of investment in H increases.

The share of X to total output, s_X, is directly obtained from (2.26) as $s_X = mc - t$. (2.30b)

The output share of variable input is thus shown to increase with mc and fall with t. As the incentive to invest in the polluting input is increased, more of the polluting variable input will be used, while as the pollution tax increases, the share of the variable polluting input naturally falls.

The share of consumption to output, s_C, is a function of s_X and is derived by first solving for q_3 using (2.26): $q_3 = (mc - s_X)\frac{Y}{P}$ and equating it to q_3 derived from (A.6). We then solve for *C/Y*:

$$s_C = \frac{t(r - R_N)}{f_N R_N} \qquad (2.30c)$$

which falls with the weight attached to environmental quality, f_N, and increases with r. As the consumer becomes more environmentally conscious, he would be willing to give up consumption in favor of savings to make it possible to have sufficient funds available for producers to invest in conservation capital which has a pollution-reducing effect. A high discount rate also increases the output share of consumption as consumers become less willing to give up present consumption for future consumption.

3.4.1. An Unregulated Economy

We now consider an unregulated economy that is achieving balanced growth in the steady state and investigate the conditions under which environmental quality increases even in the absence of government regulation. Consumers derive benefits from consumption and from environmental quality. However, in the absence of environmental regulations, consumers are unable to create incentives for producers to incorporate the negative externalities caused by *X* and the positive externalities caused by investment in *H*. This implies $t=0$ in equations (2.26) and (2.28).

The consumption share is obtained by dividing the first order condition for *C* by the first order condition for *N* in the consumer utility maximizing problem[5] $s_C = \frac{C}{Y} = \frac{(r - R_N)q_3}{f_N}\frac{N}{Y}$ (2.31)

The first order conditions for optimal levels of production capital, conservation capital, polluting input and foregone consumption from the producer's profit-maximizing problem[6], imply that:

$$r = (1-c)\frac{Y}{K} \qquad (2.32) \qquad\qquad s_X = mc \qquad (2.33)$$

$$s_M = (1-m)\frac{cg}{r} \qquad (2.34) \qquad\qquad 1 = q_2 \qquad (2.35)$$

indicating that the choice of the level for each is such that its private marginal benefit is equivalent to its private marginal cost. Note that in an unregulated economy, producers are neither forced to internalize the negative externality from their usage of *X*, nor compensated for the additional benefit arising from investment in H. This is evident in the expressions for the output share of the polluting input (2.33) and for the output share of investment in H (2.34), which do not include t as an argument (compare with (2.30a and 2.30b).

These results together imply that that if the weight attached to environmental quality is high and the discount rate is low then s_C will be low and consumers will be more willing to save. Additionally, as the value of environmental quality q_3, falls, s_C will fall and consumers will be willing to increase savings. This will enable more of the output produced to be available for investment and lower the shadow price of savings, q_2. A reduction in q_2 will increase the stock of H as well as the investment in production capital K while expenditures on X are unaffected since they are determined simply by its output elasticity and by the price of X. Through this mechanism, we can infer that even without government intervention, consumer preference for environmental quality can influence the investment in K and H by influencing the availability of savings and cost of investment.

The growth rate of environmental quality (from 2.31-2.34) in this unregulated economy is as follows:

$$\frac{\dot{N}}{N} = R_N - \frac{s_X}{s_M}\frac{(r-r)}{w}\frac{q_3(r-R_N)}{f_N} \tag{2.36}$$

which can be either positive or negative. As s_X falls and as s_M, f_N, and w increase, the growth rate of environmental quality is likely to increase because low s_X and high w imply low levels of pollution, and high f_N and high s_M imply high levels of H which has pollution-reducing effect. Substituting for s_M and s_X, we can show that for the growth rate of environmental quality to be non-decreasing in an unregulated economy we require:

$$r \leq \frac{f_N w(1-m)R_N}{m(r-R_N)q_3} \tag{2.37}$$

i.e, the growth rate of environmental quality can be positive even in an unregulated regime if the interest rate, hence, the growth rate $g=r-r$ is low enough. This implies that in the absence of regulation, environmental preservation can only be achieved if the cost of investment is low enough to stimulate investment in conservation capital, H and to some extent, input use. This suggests that for environmental quality to improve in an unregulated economy growth is sacrificed in exchange for environmental quality improvement. The extent to which the interest rate is low depends on m, r, f_N, and w. It is more likely to be low if w, and the weight attached to environmental quality in consumer preferences, f_N, are high and if m, and r are low. A low m and high w both discourage use of input X, increasing the likelihood that pollution is low and that environmental quality is increasing. A low social discount rate and a high f_N reinforce pollution reduction by increasing savings and funds available for investment in conservation capital. Thus, in an unregulated economy, if we incorporate the potential for investment in conservation capital to increase input productivity and lower pollution, and if we recognize that both the firm and consumer incentives to invest and save, respectively, we find that concerns about improving environmental quality need not be a constraint on producer behavior.

The analysis above also shows that if the conditions in equation (2.37) are not met and N falls in the steady state such that the inequality in (2.37) is reversed, then in order for an economy at the balanced growth path to avoid environmental degradation and achieve the optimal level of $N=N^*$ implied by equation (2.29), the regulator needs environmental policy instruments discussed in the next section.

3. Economic Instruments to Achieve Sustainable Balanced Growth

Regulatory instruments are necessary to achieve balanced growth as described in the social planner's model if the conditions in section 3.3.2 are not achieved or if the pollution tax, t, in section 3.3.1 is infeasible. The pollution tax in the social planner's model achieves socially optimal levels of variable input and conservation capital by simultaneously discouraging input use and stimulating investment in H. It represents the shadow value of improving environmental quality q_3, or conversely, the marginal cost of reducing N by one unit.

One alternative to the pollution tax is a pollution permit system where each firm is charged a price p per unit of pollution, X/H. Each firm is given an initial permit allocation, and its pollution level is determined by how many permits it has and how many it can purchase at price p at its profit maximizing levels of X, H, and K. It can easily be shown that the optimal level of p is equivalent to q_3, the shadow value of environmental quality, and that this pollution permit system is equivalent to a pollution tax[7]. The permit price must also grow at rate g at steady state. The difference between the pollution tax and the pollution permit lies in the revenues earned by the government. The pollution tax confers a benefit to the government equivalent to tY, while pay-offs under the tradable permit system occurs only between firms, outside of any government intervention.

Another alternative is a two-policy instrument scheme composed of a per-unit input tax and a per-unit subsidy on conservation capital investment. In choosing the optimal level of variable polluting input in (3.26), we need to impose a per unit input tax to replace the emission tax which must be equivalent to

$$t_x = q_3 \frac{P}{X} = t \frac{Y}{X} \tag{3.1}$$

so that the private decisions to use X will now incorporate its pollution-generating effect and the firm does not only equate the private marginal benefits to the private marginal costs of using X, but instead equates it with the private *plus* social marginal cost in the form of environmental damage associated with the usage of the polluting input. In addition, we also need to replace the emission tax in (3.28) by a per unit investment subsidy to induce investment in conservation capital and this must be equivalent to:

$$s_H = q_3 \frac{P}{H} = t \frac{Y}{H} \tag{3.2}$$

so that the decision to invest in H will incorporate its pollution-reducing effect. Hence, utilization of X can be controlled through the tax, while investment in conservation capital is encouraged by the subsidy to achieve both economic growth and environmental preservation. These subsidy and tax rates also ensure a balanced budget because total tax revenues will be equal to total subsidy payments:

$$t_X X = s_H H = tY \tag{3.3}$$

Thus, this two-instrument scheme also confers a zero net benefit to the government, similar to the pollution permit scheme.

To verify whether government regulation can improve environmental quality while achieving a higher level sustainable balanced growth, we want to describe the factors that influence the levels of the tax rate and subsidy rate and compare them with the conditions to be derived in section 4. Thus, we need to express the instruments as functions of the various parameters of the model. For the case of the tax, we use expression (3.1) and substitute for q_3, and s_M in (3.31) and (3.34)[8]:

$$t_X = \frac{q_3 r s_C}{(1-m)c} \qquad (3.4)$$

While for the subsidy rate, we also use expression (3.2) after substituting in the expression for q_3, s_C , s_X and s_M in (3.31), (3.33) and (3.34):

$$s_H = \frac{s_C q_3}{w}\frac{m r^2}{(1-m)^2 c} \qquad (3.5)$$

A summary of the impact of each parameter on the tax rate and subsidy rate are found in Table 1. To determine the conditions under which the increasing target level of environmental quality is consistent with economic growth given minimal government intervention, we want to investigate the conditions under which both the tax and subsidy rates are low.

Table 1. Impact of Parameters on the Input Tax and Investment Subsidy.

Parameter	t_X	s_H
m	$\frac{q_3 r s_C}{(1-m)^2 c} > 0$	$\frac{s_C q_3 r^2}{w(1-m)^2 c}\left[1+\frac{2m}{1-m}\right] > 0$
c	$-\frac{q_3 r s_C}{(1-m)c^2} < 0$	$-\frac{s_C q_3 r^2}{w(1-m)c^2} < 0$
W	$-\frac{q_3 r s_C}{(1-m)(1-c)} < 0$	$\frac{s_C q_3 m r^2}{w(1-m)^2 c}\left[\frac{2m}{1-c}-\frac{1}{c}\right] < 0$
r	$\frac{r s_C}{(1-m)c}\left[\frac{1}{r-R_N}-q_3\right] >< 0$	$\frac{m r^2 s_C}{w(1-m) c}\left[\frac{1}{r-R_N}-q_3\right] >< 0$

The per-unit subsidy on conservation capital investment and the per unit input tax fall with w and c. A high cost of the variable polluting input reduces the firm's usage of X, implying less H is needed for pollution-reduction purposes, hence, the need for a lower subsidy rate for H and lower tax rate on X. A high c, on the other hand implies high productivity of effective input which creates a natural stimulus for firms to invest in H, implying a low subsidy rate. The negative impact of c on the tax rate is a result of the high investment level in H that also functions like a tax in reducing pollution via its pollution-reducing effect. On the other hand, if X is very productive, i.e., m is high, the subsidy rate needs to be high to induce H investment and reduce pollution generated by the productive input X. Thus, the tax rate also needs to be high if *m* is high to counter the incentive of firms to use *X*. Additionally, the social discount rate increases the input tax rate and the subsidy rate if the elasticity of substitution between produced consumption and environmental quality is low[9]. A low elasticity of substitution implies that consumer preferences are such that environmental quality cannot easily be substituted for consumption, suggesting low levels of foregone consumption, low level of conservation capital, *H*, and lower incentive to use *X*. In such cases, a high tax rate and a high subsidy rate are required. Otherwise, low levels of regulation are necessary.

The preceding discussion illustrates how different values of the parameters influence the optimal choice of the tax and subsidy rates that will achieve sustainable balanced growth. The discussion above describes that with a low *m*, a low *r*, and a high *w* and *c*, we would require lower tax and subsidy rates. If these conditions are satisfied, joint attainment of environmental preservation and economic growth does not necessarily require a strong regulatory regime. It is also worth noting that the optimal levels of *H*, *X*, *K*, *M* and *C* that characterize sustainable balanced growth can be achieved using several different policy instruments. The different revenue implications however, could determine the likelihood of one being imposed over another, depending on the revenue objectives of the regulator.

4. Impact of Environmental Policy of Sustainable Growth

After having investigated the conditions under which sustainable balanced growth is attained under both an unregulated and a regulated economy, it is necessary to examine whether it is possible for government intervention to lead to a higher rate of economic growth than would have been possible under a decentralized regime. The Ramsey rule specifies growth to increase directly with *r*, $g=r-r$ and thus, implies that one way to examine the impact of environmental policy, say *t*, on the growth rate, *g*, is to examine its impact on the interest rate (Smulders 1995b, Bovenberg and Smulders 1995). We can express

r from (3.27) as
$$r = (1-c)\frac{Y}{K} \tag{4.1}$$

where the output-capital ratio takes the form (B.1):
$$\frac{Y}{K} = (P)^{\frac{mc}{1-c}}\left(\frac{s_M}{g}\right)^{\frac{c}{1-c}} \tag{4.2}$$

so that the interest rate is a function of pollution and of the share of foregone consumption. We can also alternatively express the interest rate by combining (4.1) and (4.2):

$$r = (1-c)\left[\left(\frac{s_X}{s_M}\frac{g}{w}\right)^{\frac{mc}{1-c}} \left(\frac{s_M}{g}\right)^{\frac{c}{1-c}} \right] \tag{4.3}$$

By taking the total differential of (4.3) with respect to the tax rate, we find that the impact of the tax on interest rate is composed of the negative impact on pollution (see B.3) and positive impact on the share of investment in conservation capital (B.4):

$$\frac{dr}{dt} = r\left[\underbrace{\frac{mc}{(1-c)P}\frac{\partial P}{\partial t}}_{Pollution-reducing-effect} + \underbrace{\frac{c}{(1-c)}\frac{g}{s_M}\frac{\partial s_M}{\partial t}}_{Conservation-effect} \right] \gtrless 0 \tag{4.4}$$

The pollution tax has two impacts: it reduces pollution by reducing the share of the variable input and increases the share of investment in conservation capital. A negative impact of the tax on interest rate arises if pollution reduction due to the tax is higher than the increase in the share of foregone consumption. Reduction in pollution involves a fall in the usage of the variable polluting input, given a fixed level of H, causing a reduction in output. An increase in tax also stimulates investment in conservation capital to offset the reduction in X usage, requiring higher M, hence causing an increase in the share of conservation capital investment. This inducement to invest in H is greater than the reduction in X usage in response to a tax if (from B.9):

$$r < \frac{(1-m)}{m} w R_N N \tag{4.5}$$

That is, if r is low such that the cost if investing in conservation capital is low, and m is low, such that the output elasticity of effective input ($c(1\text{-}m)$), of which H and X are components, is high, then firms would respond to environmental policy by investing high levels of H to counter the adverse productivity impact of a reduction in X. Otherwise, if there are no incentives to increase H investment, and the adverse effect on input use is stronger than the increase in H, interest rate, hence g, falls with environmental policy.

However, investigating the positive impact of the share of input and share of investment in conservation capital on r constitutes only part of the effect of the tax on growth rate. Both only capture the productivity impacts of the changes in the interest rate brought about by changes in the demand for conservation capital investment as a result of changes in the shares of X and M. They do not capture the impacts on consumption share nor the level of investment in production capital, both of which have impacts on growth other than through the interest rate. They also do not capture the potential crowding-out effect that might occur as a result from conservation capital investment. Hence, we need to use the expression for growth rate derived from the goods market equilibrium to analyze the effect of regulation on sustainable balanced growth rate.

The goods market equilibrium condition implies that the growth rate is composed of the impact on Y/K and on effects on the output shares of X, M and C.

$$g = \frac{\dot{K}}{K} = [1 - \frac{C}{Y} - \frac{M}{Y} - \frac{wX}{Y}]\frac{Y}{K} = [1 - s_c - s_M - s_x]\frac{Y}{K} \qquad (4.6)$$

where s_X, s_M and s_C are as defined in section 3.4.1 and Y/K is as defined in (4.2). To examine the impact of the choice of stock of environmental quality on the growth rate, we differentiate (4.6) with respect to t and examine the conditions under which it increases with environmental quality by examining how each component of (4.6) responds to an increase in t. The total impact of a more stringent environmental policy on growth is thus expressed as a function of several components:

$$\frac{\partial g}{\partial t} = \{1 - s_X - s_M - s_C\} \underbrace{\frac{\partial \frac{Y}{K}}{\partial t}}_{\text{Productivity-effect}} - \frac{Y}{K}\left\{ \underbrace{\left(\frac{\partial s_C}{\partial t}\right)}_{\text{Consumption-effect}} + \underbrace{\left(\frac{\partial s_X}{\partial t}\right)}_{\text{Input-effect}} + \underbrace{\left(\frac{\partial s_M}{\partial t}\right)}_{\text{Foregone consumption-effect}} \right\} \qquad (4.7)$$

which consists of the productivity effect, the consumption effect, the input use effect and the conservation effect. The productivity effect in (4.7) is captured by the two effects illustrated in (4.4) because Y/K is a function of r. It consists of the increase in the share of investment in conservation capital, net of the negative productivity impact of the reduction in X usage. We find that the net productivity effect is always positive (from B.10):

$$\frac{\partial \frac{Y}{K}}{\partial t} = \frac{Y}{K}\frac{1}{(1-c)}\left[-\frac{mc}{mc-t} + \frac{c(1-m)}{c-mc+t}\right] > 0 \tag{4.8}$$

The consumption effect is a result of an adjustment in the usage of *X* due to a higher tax, which alters savings and consumption levels. In this study, consumption effect is unambiguously positive (see B.11), implying that as tax increases and less *X* is used, the demand for *H* for pollution reduction falls, reducing the need for savings hence, increasing consumption. The consumption effect is expressed as:

$$\frac{\partial s_C}{\partial t} = \frac{(r - R_N)}{f_N R_N} > 0 \tag{4.9}$$

This positive consumption effect represents a reduction in growth rate because lower investment in conservation capital made possible by foregone consumption has an adverse productivity impact. However, the extent to which increased consumption reduces growth is reduced by higher preference for environmental quality, f_N. This indicates that as consumer preferences for environmental quality increases, consumption responds less to environmental preservation.

The input use effect and the conservation effect in (4.7) capture the adverse impact of the tax rate on growth because they represent the crowding-out effect. The crowding out-effect arises when increasing environmental stringency, hence requiring a higher level of conservation capital, *H*, crowds out investment in production capital, *K*, potentially reducing growth. Additionally, crowding out effect is manifested as the increase in the output share of *X* and that is induced by higher level of conservation capital investment because the productivity-enhancing effect of *H* stimulates *X* usage. Thus, a sufficient condition for crowding out effect to be either negative or low is for the output share of foregone consumption and variable input to fall with the target level of environmental quality. However, the impact of environmental stringency on the output share of the polluting input (input effect) is unambiguously negative (see B.13), while the impact on the share of conservation capital investment (foregone consumption effect) is unambiguously positive (B.12):

$$\frac{\partial s_M}{\partial t} = \frac{r - r}{r} > 0 \tag{4.10}$$

A sufficient condition for economic growth to increase with environmental policy is if the consumption effect plus crowding out effect is negative (B.14), i.e.,

$$r < \frac{rR_N}{r - f_N R_N} \qquad (4.11)$$

Thus, we need the social discount rate to be low enough to encourage consumers to forego current consumption, implying a weaker consumption effect. Further, a low social discount rate implies higher levels of savings which make high levels of investment in H and K possible. This induced investment in K can partially offset the production capital that has been crowded out by H. These conditions: low m and high w (implied by (4.8)), and low r (implied by (4.11)) also imply that minimal government intervention is necessary to achieve sustainable balanced growth (see Table 1). These results suggest that not only can environmental regulation achieve a sustainable balanced growth rate higher than those achieved in an unregulated regime, but such outcomes do not necessarily involve high levels of taxes, or subsidies.

To be able to compare the conditions for balanced growth under the unregulated and regulated economies, we can also express (4.11) as $r < \frac{rR_N f_N}{\left(r - R_N\right)}$. This condition can be combined with the reverse of (2.37), and (4.5), which indicates a regulatory environment to obtain (B.16):

$$\frac{c}{q_3 N} < r < rR_N < 1 \qquad (4.12)$$

This condition implies that environmental regulation can be consistent with sustainable balanced growth if the interest rate lies between the marginal return due to regenerative capacity of the environment (right hand side), and the amenity value of the environment (left hand side). This is in contrast to the condition in (2.37) which requires only that the interest rate, hence, growth rate, be low enough and as a consequence, input use and pollution to be low. In a regulated economy, conditions on the upper-bound and lower-bound for the interest rate arises because on one hand, a low enough r induces firms to invest in conservation capital, while on the other hand, a high enough interest rate stimulates savings, making investment on conservation and production capital possible. If r is too high, marginal productivity of conservation capital will be very high, and would encourage the usage of the polluting input X via the productivity effect. This suggests that very high (interest rates and) growth rates may create a countervailing effect on environmental quality when usage of polluting input goes unchecked. This upper-bound on r is influenced by the natural rate of regeneration and the social rate of discount. Higher discount rate reduces savings, hence conservation capital investment, allowing a more restrained usage of the polluting input. This is reinforced by a high regeneration rate which reduces the need for conservation capital.

The lower bound on the interest rate, on the other hand, is influenced by the shadow value of environmental quality and by the output elasticity of effective input. The higher the shadow value of environmental quality is, the lower the interest rate can be to induce savings because the higher the marginal utility gain from foregoing consumption and investing in environmental quality improvement. Thus, when consumers decide between consumption and savings, they are ultimately deciding between consumption and environmental quality. They forego consumption and save if the return from such is greater than the amenity value they derive from the environment. Firms, on the other hand make investment decision based from the relative cost and returns from investing in H and K and based from the private and social (environmental) cost associated with X usage. They will choose to invest in conservation capital if the cost of investing is less than the value of the marginal return due to natural regeneration of the environment. Because H reduces pollution and improves environmental quality, the gain in terms of improved environmental quality as a result of higher regeneration must more than offset the cost necessary to derive this environmental gain.

The preceding results show that environmental preservation can be achieved by a regulated economy in a balanced growth path given certain restrictions on the interest rate, social discount rate, and on output elasticity of conservation capital. Unlike Smulders (1995b) and Bovenberg and Smulders (1995), who utilized the effect of the tax on interest rate to deduce the effect of environmental policy on growth, we distinguish between separate components of economic growth: the productivity effect, and the crowding-out and consumption effects. We also show how the trade-off between environmental and economic concerns exist even at low levels of environmental quality[10] and how the productivity effect can be positive even if production technology does not depend on environmental stock. Further, we derive the conditions under which the economy-environment trade-off can be overcome by taking into account the crowding-out effect associated with the efficiency-enhancing technology as well as the changes in consumption pattern among consumers as result of their saving decision in response to their preference for environmental quality. The role of conservation capital as a private, rival good which is a productivity-enhancing and pollution-reducing technology, is the key component of the model. It represents the efficiency-enhancing technologies that firms invest in to increase output, while maintaining input use and reducing waste, allowing for environment-related investment partly a private responsibility. We demonstrate that environmental policy will be consistent with sustainable balanced growth if the productivity effect is strong enough, if crowding-out effects is low enough and if consumers' savings decision is such that consumption effect is low. The two former conditions are enhanced by a high output elasticity of conservation capital, while the latter is made possible by a low social discount rate. These restrictions also imply minimal government intervention in the form of low input tax rate and low investment subsidy rate.

The productivity effect of H on X also shows how it is possible to achieve a constant level of environmental quality and pollution in the face of increasing output. This is where the notion of pollution as *ineffective input use* becomes substantial. As long as conservation capital can stimulate effective input use and enhance productivity of K and X, pollution can remain constant in the face of increasing production and growth. This differs significantly from Smulders (1995b) and Bovenberg and Smulders (1995) who showed that for environmental quality to improve, pollution and resource extraction must fall, which have negative repercussions on economic growth.

4. Conclusions

This paper analyzes the interactions between economic growth and environmental quality by linking pollution to ineffective input use, the level of which is decided simultaneously with the level of investment in conservation capital and production capital. Conservation capital is modeled to increase input-use efficiency and its value both for pollution reduction and productivity enhancement is investigated. The paper further examines how it can achieve sustainable balanced growth and shows that even without regulation, the notion of conservation capital as a private rival good allows producers to invest in conservation capital to a certain extent subject to some restrictions on production and preference parameters. We show that simultaneous achievement of environmental quality and growth in an unregulated economy requires a high weight attached to environmental quality, low interest and discount rates, a high output elasticity of conservation capital, and high price of the variable input.

The paper then proceeds with the discussion of the impact of environmental policy on economic growth. We demonstrate whether regulation can achieve a growth rate higher than that attained in an unregulated economy and show how a high productivity of conservation capital, low interest rate and a low social rate of discount ensure that an emissions tax can increase economic growth rate. These conditions simultaneously enhance the productivity effect and mitigate the intensity of the crowding-out effect of investment in conservation capital by increasing the willingness of society to sacrifice present consumption, and enhance the private motive to invest in conservation capital. However, to the extent that conservation capital crowds out investment in production capital, which may reduce output, the decentralized choice of variable input use and conservation capital investment may be lower than what is socially optimal. The role of environmental policy therefore is to bring conservation capital investment and variable input use to their socially optimal values. In investigating the role of the regulatory environment in the attainment of sustainable balanced growth, we show the equivalence of a pollution permit system and of a two-instrument scheme to an emissions tax. This study also shows that the restrictions on the levels of the preference and production parameters necessary to attain sustainable balanced growth do not necessarily entail high levels of taxes and subsidies.

The analysis in this paper also shows that the assumptions required for the feasibility of balanced growth paths are fairly restrictive. Further research is needed to examine the impact of environmental policy on growth under more general assumptions about preferences and production functions.

References

AYRES, R. (1989), "Industrial Metabolism," in J.H Ausubel and H.E. Sladovich (ed.), *Technology and Environment*, National Academy of Engineering (Washington, D.C.: National Academy Press).

BECKER, G. S., K. M. MURPHY, and R. TAMURA (1990), "Human Capital, Fertility and Economic Growth," *Journal of Political Economy*, **98:5** (pt. 2).

BOVENBERG, L. A. and R.A. DE MOOIJ (1993), "Environmental Tax Reform and Endogenous Growth," CentER Discussion paper 9498. Tilburg University

BOVENBERG, L. A. and S. SMULDERS (1995), "Environmental Quality and Pollution-Saving Technology Change in Two-Sector Endogenous Growth Model," *Journal of Public Economics*, **57**, 369-391.

BROCK, W. A. (1977), "A Polluted Golden Age," in V. L. Smith (ed.), *Economics of Natural and Environmental Resources*, (New York: Gordon and Breach).

DEN BUTTER, F.A.G, and M.W. HOFKES. (1995). "Sustainable Development with Extractive and Non-Extractive Use of the Environment in Production" *Environmental and Resource Economics* . **6**:4, 341-58.

GRADUS, R. and S. SMULDERS (1993), "The Trade-off between Environmental care and Long-term Growth: Pollution in Three Proto-type Growth Models" *Journal of Economics*, **58**, 25-51**.**

HUANG, C. and D. CAI (1994), "Constant Returns Endogenous Growth with Pollution Control," *Environment and Resource Economics*, **4**, 383-400.

HUNG, V.T.Y., P. CHANGE and K BLACKBURN (1993), "Endogenous Growth, Environment and R&D," In. C. Carraro (ed). *Trade, Innovation and Environment*.

KEELER, E., M. SPENCE, and R. ZECKHAUSER (1971), "The Optimal Control of Pollution," *Journal of Economic Theory*, **4**: 19-34.

KHANNA, M. and D. ZILBERMAN (forthcoming 1997), "Incentives, Precision Technologies, and Environmental Protection," *Ecological Economics*.

KING, R., C. PLOSSER, and S. REBELO, 1988, "Production, Growth, and Business Cycles, I: The Basic Neoclassical Model," *Journal of Monetary Economics*, 195-232.

KING, R. AND S. REBELO (1987), "Business Cycles with Endogenous Growth," (University of Rochester Working Paper).

LIGTHART, J.E. and F. can der PLOEG. (1994) "Pollution, the Cost of Public Funds and Endogenous Growth". *Economic letters*. **46**, 351-361.

MICHEL, P. (1993), "Pollution and Growth Towards the Ecological Paradise," Nota di Lavora 80-93, Universite de Paris and Fondazione Eni Enrico Mattei.

MUSU, I. (1994), "On Sustainable Endogenous Growth," Nota di Lavora n. 8903, University of Venice and Fondazione Eni Enrico Mattei.

MUSU, I. (1995), "Transitional Dynamics to Optimal Sustainable Growth," (Working Paper, Dept. of Economics, University Ca'Foscari, Venice).

PEARCE, D. W., A. MARKANDYA, and E. BARBIER (1990), *Sustainable Development: Economy and the Environment in the Third World* (London: Earthscan Publications).

PORTER, M. E. and C. VAN DER LINDE (1995), "Green and Competitive," *Harvard Business Review*, September-October, 120-138.

REBELO, S. (1991), "Long-run Policy Analysis and Long-run Growth," *Journal of Political Economy*, **94**, 500-521.

ROMER, P. (1986), "Increasing Returns and Long-Run Growth," *Journal of Political Economy*. **94(5)**, 1002-1037.

ROMER, P. (1994), "The Origins of Endogenous Growth," *J of Econ. Perspectives*, **8**, 3-22.

SMULDERS, S. (1995a), "Entropy, Environment, and Endogenous Economic Growth," *International Tax and Public Finance*, **2**, 319-340.

SMULDERS, S. (1995b), "Environmental Policy and Sustainable Economic Growth: An Endogenous Growth Perspective," *De Economist*, **143**, 163-195.

SMULDERS, S. and R. GRADUS (1996), "Pollution Abatement and Long-term Growth," *European Journal of Political Economy*, **12**, 505-532.

van DER PLOEG, F. and C. WITHAGEN (1991), "Pollution Control and the Ramsey Problem," *Environmental and Resource Economics*, **1 (2)**, 215-236.

VERDIER, T. (1995). "Environmental Pollution and Endogenous Growth." In *Control and Game Theoretic Models of the Environment*. Carraro, C. and J.A. Filar eds. Birkhauser:Boston.

APPENDIX A
Sustainable Balanced Growth and Social Optimality

We maximize (2.7) subject to (2.8) using the functional specifications provided in (2.22). The first-order conditions are:

(A.1) $\quad H_C = \frac{1}{C} - q_1 = 0$

(A.2) $\quad H_M = -q_1 + q_2 = 0$

(A.3) $\quad H_X = q_1[cm\frac{Y}{X} - w] - q_3\frac{1}{H} = 0$

(A.4) $\quad H_K = q_1(1-c)\frac{Y}{K} = rq_1 - \dot{q}_1$

(A.5) $\quad H_H = q_1(1-m)\frac{Y}{H}c - q_3\frac{X}{H^2} = rq_2 - \dot{q}_2$

(A.6) $\quad H_N = \frac{f_N}{N} + q_3 R_N = rq_3 - \dot{q}_3$

Here, we show how (A.1) to (A.6) are transformed to (2.25) to (2.29) using the expressions (2.10) to (2.12) and the parameters in (2.24).

To obtain the Ramsey Rule, we need to use (2.10). Since $s = 1, s_{CN} = 0$ and $\frac{\dot{C}}{C} = g$, we obtain (2.25):

$$g + r = r$$

To obtain optimal input use, we need (2.11). Because $e_X = mc$, we derive (2.26)

$$mc - s_X = q_3 g\frac{X}{Y}$$

To obtain optimal capital use, we need (2.12). Since $e_K = 1 - c, e_E = c, y = (1-m), x = 1$. Hence, we get (2.27):

$$r = (1-c)\frac{Y}{K}$$

And (2.28):

$$r = [c(1-m) + q_3 g\frac{X}{Y}]\frac{Y}{H}$$

For optimal *N* level we use (A.6) and divide by (A.1).

$$\frac{U_N}{U_C} + q_3 R_N = rq_3 - \frac{\dot{q}_3}{q_1}$$

Note that $\frac{\dot{q}_3}{q_1} = \dot{q}_3 + \frac{\dot{q}_1}{q_1}\frac{q_3}{q_1}$ and divide by q_3 we get:

$$\frac{U_N}{q_3 U_C} + R_N = r - g$$

Solving for U_C and U_N we get (2.29):

$$r = f_N C/Nq_3 + R_{N+}g$$

APPENDIX B
Impact of Environmental Policy on Interest rate and Growth

To be able to derive *Y/K* as indicated in (4.2), we note that the technology takes the form:

$$Y = [H^{(1-m)} X^m]^c K^{(1-c)} \;\Rightarrow\; Y = \left[H\left(\frac{X}{H}\right)^m \right]^c K^{(1-c)} \quad \Rightarrow \left(\frac{Y}{K}\right)^{1-c} = \left[\left(\frac{X}{H}\right)^m \frac{H}{Y}\right]^c$$

Multiplying *H/Y* by *M/M* and letting s_M from (2.30a) and g=*M/H*, we get the expression in (4.2)

(B.1) $$\frac{Y}{K} = (P)^{\frac{mc}{1-c}} \left(\frac{s_M}{g}\right)^{\frac{c}{1-c}}$$

so that we can express r as in (4.3). We can also express P in terms of t :

(B.2) $$P = \frac{X}{H} = \frac{s_X}{s_M}\frac{g}{w} = \frac{mc - t}{(1-m)c + t}\frac{r}{w}$$

(B.3) $$\frac{\partial P}{\partial t} = -\frac{r}{w[(1-m)c + t]} - \frac{w}{r[mc - t]} < 0$$

and the s_M falls with t as can be seen from (2.30a):

(B.4) $$\frac{\partial s_M}{\partial t} = \frac{r - r}{r} > 0$$

To obtain, the *dr/dt*¸ we need to simplify (B.1):

$$r^{\frac{1-mc-1+c}{1-c}} = (1-c)\left[\left(\frac{mc - t}{w}\right)^{\frac{mc}{1-c}} (c - mc + t)^{\frac{c(1-m)}{1-c}}\right]$$

Taking the total derivative yields:

(B.5) $$\left(\frac{1-mc}{1-c}\right) r^{\frac{c(1-m)}{1-c}} dr = \frac{r}{(1-c)}\left[-\frac{mc}{mc - t} + \frac{c(1-m)}{c - mc + t}\right] dt$$

Solving for *dr/dt*, we obtain:

(B.6) $$\frac{dr}{dt} = r^{1-\frac{c(1-m)}{1-c}} \left[-\frac{mc}{mc - t} + \frac{c(1-m)}{c - mc + t}\right] >< 0$$

depending on the sign of the terms inside the bracket.: The term in the brackets is positive if:

(B.7) $$\frac{m}{mc - t} < \frac{(1-m)}{c - mc + t} \;\Leftrightarrow\; \frac{m}{(1-m)} < \frac{(mc - t)}{c - mc + t}$$

But using (B.2) we can express the right-hand side of (B.7) in terms w of *r*:

(B.8) $$\frac{m}{(1-m)} < \frac{Pw}{r}$$

Letting $P = R_N N$ at steady state and solving for *r*, the condition for a positive dr/dt is:

(B.9) $$r < \frac{(1-m)}{m} wR_N N$$ which is (4.5).

To obtain the impact of the tax on growth, we take the derivative of the goods market equilibrium condition with respect to a tax. For the productivity effect, we use (B.1) to obtain:

(B.10) $$\frac{\partial \frac{Y}{K}}{\partial t} = \frac{Y}{K}\frac{1}{(1-c)}\left[-\frac{mc}{mc-t} + \frac{c(1-m)}{c-mc+t}\right]$$

which is positive, like (B.3) if (4.5) holds. The impact on the share of consumption, input use, and foregone consumption are:

(B.11) $$\frac{\partial s_C}{\partial t} = \frac{(r-R_N)}{f_N R_N} > 0$$

(B.12) $$\frac{\partial s_M}{\partial t} = \frac{g}{r} > 0$$

(B.13) $$\frac{\partial s_X}{\partial t} = -1 < 0$$

The crowding out effect plus consumption effect is low if:

(B.14) $$\frac{(r-R_N)}{f_N R_N} + \frac{g}{r} - 1 < 0$$ which simplifies to (4.11).

The complete necessary conditions to ensure non-decreasing environmental quality for an economy in balanced growth equilibrium consists of the reverse of (2.37), (4.5) and (4.10). By letting $A = wR_N N\left(\frac{1-m}{mc}\right)$ in (4.5) and reversing the sign in (2.37), we have:

(B.15) $$A > r > \frac{Af_N c}{(r-R_N)q_3 N} \quad \Leftrightarrow \quad 1 > r > \frac{f_N c}{(r-R_N)q_3 N}$$

Using (4.10), and combining with (B.15):

(B.16) $$rR_N > r > \frac{c}{q_3 N}$$ which is (4.12)

[1] The role of environmentally friendly (human) capital that increases the productivity of polluting inputs is also recognized by Bovenberg and Smulders (1995). However they do not distinguish between its dual roles (input productivity-enhancing and pollution-reducing) since they define pollution to be identical to input-use. They also consider human capital to be a pure public good that would not be provided in a pure market economy. In contrast, environmentally friendly (conservation) capital is considered a rival input in this paper and the decision to invest in it is driven partly by private incentives to augment input productivity and is partly induced by environmental regulations.

[2] Previous work model pollution to be directly dependent on the level of capital (Chung-Huang and Deqin, 1994; Smulders and Gradus, 1996), input-use (Bovenberg and de Mooij, 1994; Bovenberg and Smulders, 1995; Smulders, 1995) or consumption (Hung, Chang and Blackburn, 1993; Verdier, 1993) and that pollution control would require a reduction in these levels (Smulders, 1995, Michel and Rotillon, 1992) or a redirection of resources from productive activities towards clean up through investment in abatement capital (Smulders and Gradus, 1996; Chung-Huang and Deqin, 1994; den Butter and Hofkes, 1995). Keeler et al. (1971) and Brock (1977) treated pollution both as an inevitable by-product of production and as an input that contributes positively to production. While Brock does not consider abatement possibilities, Keeler et al. (1971) allow for expenditure on pollution control and show that capital stock and output are higher when there is no expenditure on pollution control. More recently van der Ploeg and Withagen (1991) also relate pollution to output and consider both the negative effects of the stock of pollution and the flow of pollution on utility in the Ramsey model with no technological progress. They show that an emissions tax lowers consumption, capital and output in the steady state but do not examine the impact of environmental regulations on growth

[3] This law states that the mass of all material inputs from the environment (energy and raw materials) to the economy must equal the mass of final products plus the mass of residuals discharged to the environment minus the mass of materials recycled.

[4] Differentiating 3.11 with respect to time, we get: $0 = \dot{q}_3 gX / Y - gq_3 xgX / Y \Rightarrow \dot{q}_3 / q_3 = xg$.

[5] $Max\ H = \ln C + f_N \ln N + q_1 [rK + rH - C] + q_3 \left[R_N N - \frac{X}{H} \right]$

[6] $Max\ H = (H^{1-m} X^m)^c K^{1-c} - wX - M - rK + q_2 M$

[7] The firm's maximization problem must be formulated as:

$$Max\ H = (H^{1-m} X^m)^c K^{1-c} - wX - M - rK + q_2 M - p \frac{X}{H}$$

This yields first-order conditions for X and H similar to those in a social planner's model

[8] We use s_C in (3.31) which is also functions of several parameters, q_3 from (A.6) and r from (5.1) which is a negative function of w.

[9] The positive impact of the social discount rate on input tax is possible only if $\frac{1}{q_3} > r - R_N = \frac{U_N}{U_C q_3}$ from (3.14).

[10] Smulders (1995b) and Bovenberg and Smulders (1995) assume that the regenerative capacity of the environment exhibits an inverse-U-shape. This implies that at low levels of environmental, regenerative capacity increases, but at higher levels of N, it becomes more difficult to improve an almost pristine state. This assumption is the source of the trade-off in their studies. In this study however, we only focus on the upward-sloping portion of the curve, and show that even at low levels of environmental quality, a trade-off between economic growth and environmental quality still exist.