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OF THE CONTROL OF ENVIRONMENTAL EXTERNALITIES

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THE MACROECONOMIC BENEFITS OF THE CONTROL OF ENVIRONMENTAL EXTERNALITIES

By

David Everett Schimmelpfennig

A DISSERTATION

Submitted to
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ABSTRACT

THE MACROECONOMIC BENEFITS OF THE CONTROL OF ENVIRONMENTAL EXTERNALITIES

By

David Everett Schimmelpfennig

The essays in this dissertation take a theoretical and an empirical approach to determining the benefits, from a macroeconomic perspective, of controlling environmental problems.

(1) Long-run Equilibria in an Economy with a Greenhouse Effect

In this theoretical section, the behavior of perfectly competitive agents with perfect foresight is shown to be different in an unconstrained economy and one with a global warming threshold externality. In this overlapping generations model, when a gas constraint is not binding, a constant per capita steady state equilibrium exists. A different constant per capita steady state equilibrium is shown to exist, when the greenhouse gas constraint binds on the economy. Agents adapt to the gas constraint by foregoing consumption when young, even though they would be dead before the threshold was reached. The possibility exists for a coordination failure in this case.

(2) An Empirical Investigation of the Capital-Environment Tradeoff

In this section, dynamic causal relations are established between various measures of income and air pollution by extending recent panel-data techniques for lagged dependent variables. The results from this new

Granger test are interpreted in a static framework and used to specify two models that take advantage of both the information about the exogeneity of variables and the panel structure of the data. There is shown to be some evidence of external benefits from pollution control. This indicates that better air quality can contribute to the well-being of future generations by contributing to economic growth. Improved worker health, stimulates investments in human capital and adds to worker productivity, leading to increased income.

DEDICATION

To my parents, Jeanne and Hal.

ACKNOWLEDGMENTS

More than anyone else, the chair of my dissertation committee, Dr. Lawrence Martin, helped me with this project. When the sky grew dark and storms gathered, it was Larry who found a way to cast light on the problems, and to reemphasize the soundness of the overall direction taken by this research. He called this a "big idea," and without his support it would not have been completed in its present form.

I am indebted to the other members of my committee for reading the entire manuscript. John Hoehn, guided the empirical work, and was particularly helpful in attempting to get outside funding for the project. Andrew John gave his thoughtful input on the theoretical work from the time of the first meeting on my second year paper, up to today. Carl Davidson made many insightful comments, and was very helpful in portraying the steady state dynamics.

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I am very lucky to have spent the last four, plus, years with my friends and colleagues, Thomas Klier, Michael McPherson and Patricia Pollard; who gave of themselves in many ways. Linda Schimmelpfennig, helped start this process, because she knew that I would not quit until it was completed. Finally, with constant care and understanding, my family, Hal, Jeanne, Nancy and David, instilled in me the qualities that I needed to get PhinisheD. Whether I actually have those qualities or not, they make me think I do.

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CHAPTER ONE — ESSAY ONE
LONG-RUN EQUILIBRIA IN AN ECONOMY WITH A GREENHOUSE EFFECT

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I am happy to have this opportunity to thank the chair of my dissertation committee, Lawrence W. Martin, for keeping this project on track; and Andrew John, Rowena Pecchenino, Stacey Schreft, Carl Davidson, Jim Poterba, Robert Haveman and seminar participants at Michigan State University and the 1990 Western Economic Association meetings, for discussions and comments.

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ABSTRACT

Long-run Equilibria in an Economy with a Greenhouse Effect

This paper describes how the behavior of perfectly competitive agents with perfect foresight differs in an unconstrained economy and one in the shadow of a potentially devastating production externality: a global warming threshold externality. In this overlapping generations model, greenhouse gas is a by-product of production, and trees, the capital in the economy, absorb greenhouse gas. Two kinds of equilibria are shown to exist. When a gas constraint is not binding, a constant per capita unconstrained steady state equilibrium exists. When parameters are changed so that the gas constraint is binding on the unconstrained per capita values, too much gas may accumulate. The global warming threshold could be reached in this case, and the unconstrained price path unravels. A different constant per capita steady state equilibrium is shown to exist, when the greenhouse gas constraint binds on the economy. Agents adapt to the gas constraint by holding more trees and foregoing consumption when young, even though they would be dead before the threshold was reached. The possibility exists for a coordination failure when no trees are held, in this case. The efficient equilibrium when the correct number of trees are held by each agent is not achieved without coordinated behavior. All parameters, except the rates of tree and population growth, have the same comparative static effect on prices that they have on the tree stock.

We should think of our resources not as having been left to us by our parents, but as having been loaned to us by our children.[1]
Kenyan Proverb

1. INTRODUCTION

The greenhouse effect, cited repeatedly since the summertime drought in 1988, refers to a potential for global climatic change caused primarily by the emission of carbon dioxide into the atmosphere. A natural greenhouse effect undeniably exists and is essential for the earth to support life; without it the planet would be too cold. However, man-made gases may exaggerate the natural greenhouse effect, leading over time to increases in surface temperatures that may disrupt agricultural production and cause coastal flooding.

Will rational agents avoid behavior that could lead to catastrophic global change? While the United Nations and international scientific panels formulate responses to the problem (World Meteorological Organization, 1990), this paper is a first step in addressing this question. The paper presents a model of an environment in which the production of goods generates a gas that remains in the atmosphere for a long period of time. If the stock of the gas reaches a critical level, the "greenhouse effect" is assumed to reach a threshold where it suddenly

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[1]David Makanda, a Kenyan graduate student assures me that this is something that the coastal Kenyans say.

causes global warming sufficient to prevent further production. As called for by Schelling (1992), the paper "concentrate(s) on the extreme possibilities."

Natural systems often respond to stresses in this way. Individual crops or tree species adjust to increases in temperature as far as they can, and then succumb. Crop varieties have been bred for their ability to adjust to increased temperature and evaporation. Drought resistant or not, as temperatures rise, crops eventually reach a threshold, known as their "wilting point" where they wilt and die (Ritchie et al, 1972). Droughts, falling water tables, and changing climates have led to the collapse of ecosystems, notably Sugar Maple ecosystems in Florida and Kirtland's Warbler habitat in Michigan. "The possibility has to be considered that if temperature increases ... and continues to rise ... some atmospheric or oceanic circulatory systems may switch to alternative equilibria, producing regional changes that are both sudden and extreme" (Schelling, 1992). Catastrophic thresholds, a topic in pure mathematics (Thom, 1975, Zeeman, 1977), have been considered by d'Arge and Kogiku (1973) in a materials-balance economic model of waste accumulation, by Varian (1979) in business cycles, and by Gennotte and Leland (1990) in stock market crashes. As recent research has described the catastrophic results of potential global warming in vivid detail (Firor, 1990, Schneider, 1990), it may be important to once again consider a potential catastrophe in an economic model.

The model, a variant of Samuelson's (1958) and Allais' (1947) classic, is an overlapping generations (OLG) model with two-period-lived agents. Like Diamond's (1965), this model has production. In contrast to Löfgren (1991) who includes both trees and capital in his model, the trees in this paper are the capital. In an infinite life setting, agents are alive as long as the economy and so if a catastrophe occurs the agents who caused it are still alive, but in the environment in this paper, future generations have no voice in present decisions, so no obvious mechanism to avoid the catastrophe exists. The gas accumulates at a rate that depends on the rate of production and the stock of trees, a renewable resource. Trees, also an input into the production process, are capable of absorbing the gas. These features imply that the consumption, production and resource-use decisions made by agents in the present may impose negative externalities on future generations through a greenhouse induced catastrophic change in climate. The OLG model provides a simple framework for a dynamic analysis focusing on intergenerational tradeoffs.

This paper shows the existence of a steady-state equilibrium in which the stock of gas remains at a constant level below the catastrophic threshold and per capita values are constant, even with population growth. In this situation, the gas constraint is binding and agents adjust their behavior to avoid the catastrophe even though they would be dead before it occurred. Another equilibrium is also shown to exist in which the stock of gas increases given certain parameter values, and eventually the catastrophic threshold would be reached. Interestingly, per capita values are also constant, but at a different level, in this equilibrium. Present and future generations are similar in several ways. Most importantly, both maximize their consumption, and both own capital represented by trees.

The problem of atmospheric pollution has been the subject of much research using dynamic models. Dasgupta (1982, chapter 8) provides a conceptual overview of this literature. The vast majority of this literature, of which Keeler, Spence and Zeckhauser (1971) is an example, uses optimal control theory to analyze pollution control. A common assumption of such models is that all agents are identical, possessing infinite lifespans and time invariant utility functions. Models with these assumptions cannot begin to address questions concerning intergenerational tradeoffs. Spash and d'Arge (1989) is an exception to this line of research. They use a model with two periods and production to study the implications of the greenhouse effect on intergenerational equity. However, the existence of a greenhouse effect externality is assumed to exist in equilibrium in their model, whereas in the model of this paper, its existence (or not) arises from the primitive characteristics of the economic environment.[2]

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[2]Little attention has been paid to negative dynamic externalities more generally. Exceptions include Sandler's (1982) study of the optimal provision and maintenance of club goods; John, Pecchenino and Schreft's (1989) analysis of the tradeoffs associated with the stockpiling of weapons; and John, Pecchenino, Schimmelpfennig and Schreft's (1990)

The existence of mean global temperature increases has been the topic of considerable debate. Hansen and Lebedeff (1987) predict global warming in a three dimensional general circulation model utilizing surface air temperatures recorded since 1880. The American Society of Mechanical Engineers (1989) contend that " ... the results from different models do not agree well with each other ... As a result, the rate, magnitude and regional pattern of climate change are uncertain." More recently, the National Oceanic and Atmospheric Administration has found that the location of some weather stations in urban areas has led to a warm bias in the temperature data of about 0.06°C (Karl, et al, 1988).

Batie (1989), reporting on the work of Pearce (1987) and Norgaard (1984), cites this controversy over whether global warming is occurring and, if it is, the date at which severe ecological change might occur, as a hindrance to the ability of theoretical models to address issues such as the greenhouse effect. However, as long as the potential for greenhouse-induced catastrophic climatic change remains, the analysis of this paper, which assumes only a natural (not man-made) level of greenhouse gases in the atmosphere, may be valuable. Evidence of atmospheric change caused by other factors certainly exists. The change in the ecosystems of Europe and Scandinavia from acid rain, itself a by-product of the production process, is one example (Environmental

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research on external increasing returns and long-lived waste.

Resources Limited, 1983; Thunberg, 1984), ozone depletion from chlorofluorocarbons is another.

The rest of the paper is organized as follows. Section 2 presents the model and, in subsection 2.2, the solution to the representative agent's choice problem and, in subsection 2.3, the problems of the firms along with behavioral comparative static results, in subsection 2.4. An equilibrium is defined, and the existence and dynamic properties of a steady state equilibrium when the gas constraint is not binding are presented, in subsection 3.1. This price path unravels if parameters in the model are changed in subsection 3.3, and a new equilibrium when the gas constraint is binding is presented along with multiple Nash equilibria, in subsection 3.4. General equilibrium comparative static results when the gas constraint is binding are presented, in section 4. Conclusions follow in section 5.

2. THE MODEL

The model is of an infinite horizon, discrete time economy. At each date $t=1,2,\ldots$, a new generation of $N_t>0$ identical two-period lived agents is born. Population growth is given by $N_t=(1+n)N_{t-1}$. Agents in the first period of life are referred to as the young, while those in the second and last period of life are the old. At the initial date, $t=1$, the old (i.e. members of generation zero) are endowed in the aggregate with the stock

$R^o{}_1 \geq 0$ of trees ($R^o{}_t \geq 0\ \forall t$).[3]

Subsections 2.1 through 2.3 describe a series of transactions involving; labor, the production of consumption goods, and capital, represented by trees. Each period the old generation supplies harvested trees to the firms and standing trees to the young, who supply labor to the firms. The firms produce output, which is demanded by the young, the old, and the firms, who can turn output into new trees next period. Standing trees are sold at the end of each current period to the next young generation, so capital, or the trees, may be carried over from period to period and it is possible for old growth forests to exist, or for tree communities to persist.

2.1 THE TECHNOLOGY

Young agents are endowed with time that they supply inelastically at the wage w_t to output firms, who own a portion of a constant returns to scale technology, $F(Z_t,N_t)=N_t af(Z_t/N_t)$ which produces a non-storable consumption good from harvested trees, denoted by $z_t=Z_t/N_t$, a non-negative number. In intensive, or per capita form, this production technology is continuous, strictly increasing, strictly concave and $f(0)=0$. In the aggregate, production is given by

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[3]Unlike Löfgren (1991), each generation is not endowed with another stock of trees, so population growth does not exogenously determine the size of the tree stock in this model.

$$Y_t = N_t a f[z_t], \tag{1}$$

which is the sum of production by young agents and where "a" in (1), is a scale parameter. The greenhouse effect is caused by the accumulation of greenhouse gases, G, in the atmosphere. Once G exceeds a threshold level, G^{max}, a climatic catastrophe occurs at which point production ceases forever.[4] Incorporating this fact into the per capita version of (1), yields the firm's technology constraint

$$y_t = \begin{cases} af[z_t] & \text{if } G_t \le G^{max} \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

Note that a firm's production is limited by an aggregate constraint and that each firm hires one worker. Capital letters denote the aggregate counterparts of lower case per capita values.

Each old generation sells all of its trees to either the young as standing timber for some of their production, or to output firms as cut down trees. The young then own all of the standing trees, denoted $R^y{}_t$. The gross real rate of return on trees is $p_{t+1}(1+\delta)/p_t$, where p_t is the price of the resource in terms of the consumption good at date t, and the parameter $\delta>0$ is the proportion of the stock of trees that grow up from

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[4]This modelling tool can be thought of as occurring when the polar ice caps melt and all production facilities are flooded in perpetuity.

naturally occurring seedlings and become harvestable trees each period. The rate of population growth, n, is assumed to be greater than the natural rate of tree growth, δ, so that agents must take actions to ensure that sufficient trees are available in the economy. The economy with $n<\delta$, is analyzed in Schimmelpfennig (1992), along with short-run dynamic equilibria in a similar model. The price p_t comes from the aggregate demand for trees, which is the horizontal sum of the demand for inputs and the demand for standing trees by the young for saving, and the aggregate supply of trees, which is the sum of the supply of trees by the old generation and investment in new trees, discussed in subsection 2.3. The aggregate stock of trees held by the old generation evolves according to,

$$R^{o}_{t+1} = (1+\delta)R^{y}_{t}, \tag{3}$$

so the old generation's per capita savings when young is given by,

$$r^{o}_{t+1} = (1+\delta)r^{y}_{t}. \tag{4}$$

Trees are the sole store of value in the economy.

When the decision is made to use the production technology to produce per capita output, y_t, agents unavoidably produce greenhouse gases $\gamma[N_t y_t]$ or in aggregate form $\gamma[Y_t]$, that are uncontrollably released into the atmosphere, $\gamma>0$. Young agents monitor the aggregate stock of gases, denoted G_t. Trees absorb atmospheric gases during their life process; thus the stock of gases evolves according to,

$$G_{t+1} = (1-\Delta)G_t + \gamma Y_t - hR^y{}_t \tag{5}$$

where h>0. The stock of G at the beginning of date t=1 is $G_1=0$ and represents the natural level of these gases in the atmosphere. The parameter $\Delta \in [0,1]$ is the proportion of the stock of gas that is absorbed each period other than by trees.[5]

2.2 THE REPRESENTATIVE AGENT'S CHOICE PROBLEM

In this environment, the representative agent makes economic choices which are restricted by his budget constraints when young and old, respectively:

$$c^y{}_t + p_t r^y{}_t = w_t \tag{6}$$

$$c^o{}_{t+1} = p_{t+1} r^o{}_{t+1}. \tag{7}$$

[5]The oceans, for instance, are known to act as large carbon dioxide and heat sinks (Pearce and Turner, 1990). By first absorbing carbon dioxide and heat and storing both of them, the oceans could later release these greenhouse agents, contributing to the likelihood that the "climatic consequences might be both sudden and severe" (Schelling, 1992).

Equation (6) states that an agent's earnings, w_t, can be divided among the non-storable consumption good, and payment for the resource, $p_t r^y_t$, purchased when young, and (7) shows that consumption when old is limited by the value of the agent's tree holdings.

The representative agent of generation t has preferences over consumption when young, c^y_t, and consumption when old, c^o_{t+1}. These preferences are represented by the utility function, $U[c^y_t] + \beta V[c^o_{t+1}]$.[6] $U[\cdot]$ and $V[\cdot]$ are twice continuously differentiable, strictly increasing, strictly concave and satisfy the Inada conditions, $U[0]=0$, $V[0]=0$, $U'[0]=\infty$, $V'[0]=\infty$, $U'[\infty]=0$, $V'[\infty]=0$. The choice problem of the representative agent of generation t is to choose non-negative values of c^y_t and c^o_{t+1}, taking prices and wages, p_t and w_t, as given to maximize

$$U[c^y_t] + \beta V[c^o_{t+1}]$$

subject to equations (4), (6), (7), $r^y_t \geq 0$ and $G_t \leq G^{max}$, $G_{t+1} \leq G^{max}$.

The assumptions on preferences guarantee an interior solution for consumption in both periods of life, and so also for the production input z_t. The solution to the representative agent's intertemporal choice problem is characterized by the following first order conditions (FOCs):

$$-U'[\cdot]p_t + \beta V'[\cdot]p_{t+1}(1+\delta) = 0 \text{ if } \mu_t=0,\ r^y_t>0;\ < 0 \text{ if } \mu_t>0 \qquad (8)$$

[6]Intergenerational altruism is ruled out.

$$(1-\Delta)G_t + \gamma Y_t - h\sum_{i=1}^{N_t} r^{y^i}{}_t \leq G^{max}, \; if\; \mu_t>0 \qquad (8')$$

where $G_0<G^{max}$, i indexes the ith individual, and μ is a non-negative Lagrangean multiplier representing the marginal utility of relaxing the gas constraint when it binds. Equation (8) reveals that to maximize utility, when the gas constraint does not bind, the agent equates his intertemporal marginal rate of substitution to the gross rate of return in the economy,

$$\frac{\beta V'[\cdot]}{U'[\cdot]} = \frac{p_t}{p_{t+1}(1+\delta)} \,. \qquad (9)$$

It should be emphasized that (9) holds when the aggregate gas constraint never binds. The distortion to each individual agent's behavior caused by the greenhouse gas constraint, when the constraint does bind is discussed in subsection 3.4.

2.3 TWO REPRESENTATIVE FIRM'S PROBLEMS

The young agent supplies his labor inelastically, and the old agent supplies harvested timber z_t at the price p_t, to an output firm that possesses the technology af[•], hires one worker at the price w_t, and maximizes profit,

$$y_t - p_t z_t - w_t, \tag{10}$$

taking the price of trees p_t and the non-negative wage rate w_t as given. After substituting (2), the FOC for the output firm is,

$$af'[z_t] = p_t. \tag{11}$$

The output firm exists for one period, and buys tree inputs until their marginal product equals their price, without considering the greenhouse constraint. Each firm hires the worker if his marginal product, $y_t - p_t z_t$, equals, at least, the price of his labor w_t, and does not operate otherwise. Firms are identical, so in the aggregate,

$$Y_t = p_t Z_t - N_t w_t. \tag{12}$$

Investment firms possess an investment technology which turns output into new trees, without labor. Aggregate investment in new trees, X_t, depends on how much output firms demand in the goods market and contribute to the replanting technology, $\Psi(X_t) \Rightarrow N_t b\psi(X_t/N_t) = N_t b\psi(x_t)$. In intensive form this replanting technology is continuous, strictly increasing, strictly concave and $\psi(0) = 0$. The investment firm exists for two generations and maximizes the present value of investment profit,

$$p_{t+1}b\psi[x_t]/\{(1+\delta)p_{t+1}/p_t\} - x_t, \quad (13)$$

which is the value of the trees produced, that will enter the tree market next period, deflated by the rate of return in the economy, minus input costs. There is no wholesale market for replanted trees, so output firms are not able to buy and cut down trees from investment firms for use in the production of output. Investment trees must pass through the tree market. The FOC for the investment firm is,

$$b\psi'[x_t] = (1+\delta)/p_t. \quad (14)$$

By preference assumptions z_t is positive, therefore so is p_t in (11). The second order conditions for a maximum in the representative agent's problem and the problems of the both firms are satisfied,[7] and demand functions as unique solutions to (9), (11) and (14), can be written either implicitly or explicitly as (15), (15'') and (15"'), where stars indicate agent optimization,

$$r^{\gamma*}_t = r^{\gamma*}_t[p_{t+1}, p_t, w_t; a, b, \beta, \delta] \text{ if } \mu_t=0 \quad (15)$$

[7]The second order condition (SOC) of the individual is, $U''[\cdot]p_t^2 + \beta V''[\cdot]p_{t+1}^2(1+\delta)^2 < 0$, of the investment firm is, $b\psi''[x_t] < 0$, and of the output firm is, $af''[z_t] < 0$.

$$r^{Y,k}{}_t \geq \frac{(1-\Delta)G_t + \gamma Y_t - h\sum_{i\neq k=1}^{N_t} r^{Y^i}{}_t - G^{max}}{h}, \ if\ \mu_t>0 \quad (15')$$

$$z^*{}_t = invf'[p_t/a]. \quad (15'')$$

$$x^*{}_t = inv\psi'[(1+\delta)/bp_t]. \quad (15''')$$

where "inv" is the inverse function. Demand function (15') comes from the gas equation (5), and unlike the other demand functions (15, 15''and 15"') is not a simple decision rule based on the price of trees. The demand for trees by the young when the gas constraint is not binding (15), is governed by prices. The agents maximize, in this situation, by myopically following the decision rule that says: choose a tree stock for the purpose of saving, that equates (9) given the choices of the firms and the parameters in the economy. When the gas constraint is binding, it alters each individual's behavior, but not that of either firm, as the firms continue to myopically follow (15'') and (15"'). In this situation, the agent chooses a stock of trees to maximize his utility that satisfies the gas constraint, given the stocks of trees chosen by all other agents, the aggregate stock of gas and aggregate output, which are all taken as given by the agent. (15') is the binding gas constraint reaction function for agent k, which takes the actions of all other (i≠k) agents into account. In addition to prices, aggregate output, the gas stock and all other young agent's tree savings; wages are also endogenous to the model but are taken as given by the perfectly competitive agents and firms.

2.4 COMPARATIVE STATICS OF CONSUMER AND FIRM BEHAVIOR

Comparative static results for the individual can be obtained by differentiating the FOC (9). These derivatives indicate the response of individual agents to changes in exogenous parameters of the model, and endogenous prices. Individuals make the adjustment to the greenhouse effect in subsection 3.4, and the following derivatives provide insight into the behavior of these individuals. First period consumption increases with a rising current price of trees, and falls with increases in next period's price, the subjective discount rate and the rate of growth of new trees, as shown below,

$$\frac{dc^Y{}_t}{dp_t}=\frac{-U'}{U''\,p_t}>0 \qquad \frac{dc^Y{}_t}{dp_{t+1}}=\frac{\beta V'\,(1+\delta)}{U''\,p_t}<0$$

$$\frac{dc^Y{}_t}{d\beta}=\frac{V'\,p_{t+1}(1+\delta)}{U''\,p_t}<0 \qquad \frac{dc^Y{}_t}{d\delta}=\frac{\beta V'\,p_{t+1}}{U''\,p_t}<0. \tag{16}$$

Second period consumption is affected in the opposite direction by the same parameters,

$$\frac{dc^{o}_{t+1}}{dp_t}=\frac{U'}{\beta V''\,p_{t+1}(1+\delta)}<0 \qquad \frac{dc^{o}_{t+1}}{dp_{t+1}}=\frac{V'}{-V''\,p_{t+1}}>0$$

$$\frac{dc^{o}_{t+1}}{d\beta}=\frac{V'}{-\beta V''}>0 \qquad \frac{dc^{o}_{t+1}}{d\delta}=\frac{V'}{-V''\,(1+\delta)}>0. \qquad (16')$$

Comparative static results for the output firm can be obtained by differentiating the FOC (11). The size of productive inputs are smaller the higher is the price of trees, and larger the more productive is the technology, as shown below,

$$\frac{dz_t}{dp_t}=\frac{1}{af''}<0 \qquad \frac{dz_t}{da}=\frac{-f'}{af''}>0. \qquad (17)$$

For the investment firm, the amount of output devoted to making new trees is greater the higher is the price of trees, the more productive is the investment technology, and the faster that trees grow naturally,

$$\frac{dx_t}{dp_t}=\frac{-(1+\delta)}{b\psi'' p_t^2}>0 \qquad \frac{dx_t}{db}=\frac{-\psi'}{b\psi''}>0 \qquad \frac{dx_t}{d\delta}=\frac{-1}{b\psi'' p_t}>0. \qquad (18)$$

The next two sections will characterize various competitive equilibria.

3. EQUILIBRIA

A perfect foresight competitive equilibrium in this model is defined as a consumption allocation $\{c^y{}_t,\ c^o{}_{t+1}\}_{t=1}^{\infty}$ and a set of sequences for $\{G_t,\ p_t,\ r^y{}_t,\ r^o{}_t,\ x_t,\ w_t,\ y_t,\ z_t\}_{t=1}^{\infty}$ such that

(a) agents optimize, i.e. maximize utility subject to equations (4), (6) and (7) and the gas constraint. The FOC for optimization is (8) rewritten as (9).

(b) Firms maximize profits (10) and (13). The FOCs for a maximum are (11) and (14).

(c) The consumption good market clears:

$$y_t = c^y{}_t + \{c^o{}_t + p_t b\psi[x_{t-1}]\}/(1+n), \tag{19}$$

(d) The tree market clears:

$$\{b\psi[x_{t-1}] + r^o{}_t\}/(1+n) = r^y{}_t + z_t \tag{20}$$

and the labor market clears: when the perfectly inelastic labor supply, determined by aggregate wages, equals the perfectly elastic labor demand, determined by the profits of the firms, or from (12),

$$N_t w_t = Y_t - p_t Z_t. \tag{21}$$

By Walras' law, if the tree and labor markets clear, then the goods market does also.

3.1 THE ECONOMY WITHOUT THE GAS THRESHOLD - AN UNCONSTRAINED STEADY STATE EQUILIBRIUM (USSE)

There are only two possible classes of steady state equilibria in this economy: equilibria in an economy with a binding gas constraint and equilibria in an economy without one. This subsection considers the equilibrium in which the gas constraint does not bind (i.e. $\mu_t=0$, $\forall t>0$) and agents follow the FOC (15). Perfect foresight agents are aware of the gas constraint, but the constraint does not effect economic activity in this subsection because it is assumed that the level of the gas and the parameters in the economy are such that the threshold can not be reached. In these circumstances the greenhouse effect can not cause the suspension of production.

It is not possible to precisely define a parameter space where the equilibrium exists, because the size of parameters consistent with the gas constraint not binding is a function of the endogenous variables y_t and $r^y{}_t$. In subsection 3.4, the economy is considered when the gas constraint is binding and agents follow the reaction function (15′) and not the FOC (15).

3.1.1 THE EXISTENCE OF A USSE

It is possible to write (2), (4), (6), (7), (9), (15′′) and (21) as,

$$U'\{af[z^*_t] - p_t z^*_t - p_t r^Y{}_t\}p_t - \beta V'\{p_{t+1}(1+\delta)r^Y{}_t\}p_{t+1}(1+\delta) = 0, \quad (22)$$

which together with (4), (15), (15'') and (20),

$$[b\psi(x^*_t) + (1+\delta)r^Y{}_t]/(1+n) - r^Y{}_{t+1} - z^*_{t+1} = 0, \quad (23)$$

represent the per capita system (2), (4), (6), (7), (9), (15"'), (15''), (20) and (21) as two equations in the two unknowns $p(\cdot)$ and $r^Y(\cdot)$.

PROPOSITION 1: A unique steady state equilibrium exists if the gas constraint is not binding, in which all per capita values are constant.

Proof: Writing (22) in steady state form,

$$U'\{af[z^*] - pz^* - pr^Y\}p - \beta V'\{p(1+\delta)r^Y\}p(1+\delta) = 0, \quad (24)$$

and differentiating and substituting the steady state FOCs, this accumulation equation has the slope,

$$\frac{dp}{dr^y} = \frac{U''p^2 + \beta V''p^2(1+\delta)^2}{-U''[z^*p + r^yp] - \beta V''(1+\delta)^2 r^y p} < 0. \quad (25)$$

Writing (23) in steady state form, the tree stock equation is,

$$\{b\psi[x^*(p)] + (\delta-n)r^Y\}/(1+n) - z^*(p) = 0, \tag{26}$$

and, again, differentiating r^Y with respect to p,

$$\frac{dp}{dr^Y} = \frac{\delta-n}{(1+n)z^{*\prime} - b\psi'(\cdot)x^{*\prime}} > 0, \tag{27}$$

since $\delta<n$, i.e. since the tree stock naturally grows slower than the population, and,

$$\frac{d^2p}{dr^{Y2}} = \frac{-(\delta-n)[(1+n)z^{*\prime\prime} - b\psi''(\cdot)x^{*\prime 2} - b\psi'(\cdot)x^{*\prime\prime}]}{[(1+n)z^{*\prime} - b\psi'(\cdot)x^{*\prime}]^2} < 0, \tag{28}$$

in (p,r^Y) space. (22) is asymptotic to both axes in (p,r^Y) space, by the Inada conditions, stated earlier. (23) intersects the horizontal axis at the negative $\langle r^Y\rangle=\{(1+n)z^*(0) - b\psi[x^*(0)]\}/\delta-n$ and the vertical axis at the implicit positive price defined by $(1+n)z^*(p) = b\psi[x^*(p)]$. Since all functions are continuous, (22) and (23) cross at one point and determine equilibrium values for r^Y and p. See Figure 1.

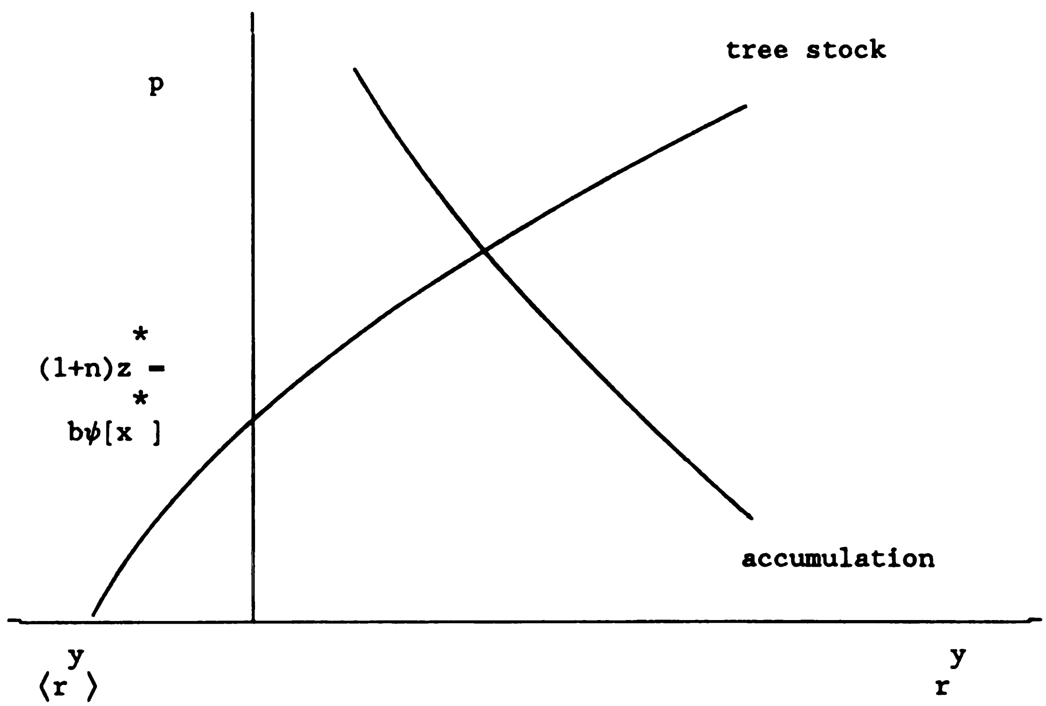

Figure 1

This r^y is the equilibrium per capita stock of trees held by the young given by (15) in steady state form, and is non-negative. Since z, the per capita production input, is non-negative, then p is also. The equilibrium values for p and r^y, from the solution to (22) and (23) in steady state form, is an ordered pair lying in the positive orthant. This result implies that equilibrium values exist for all other steady state variables. Equilibrium p determines non-negative equilibrium values for x, y and z from the FOCs of the firms (15'' and 15"') and the production technology (2). Equilibrium r^y determines a non-negative equilibrium value for r^o from (4), c^o from (7), and c^y from (6). The steady state equilibrium shown to exist is unique, because the solutions to (15), (15'') and (15"') are unique.∘

The qualitative result of proposition 1, is that in an economy that is unconstrained by the aggregate gas constraint and where agents must forego consumption and augment the tree stock themselves, even with population growth, there is a steady state equilibrium.

3.1.2 CHARACTERIZING THE USSE

The local stability properties of the USSE can be described using a Taylor series linearization.

PROPOSITION 2: The constant per capita steady state equilibrium when the gas constraint is not binding, is saddlepath stable.

Proof: In the appendix.

Saddlepath stability implies dynamic stability of the per capita system, since p, the price of the resource, is a jump variable and the equilibrium is forward looking. The equilibrium is forward looking because r^y is the only predetermined variable and "the non-predetermined variables depend on the past only through (their) effect on the current predetermined variable(s)" (Blanchard and Kahn, 1980). The dynamic behavior of the equilibrium can be determined qualitative-graphically by examining the signs of the elements of the coefficient matrix in (32) in the appendix. Using the signs in that matrix it is possible to draw the familiar phase diagram arrows (in Figure 2), and by inspection determine that the equilibrium is saddlepath stable. One unstable arm is a dotted line in the southwest corner of the phase diagram because for small enough values of the price and the resource stock, the gas constraint is violated, so on that unstable arm, the economy would get further and further away from the equilibrium and eventually the gas constraint would be violated.[8]

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[8]The phase diagram illustrates the adjustment of values of p_t and r^y_t on the saddle to the steady state, in a neighborhood of the steady state. The diagram is inaccurate for large deviations from the steady state. The

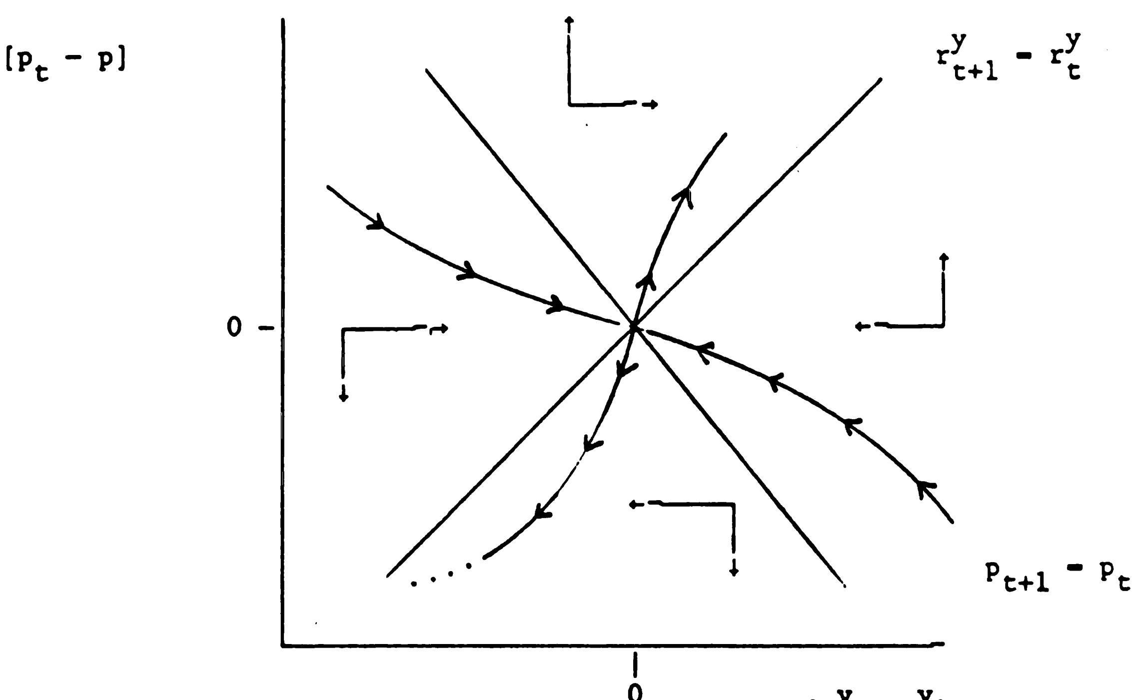

Figure 2

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closeness of the values of p and r^y in the small population steady state to catastrophic levels of these variables, determines how much of the saddle should be dotted in the southwest corner of the phase diagram.

The curves in Figure 2 are loci where either p or r^y is constant and satisfy both of the equilibrium conditions (22) and (23), by (31) in the appendix. The p locus is downward sloping and the r^y locus upward sloping because in the proof of proposition 1 in subsection 3.1.1, the slope of the price ratio equals marginal rate of substitution equation (22) is negative, and the slope of the tree stock equation (23) is positive.

These constant per capita values are not equilibrium values if exogenous factors are slightly different and the gas constraint is binding. With $\mu_t>0$ these constant per capita values may lead to an increasing stock of gas, and if the gas stock approaches the G^{max} catastrophic level, the reaction of forward looking perfect foresight agents to the prospect of catastrophe is discussed in the next subsection. It should be emphasized that the equilibrium in this subsection only exists when the gas constraint is not binding. As subsection 3.3 shows, if a binding gas constraint is imposed on the equilibrium price path shown to exist in subsection 3.1.1, the constraint may be violated, and if it is, the equilibrium no longer exists, it unravels.

3.2 THE GAS CONSTRAINT

The result of proposition 1 is that without a gas constraint, a steady state equilibrium exists. To put the gas constraint explicitly into the analysis, it is possible to define a region in (p,r^y) space, with coordinate axes in steady state values, where the stock of gas is constant or declining. In that region the following inequality constraint must hold, derived from (5),

$$y_t \leq hr^y{}_t/\gamma, \tag{29}$$

after setting $\Delta=0$ for convenience. For $\Delta>0$, the algebra is more complicated because aggregate values are introduced, but the results of this section still hold. With $\Delta>0$, a constant gas stock implies additions to the gas stock equal to subtractions, where additions are given by $\gamma N_t y_t$ and subtractions by $\Delta G_t + hN_t r^y{}_t$.

In steady state, the region in (p,r^y) space where the gas level is constant or declining, and thus the gas constraint is never violated is,

$$af[z^*] \leq hr^y/\gamma.^9 \tag{30}$$

For the subsequent analysis the area in (p,r^y) space where (30) holds is referred to as the gas constraint feasible region. The frontier of this function is negatively sloped ($\gamma f'[\cdot]z^{*\prime}/h < 0$) and convex, if and only if

[9] Future research will explore the possibility of the existence of equilibria with a gas stock that increases at a decreasing rate.

$f''[\cdot]z^{*\prime} > f'[\cdot]z^{*\prime\prime}$.[10] The inequality in (30) requires that the per capita tree stock be larger than (or equal to) the tree stock size lying on the frontier, for any given price of the resource.

When the gas constraint is never binding the intersection of the tree stock and the accumulation equations, shown to exist in subsection 3.1, occurs inside of the gas constraint feasible region, depicted in Figure 3.[11]

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[10]This is a condition on production, not directly related to the gas stock, that the elasticity of the marginal product be greater than the elasticity of the marginal input.

[11]The intersection of the tree stock and the accumulation equations could occur on the gas constraint frontier, in which case the gas stock is constant.

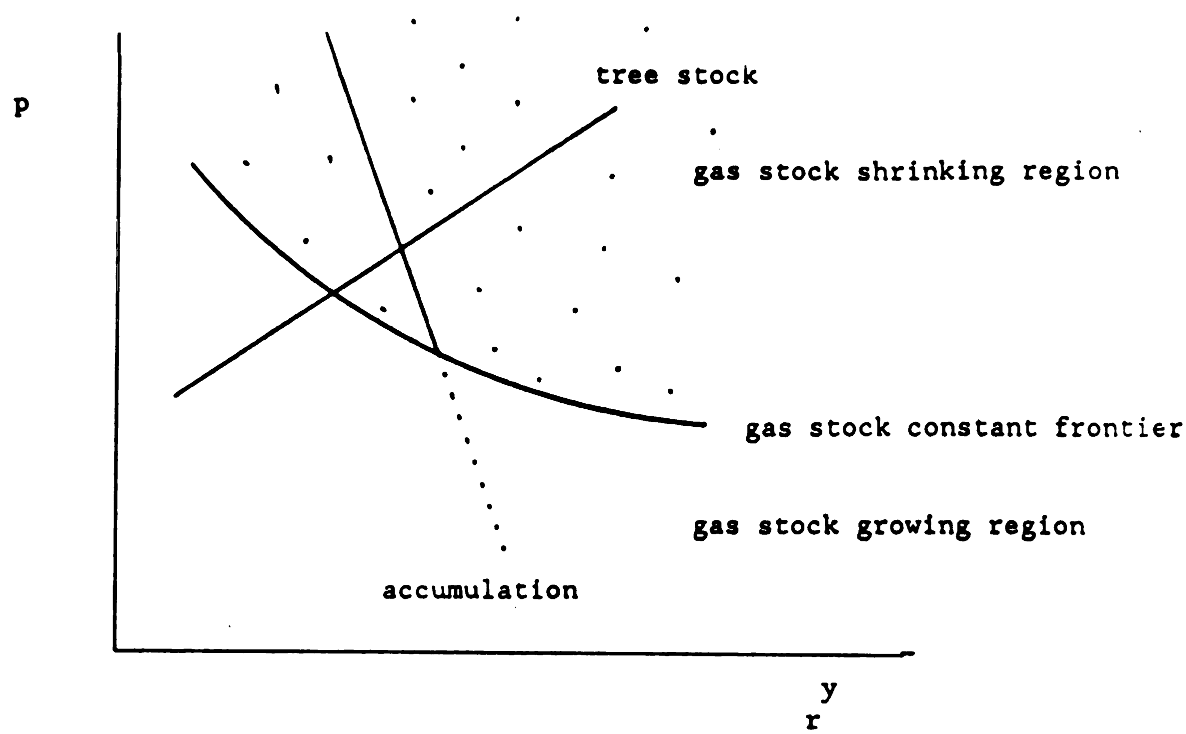
p
tree stock
gas stock shrinking region
gas stock constant frontier
gas stock growing region
accumulation
y
r

Figure 3

3.3 UNRAVELING OF A PRICE PATH

An unconstrained constant per capita steady state equilibrium was shown to exist in subsection 3.1. The * values for p and r^y in this equilibrium lie inside of the gas feasible region, in the gas shrinking or constant region in Figure 3. This subsection answers the questions: What if the price path of the economy is the one in the unconstrained equilibrium and the gas constraint is binding on the economy? How would an economy be different, if the only thing that changed was that it happened to lie in the gas growing region, outside of the gas frontier? If the gas constraint is binding on the price path in subsection 3.1, the gas constraint could be violated and a catastrophe could occur. The following proposition sets out how perfect foresight forward looking agents react to that hypothetical situation.

PROPOSITION 3: The steady state equilibrium in proposition 1, does not exist in the gas growing region defined in subsection 3.2 and the equilibrium price path unravels.

Proof: Let a catastrophe occur in period T, i.e. $G_T > G^{max}$. Then $y_T = 0$ by (2), and $p_T z_T = 0$, $w_T = 0$ from (10) since z_t and w_t are non-negative $\forall t$. Then $af[z_T] = 0 \Rightarrow z_T = 0$ since $f(0) = 0$. Since there is no production then $c^y{}_T = 0$ in (6) and the term $p_T r^y{}_T$ in (6), representing payment by the young in period T for the old generation's trees must also be zero. The period T old receive nothing for their trees, R^{Y}_{T}, from the young and so are unable to purchase the consumption good, if any was available. With perfect foresight the period T old are unwilling to sell their trees, R^{o}_{T}, to the young and receive nothing in return. When young, in period T-1, that same generation decides if it should have purchased the trees in the first place, while it monitors the stock of gas. If it does, it would not want to carry trees forward to the next period, and so all of the trees in the aggregate environment are used to produce consumption good, i.e. $R^{Y}_{T-1}=Z_{T-1}$. This violates the firm's FOC unless the price of trees is very low. This low price is only possible for one period, and the steady state unconstrained equilibrium price path unravels.∘

Proposition 3 describes the situation where the economy will end in an arbitrary period because of a catastrophe, and agents bring about the end of the economy in the period before so that they have a chance to use all of their resources before the economy ends. This process is self perpetuating. Agents treat the end of the economy brought about by agents in the same way as one caused by catastrophe, so with perfect foresight, agents will progressively end the economy one period earlier and the price path unravels back to the present. If agents were not in a steady state equilibrium they might adjust their consumption pattern to avoid the catastrophe, but this unconstrained equilibrium price path (by proposition

1) is a constant per capita steady state. The unconstrained equilibrium price path unavoidably unravels.

What is needed to avoid the unraveling and to satisfy the gas condition is the adjustment of the agent's behavior to take the gas constraint into account. This adjustment is described in the following subsection which is the main focus of the paper.

3.4 A BINDING GAS CONSTRAINT EQUILIBRIUM

The gas stock in any variant of this economy is either increasing, decreasing or constant. The unconstrained economy (see 3.1 - 3.3) has constant per capita values, and is saddlepath stable, and without a gas constraint, the gas stock is either decreasing or constant in equilibrium, or is increasing, leading to the unraveling of the unconstrained price path. In this subsection a search will be made for an equilibrium in which the gas constraint is binding and is not violated. Forward looking agents are aware of the gas constraint and see that unless they behave a certain way the economy will collapse, because the level of the gas and the parameters in the economy are such that the threshold can be reached. The unconstrained and the constrained equilibria are compared graphically.

3.4.1 THE EXISTENCE OF AN EQUILIBRIUM WHEN THE GAS CONSTRAINT IS BINDING

The following proposition describes the shapes of the equilibrium conditions in any steady state and shows the existence of a binding gas constraint equilibrium. When the gas constraint binds, agents no longer myopically follow their FOC (9) and the associated demand function (15), but their behavior is governed by the gas constraint and the associated reaction function (15′) that the constraint implies. The smallest tree stock possible, is chosen by each agent, that together with the choices of all other agents, means that the constraint is not violated, and the gas stock is constant or declining.[12] The binding gas constraint equilibrium therefore lies on the frontier, and since the FOC is unattainable, it is the intersection of the tree stock equation and the frontier that determines equilibrium values for p and r^Y.

PROPOSITION 4: The system of equations in any constant per capita steady state equilibrium can be represented conveniently as three equations in (p, r^Y) space: the accumulation equation (22), is negatively sloped; the stock equation (23), is positively sloped; and the gas feasible region is convex lying to the northeast, all three in the positive orthant. A binding gas constraint equilibrium exists.

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[12]cf. fn. 9.

Proof: The accumulation equation (22) in steady state form, is negatively sloped, and the stock equation (23), is positively sloped, both by proposition 1. The gas constraint feasible region (30) has a frontier which is convex and negatively sloped, so the stock equation and the gas constant frontier must intersect at one point in the positive orthant (point C in Figure 4) and a constant per capita steady state equilibrium exists when the gas constraint binds. The equilibrium values are non-negative for the same reasons that the equilibrium values in subsection 3.1 are non-negative.∘

To delve deeper into why it is the intersection of the frontier and the stock equations that is necessary for an equilibrium if the gas constraint is ever binding, it is informative to compare the constrained and unconstrained equilibria on the same set of axes. The unconstrained equilibrium, represented by the intersection of the tree stock and the accumulation equations, is drawn outside of the gas constraint feasible region, as point A in Figure 4.

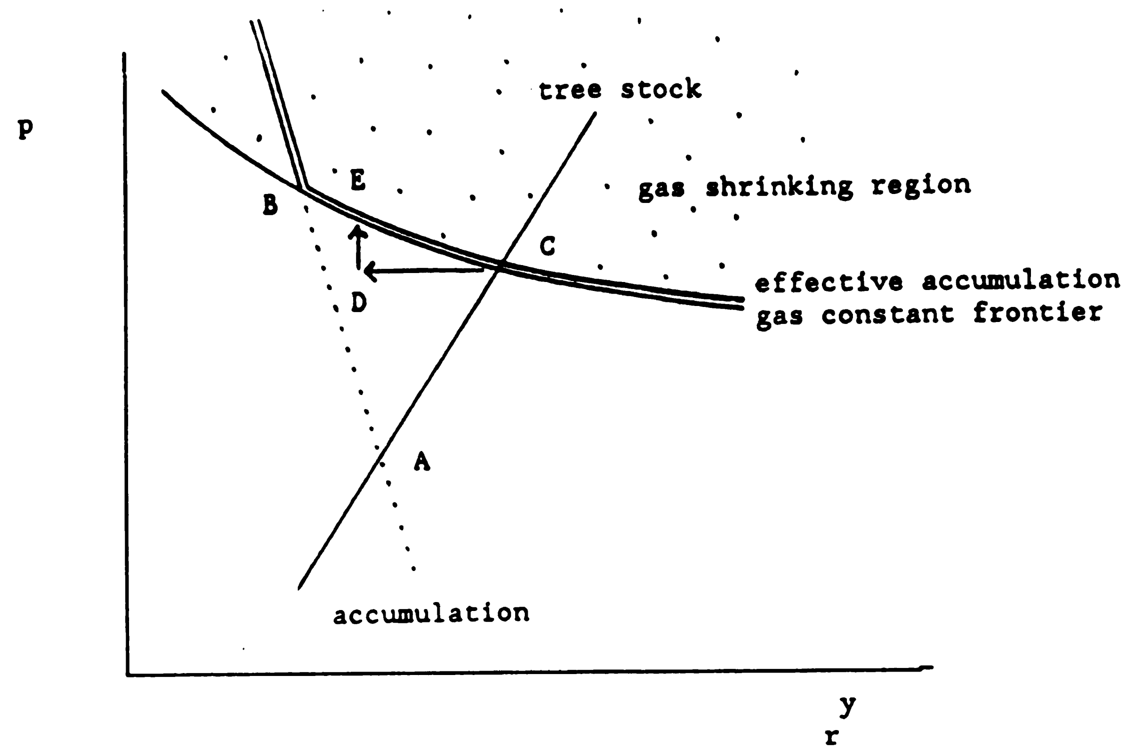
p
tree stock
gas shrinking region
E
B
C
D
A
effective accumulation
gas constant frontier
accumulation
y
r

Figure 4

Drawing the tree stock and the accumulation equations so that A lies outside of the feasible region is the graphical equivalent of imposing the gas constraint on an unconstrained equilibrium price path that will unravel as shown in proposition 3.[13]

An equilibrium when the gas constraint is binding must lie in the feasible region as in Figure 3. The tree stock equation simply shows the adjustment of the tree stock to a change in equilibrium prices, which are taken by the perfectly competitive agents. It is the accumulation equation which reflects changes in individual behavior when the constraint binds, and it is agents who adjust their consumption pattern. The accumulation equation does not exist outside of the feasible region (hence the dotted line in Figure 3 and between A and B in Figure 4), because consumption decisions outside of the feasible region lead to catastrophe.

The equilibrium solution when the gas constraint binds (i.e. $\mu_t>0$, $\forall t>0$) does not lie on the stock equation in the interior of the gas constraint feasible region. Agents are not able to choose some points on the accumulation equation, and this is the reason that the accumulation equation is dotted, discussed above. Agents would prefer to choose points on the accumulation equation outside of the feasible region, because those points represent greater output and greater undiscounted first period

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[13]The intersection point A could occur on or inside the frontier, in which case the unconstrained equilibrium would have a constant or declining gas stock respectively, and if a binding gas constraint was imposed on the equilibrium it would not unravel.

consumption, all else being equal. In other words, the accumulation equation represents the individual's own optimal decision if he was able to ignore the gas constraint. In trying to move in the direction of reducing r^y, and toward the accumulation equation, the agent bumps up against the gas constraint. Equilibria without a binding gas constraint can lie in the interior of the gas constraint feasible region, but if the gas constraint binds, optimizing behavior leads agents to choose points on the gas constraint frontier. The accumulation equation is therefore kinked (at point B in Figure 4), with the constant gas frontier determining the effective accumulation condition for tree stock sizes larger than at point B.

The equilibrium when the gas constraint is binding occurs at point C, the intersection of the frontier/effective accumulation condition and stock equations, and the requirement for the existence of an equilibrium in this subsection is "effectively" the same as in subsection 3.1. The tree stock is unequivocally larger when the gas constraint binds, and this is consistent with recent concerns about the effect of tropical deforestation on global warming. When the demand for trees by the young increases, the price of trees rises and the output firms demand fewer trees as inputs and the investment firms demand more output to turn into trees. Both of these myopic responses by firms equilibrate the tree market at the higher price. This price is such that agents internalize the constraint and forego consumption when young. The startling result is that price taking agents internalize the public bad, a result made more transparent by the strategic behavior and game theoretical results described below. The intuition that intragenerationally, identical agents will respond to the greenhouse effect in the same way, is reinforced by the intergenerational results of this paper, where even different generations behave in the same way.

The equilibrium when the gas constraint is binding is, as in the unconstrained case, a constant per capita steady state. How can per capita values be constant, the population grow, implying that aggregate values are growing, and an aggregate absolute like the G^{max} gas constraint not be violated? The answer is that aggregate values, including output, can rise as long as the additions implied to the gas stock equal subtractions, and the tree stock is growing along with output. Each new agent born, must add to the tree stock if he is to produce output.[14]

3.4.1.1 NASH EQUILIBRIA

This knife-edge result leads to several interesting but stark conclusions about the binding gas constraint equilibrium, which derive from the special nature of the threshold externality. An infinite number of perfect information, Nash equilibria exist, in which no agent can

[14] Land availability is assumed not to limit the size of the tree stock.

improve his position by deviating from the equilibrium. Each equilibrium exists without a free rider problem. The FOC gas constraint (8') is binding in this equilibrium i.e. $\mu_t>0$, $\forall t>0$. In evaluating this constraint, an arbitrary kth agent chooses as small a tree stock as possible, foregoing as little undiscounted first period consumption as possible, while taking the size of all other agent's tree stocks as given, so that his reaction function after rewriting (15') slightly is,

$$r^{Y,k} = \frac{(1-\Delta)G + \gamma Y - h\sum_{i\neq k=1}^{N_t} r^{Y,i} - G^{max}}{h} . \tag{31}$$

Graphing this reaction function in (r^{Y*k}, $\Sigma i\neq k\ r^{Y*i}$) space, the curves for each agent lie on top of each other.

Two symmetric Nash equilibria (SNE) exist. If all agents except agent k choose to hold zero trees, then so does agent k. The agents would produce as much output as possible, as described in the unraveling scenario, consumption binge in their youth, and bring about the end of the economy in the following period. In the second symmetric equilibrium, each identical agent chooses the same stock of trees so that together with the tree stocks of all other agents, the aggregate tree stock is just big enough to keep the gas stock constant, and no bigger. This SNE with $r^{Y*i}=r^{Y*k}$ is a focal point. In this equilibrium the economy does not end, and all identical agents act in the same way, which "tends to focus the players' attention (on it) mak(ing) them all expect it and hence fulfill it" (Myerson, 1991). A coordination failure could result if the economy ends, because that SNE is Pareto inferior to the SNE when the gas stock is constant. There is no central authority to require that the correct number of trees are held in this economy. If the coordination failure, described above, occurs among agents alive at the same time, then a coordination failure results between different generations. Future generations are in a situation that is Pareto inferior to one when the economy continues, again indicating the interdependency between generations in this economy.

An infinite number of asymmetric Nash equilibria also exist. If k chooses a smaller tree stock than in the symmetric case, the response of the other $i \neq k$ agents is symmetric, each choosing a larger r^{yi} so that (31) holds. All of these Nash equilibria have the property that $G = G^{max}$, and $\exists$ an infinite number of asymmetric Nash equilibria, one for every possible size r^{yk} over all $k = N_t$ agents.

The result is that in the focal point Nash equilibrium, price taking agents internalize the greenhouse public bad. This result is consistent with the efficient private provision of a public good described by Bagnoli and Lipman (1989). There, a discrete public good is provided because each agent provides the marginal dollar that supplies the streetlight. Here, each agent saves the additional tree that keeps the catastrophe from occurring.

The result that the tree stock is larger when the gas constraint binds, is intuitively appealing because trees absorb greenhouse gases. Since the environmental good (the tree stock) and the individual good (output), can be substituted for each other (through harvesting and investment), agents give up some of their individual good to avoid the catastrophe, which raises the price and further induces investment by firms. It is interesting to note that in the focal point, the substitution from the individual to the environmental good is done symmetrically, with the burden for avoiding the catastrophe being shared uniformly by all generations. The adjustment to the greenhouse effect is also carried out by altering individual behavior, without changes in technology. The larger forest of trees drives up the price and myopic firms choose the right amount of harvesting and investment to maintain the larger forest. The price serves the standard coordination function between the supply and demand of trees in the economy.

Additional research in this economy may be able to establish if the subsection 3.1 equilibrium could exist with a binding gas constraint, if the production technology exhibited external increasing returns to scale, or technological innovation.

3.4.2 CHARACTERIZING THE BINDING GAS CONSTRAINT EQUILIBRIUM

To gain some insight into the behavior of the economy when it is perturbed away from the constrained steady state equilibrium, consider an experiment in which the economy starts out at point C in Figure 4, and a disease is found that will kill at least one tree in the following period. Without a social planner, or government, with the authority to enforce changes in output by all agents, the economy is headed for catastrophe at point D. The agent who lost the tree, everything else being equal, is faced with smaller second period consumption and,

$$\frac{\beta V'[\cdot]}{U'[\cdot]} < \frac{p_t}{p_{t+1}(1+\delta)} \quad . \tag{32}$$

The change in accumulation decisions to equate the left and right hand sides of (32), by one agent in an N_t population of agents, does not affect the economy as a whole and specifically prices, in perfect competition. Perfect foresight agents are aware of the approaching catastrophe, and the situation is similar to the one in proposition 3, when the equilibrium unraveled.

The situation is similar, but not the same. The difference in this experiment is that the economy is not in equilibrium at D, and the jump variable, price, rises as the old generation's tree supply shrinks, because a tree died, along a normal negatively sloped aggregate demand for trees. The demand for trees is negatively sloped because the harvesting firms who demand trees as productive inputs, by (11), demand fewer trees when the price rises. When the young demand fewer trees the price also rises affecting the harvesting and investment decisions of the firms. This ensures that all trees are either saved or consumed. The higher price effects the accumulation decisions of all agents, and the price continues to rise and the tree stock grow, until the economy reaches point E on the gas constraint frontier.

The tree stock in the economy grows, represented by a movement along the double line, i.e. the gas constraint frontier/effective accumulation condition, until the tree stock equilibrium equation is reached. The speed of adjustment from point E to point C is determined by δ, the natural rate of tree growth, and the amount of investment.

The cost to society of avoiding the catastrophe in terms of foregone consumption, is represented by the difference between the price at A and at C multiplied by the number of additional trees held by the young. The cost to society of violating the G^{max} threshold is clearly infinite, so the value of the additional tree saved that satisfies the gas constraint is infinite. If policymakers were to use this cost of foregone consumption, discounting intergenerationally at the rate of time preference, β^2 (Schmid, 1989), the cost would clearly be some finite amount. Without having to quantify the level of the gas called G^{max}, just realizing that catastrophic global climate change would occur at some level, and simply weighing the costs of the two alternatives, the cheaper alternative is for the economy not to destroy itself. In the constrained equilibrium the greenhouse gas constraint is binding on the economy, and agents adjust their behavior accordingly.

4. COMPARATIVE STATICS

General equilibrium comparative static results follow in Table 1.1 for the binding gas constraint constant per capita equilibrium.[15] A result of subsection 3.4.1 is that the equilibrium lies on the gas constraint frontier, so only the case when (30) holds with equality is considered.

[15]These results can be obtained by totally differentiating the system made up of (22), (23) and (29) in steady state form and applying Cramer's rule.

Table 1.1

General Equilibrium Comparative Statics for the Binding Gas Constraint

Constant Per Capita Equilibrium

	a	b	δ	h	γ	n
$\frac{dp}{d\,\cdot}$	+	−	−	−	+	+
$\frac{dr^{y}}{d\,\cdot}$	+	−	+	−	+	−

These results indicate that increases in the population growth rate (n), the productivity of investment (b) and the rate of gas absorption by trees (h), lead to a smaller per capita tree stock. Increases in the productivity of production (a), the rate of new tree growth (δ), and the rate of greenhouse gas emission (γ), lead to a larger per capita tree stock. Several of these parameters (a, b, h and γ) have the same effect on prices as they had on the tree stock. Very neatly, the parameters that provide the crucial tradeoff that gave the tree stock equation its positive slope, and made it necessary for there to be investment in the model (i.e. δ and n), have the opposite effect on prices that they have on the size of the tree stock when all other parameters in the economy are held constant. This means that when the affect in the economy as a whole of the parameters δ and n are isolated, they have the opposite affect on p and r^y, highlighting the dominance of the downward sloping gas frontier in a constrained equilibrium.

5. CONCLUSIONS

This paper has presented a simple model of an economy with a threshold negative production externality caused by the greenhouse effect. Section 3 shows the existence of two kinds of equilibria. An unconstrained, constant per capita steady state competitive equilibrium exists when the gas constraint is not binding. If the economy is reparameterized so that a binding gas constraint is imposed on that equilibrium price path, too much gas may accumulate, the catastrophic threshold could be violated and if so the price path unravels. A different equilibrium exists, in which the stock of gas remains constant and catastrophe is averted, when the catastrophic threshold is binding on the economy and agents adapt their behavior to it, a focal point. In both equilibria per capita values are constant. The extreme position has been taken that perfect information exists about, among other things, the level of a greenhouse effect catastrophic threshold, and that a severe penalty exists for violating the gas constraint, leading to the internalization of the constraint through markets. These assumptions allow the research to focus on intergenerational aspects of the global warming problem made more concrete by several game theoretical results. The results indicate that overlapping generations in an economic model are interdependent. In the focal point, all of the agents make the sacrifice to forego undiscounted first period consumption, and hold a greater stock of trees when young to avoid the catastrophe. When none do, a coordination failure exists, where this equilibrium is Pareto inferior to the one when all agents make the adjustment and hold more trees. When on a price path leading to a catastrophe, all generations are unwilling to hold trees.

Additional equilibria that can lead to catastrophe, and that never do, may exist. The perfect foresight growth path of the economy in the gas constraint binding equilibrium could be considered. Extensions will investigate if these results hold when there is a probability of catastrophe in which the catastrophic level of the gas is revealed over time, and when the tree stock is a public good. Analysis of these different scenarios will contribute to our understanding of rational behavior in response to the greenhouse effect, and when under the threat of catastrophic events in general.

APPENDIX

APPENDIX

Proof of Proposition 2: The Jacobian determinant of the system made up of (22) and (23) is non-zero by inspection, so it is possible to characterize the local stability properties of the system by linearizing around the steady state. Linearization of (22) around the constant per capita steady state yields an equation in $[p_{t+1} - p]$, $[p_t - p]$ and $[r^{y}_{t} - r^{y}]$. Linearization of (23) yields an equation in $[p_{t+1} - p]$, $[p_t - p]$, $[r^{y}_{t+1} - r^{y}]$ and $[r^{y}_{t} - r^{y}]$. These two equations can be rewritten as,

$$\begin{bmatrix} p_{t+1}-p \\ r^{y}_{t+1}-r^{y} \end{bmatrix} = \begin{bmatrix} \frac{-G}{1+n}-\frac{z^{*\prime} b\psi' x^{*\prime}}{F} & \frac{-H}{1+n}-\frac{(1+\delta)z^{*\prime}}{F} \\ \frac{b\psi' x^{*\prime}}{F} & \frac{(1+\delta)}{F} \end{bmatrix} \begin{bmatrix} p_t-p \\ r^{y}_{t}-r^{y} \end{bmatrix} \qquad (33)$$

where,

$F = -\beta V''(1+\delta)^2 r^{y} p - \beta V'(1+\delta) < 0$ if $\eta_{v,co} = -V'/V''c^{o} > 1$,

$G = U''[af' z^{*\prime} p - z^{*} p - z^{*\prime} p^2 - r^{y} p] + U' > 0$ since $af'(\cdot) = 0$,

$H = -U'' p^2 - \beta V'' p^2 (1+\delta)^2 > 0$.

Using these results, it is possible to sign the coefficient matrix as follows,

$$\begin{bmatrix} p_{t+1}-p \\ r^y_{t+1}-r^y \end{bmatrix} = \begin{bmatrix} <0 & >0 \\ <0 & <0 \end{bmatrix} \begin{bmatrix} p_t-p \\ r^y_t-r^y \end{bmatrix} \tag{34}$$

This system is saddlepath stable, as determined qualitative-graphically in Figure 2.∘

LIST OF REFERENCES

REFERENCES

Allais, Maurice. 1947. Economie et intérêt. Imprimerie Nationale, Paris.

The American Society of Mechanical Engineers. 1989. "Energy and the Environment." A general position paper of The American Society of Mechanical Engineers (July): 29-30.

Blanchard, Olivier Jean and Charles M. Kahn. 1980. "The Solution of Linear Difference Models Under Rational Expectations." Econometrica 48(5): 1305-11.

Batie, Sandra S. 1989. "Sustainable Development: Challenges to the Profession of Agricultural Economics." Presidential Address, American Journal of Agricultural Economics 71(5): 1083-1101.

d'Arge, R. C. and K. C. Kogiku. 1973. "Economic Growth and the Environment." Review of Economic Studies 40(1):61-77.

Dasgupta, Partha. 1982. The Control of Resources. Basil Blackwell Publisher, Ltd., Oxford, England.

Diamond, Peter A. 1965. "National Debt in a Neoclassical Growth Model." American Economic Review (December): 1126-1150.

Environmental Resources Limited. 1983. Unipub for the Commission of the European Communities. Directorate-General for Environment. Acid Rain: A Review of the Phenomenon in the EEC and Europe.

Firor, John. 1990. The Changing Atmosphere: A Global Challenge. Yale University Press, New Haven.

Gennotte, Gerard and Hayne Leland. 1990. "Market Liquidity, Hedging, and Crashes." American Economic Review 80(5):999-1021.

John, Andrew, Rowena Pecchenino and Stacey Schreft. "The Macroeconomics of Dr. Strangelove: An Overlapping-Generations Model of the Apocalypse." The American Economic Review forthcoming.

John, Andrew, Rowena Pecchenino, David Schimmelpfennig and Stacey Schreft. 1990. "Short-Lived Agents and Long-Lived Environment." Michigan State University, Department of Economics, Econometrics and Economic Theory Paper No. 8903.

Hansen, James and Sergej Lebedeff. 1987. "Global Trends of Measured Surface Air Temperature." Journal of Geophysical Research 92(D11): 13,345-372.

Karl, Thomas R., H. E. Diaz, and G. Kukla. 1988. Journal of Climate 1:1099.

Kemp, Murray C. and Ngo van Long. 1980. "The Underexploitation of Natural Resources: A Model with Overlapping Generations." Exhaustible Resources, Optimality, and Trade. North-Holland Publishing Company, Amsterdam.

Keeler, Emmett, Michael Spence and Richard Zeckhauser. 1971. "The Optimal Control of Pollution." Journal of Economic Theory 4:19-34.

Löfgren, Karl-Gustaf. 1991. "Another Reconciliation between Economists and Forestry Experts: OLG-Arguments." Environmental and Resource Economics 1(1):83-95.

Myerson, Roger B. 1991. Game Theory: Analysis of Conflict. Harvard University Press, Cambridge, Massachusetts.

Norgaard, Richard B. 1984. "Coevolutionary Development Potential." Land Economics 60:160-73.

Pearce, David. 1987. "Foundations of an Ecological Economics." Ecological Modeling 38:9-18.

Pearce, David W. and R. Kerry Turner. 1990. Economics of Natural Resources and the Environment. The Johns Hopkins University Press, Baltimore.

Ritchie, Joe T., Earl Burnett, and R.C. Henderson. 1972. "Dryland Evaporative Flux in a Subhumid Climate: III. Soil Water Influence." Agronomy Journal 64:168-173.

Samuelson, Paul A. 1958. "An Exact Consumption-loan Model of Interest With or Without the Social Contrivance of Money." Journal of Political Economy 66(6): 467-482.

Sandler, Todd. 1982. "A Theory of Intergenerational Clubs." Economic Inquiry 20:191-208.

Schelling, Thomas C. 1992. "Some Economics of Global Warming." The American Economic Review 82(1):1-14.

Schimmelpfennig, David E. 1992. "The Dynamics of Overlapping Generations Economies with Thresholds." Michigan State University, Department of Economics, mimeo.

Schmid, A. Allan. 1989. Benefit-Cost Analysis: A Political Economy Approach Westview Press, Boulder.

Schneider, Stephen H. 1990. Global Warming: Are We Entering the Greenhouse Century? Vintage Books, New York.

Spash, Clive L. and Ralph C. d'Arge. 1989. "The Greenhouse Effect and Intergenerational Transfers." Energy Policy (April): 88-96.

Thom, René. 1975. Structural Stability and Morphogenesis: An Outline of a General Theory of Models W. A. Benjamin, Inc. Reading, Massachusetts.

Thunberg, Bo. 1988. "End Result in Acid Lakes: Just a Few Species Survive." Acid Magazine 7: 6-7.

Varian, Hal R. 1979. "Catastrophe Theory and the Business Cycle." Economic Inquiry 17(1): 14-28.

World Meteorological Organization. 1990. Policymaker: Summary of the Scientific Assessment of Climate Change report to the Intergovernmental Panel on Climate Change, Blackwell, United Kingdom.

Zeeman, E.C. 1977. Catastrophe Theory: Selected Papers, 1972-1977 Addison-Wesley Publishing Company, Reading, Massachusetts.

CHAPTER TWO — ESSAY TWO
AN EMPIRICAL INVESTIGATION OF THE CAPITAL-ENVIRONMENT TRADEOFF

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ABSTRACT

An Empirical Investigation of the Capital-Environment Tradeoff

Two types of analyses are undertaken. In a time-series approach, dynamic causal relations are established between various measures of income and air pollution by extending recent panel-data techniques for lagged dependent variables. Causation is bidirectional when the income measure and pollution are closely linked, by the theoretical framework. Income causes pollution when the measures are not closely linked. The results from this new Granger test are interpreted in a separate structural framework and used to specify two static models that take advantage of both the information about the exogeneity of variables and the panel structure of the data. There is some evidence of external benefits from pollution control.

"... environmental damage increases until per capita income increases to a point where people ... feel they can ask government to trade some growth for environmental healing."
George F. Will, columnist[16]

1. INTRODUCTION

Adding together the direct costs of pollution control is an accounting exercise. Guidelines for performing that exercise exist (EPA, 1990). Included are the costs to install pollution control devices, maintenance and cleaning of the device, and opportunity costs during down time. The overall cost to society of environmental control, however, can not be evaluated until the countervailing benefits of pollution control are also considered. These benefits include public goods that affect macroeconomic variables. For instance, improving air quality improves worker health, resulting in fewer sick days, improved productivity and increased output. Improved air quality also adds to life expectancy and increases the cost effectiveness of investments in human capital, hypothetically again, increasing worker productivity.

This paper tests these relationships and makes explicit the nature

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[16]George F. Will is a member of the Washington Post Writer's Group. The quote is from a column "The high anxiety level of gloomy environmentalists," that appeared May 31, 1992.

of the tradeoff between the environment and selected macroeconomic variables. Granger causality in dynamic panel-data is found to run from air pollution to income, with the level of ambient suspended particulates having a positive effect on the level of real per capita income in a U.S. county. When Granger causality runs in both directions, the income coefficient in the structural model flips sign and a higher level of income is associated with lower level of pollution. The conceptual framework in section 2, explores factors that raise income when pollution falls. These factors are classified generally as market benefits from pollution control.

Relative to non-market values that can only be captured by contingent, travel cost and hedonic methods, "these fine (market) measures of benefits can easily be captured in macro models" (Mendelsohn, 1992), and have been analyzed in theoretical settings (Becker 1982 and John et al 1991). The existence of market benefits has not been tested empirically however, and in fact U.S. macroeconomic variables have not been analyzed in an empirical model with pollution at all.

Existing evidence regarding the impacts of pollution control has been obtained at the industry level and is, at best, somewhat mixed. MacAvoy (1987) examined the relationship between investment in pollution control and industry emissions. He found significant statistical relationships that indicated that investments in control equipment led to reductions in industry emissions (pp. 118 and 120-121). Broder (1986) examined the relationship between industry-level pollution control and ambient air quality and found no statistically significant relationship. These two pieces of evidence together imply that while pollution control may reduce emissions, these reductions may have little impact on ambient air quality and, as a consequence, generate few of the benefits that may improve worker health and productivity.

The approach of this paper is to use a new twist on Granger's (1969) test and other current econometric tools to examine annual county level air pollution, income and manufacturing data. The conceptual model is presented in section 2, and the econometric models are discussed in section 3, along with statistical results. Conclusions follow in section 4.

2. THE CONCEPTUAL MODEL

A standard neoclassical production function is the most useful economic model in which to consider the macroeconomic relationship between pollution and income. The production function, describing the supply side and used in the derivation of the cost function, explains output as a function of capital and labor. Here, in equation (1), the amount of pollution generated by a firm i in period t (e_t^i) is a function (h_t^i) of the amount of output produced (Y_t^i) and the firm's investment in abatement capital (A_t^i).

$$e_t^i = h_t^i(Y_t^i, A_t^i) \tag{1}$$

This framework predicts that increases in output and decreases in abatement, add to pollution. The ambient level of pollution (E_t) is the sum of pollution by each firm or,

$$E_t = \sum_{i=1}^{n} e_t^i = \sum_{i=1}^{n} h_t^i(\cdot, \cdot) \tag{2}$$

where n is the number of firms. The production function framework can also be used to describe the relationship, in (3), where the inputs, capital (K), labor (L) and the by-product pollution, jointly produce output, or equivalently income.

$$Y_t^i = f^i(L_t^i, K_t^i, E_t, e_t^i) \tag{3}$$

where a higher ambient level of pollution adversely affects income, but a higher level of pollution by firm i, besides adding to the ambient level of pollution, also increases firm i's output. Whether it is (1) or (3) that exists in practice, can be tested by determining the direction of causality between income and pollution. In (1) income causes pollution, while in (3) pollution causes income. A hint of these causal relationships can be obtained with panel-data using the technique in section 3. The results of these tests do not give a complete picture of the causal relationship between two variables, because the test does not say anything about contemporaneous causality. The test gives an accurate picture of the effect of past values of a variable on the current value of another variable. The paper tests the structural models (1) and (3) directly, and this estimation is carried out with limited data. In addition, in testing the structural models the assumption is made that the dynamic causal relationship found in the Granger test also holds for contemporaneous causality.

The nature of the data limitations are that information about all polluting firms nationwide is not available. The conceptual model indicates that if firm level data was available it would be useful to include it in the structural model. The aggregate counterparts of the structural equations (1) and (3), can be estimated, providing a second way of looking at the available data. The aggregate structural equations provide a test for market benefits,[17] by determining if the relationship between pollution and income is positive or negative.

A positive or negative relationship says something about market benefits in (1), because if the relationship is negative, pollution reduction generates macroeconomic benefits reflected in a higher level of income. If on the other hand, if the relationship is positive in (1), pollution can be thought of only as a by-product of production, without

[17]Nonmarket environmental services are not easily captured in the current framework.

macroeconomic benefits. In (3), a negative relationship indicates the existence of a pollution externality, and lower pollution leads to higher income through macro-benefits. In contrast, once again, a positive relationship indicates that a larger pollution externality is associated with higher levels of income, and benefits of pollution reduction are not indicated in the current framework.

These aggregate tests for macro-market benefits work regardless of the direction of causality. If causality runs from income to pollution, as in (1), or from pollution to income, as in (3), a negative relationship indicates the existence of macroeconomic benefits from the control of the ambient level of pollution. A positive relationship in either (1) or (3) indicates the absence of benefits.

In a static model the production technology is, ceteris nonparibus, assumed to be constant. A time-series model with allows for technological innovation with the possibility for a new "constant" production function each period. Cross-sectionally, the production function may be constant within one county over time, but may vary between counties within one time period. These technological factors can both be tested for, in a fixed effects panel-data model. The former are time or period fixed effects and the latter are county fixed effects, and both are shown to exist in the models in subsection 3.3.

3. EMPIRICAL RESULTS

The conceptual model in section 2 points to two possible avenues through which income and pollution effect each other. It may be possible to estimate an aggregate form of (1) by itself. In order to do this, income must be strictly exogenous. It is possible to get an idea if this is the case using the novel panel-data Granger causality test in subsection 3.2. The test gives the direction of dynamic causality.

If the direction of contemporaneous causality is the same as the direction of dynamic causality, then strict exogeneity can be established. Sargent (1981) discusses the importance of strict exogeneity in econometric modelling. A test of contemporaneous causality does not exist, so contemporaneous and dynamic causality are assumed to run in the same direction. With this assumption, a static pooled time series-cross section structural model based on (1), can be specified and the results from that model interpreted. If income and pollution are determined simultaneously, both (1) and (3) must be estimated simultaneously.

3.1 THE DATA

Estimating the structural system in section 2 is not possible. Data does not exist on the levels of pollution and abatement undertaken by all polluting firms. It is possible, however, to estimate aggregate forms of either model (1) or (3), or both, using macroeconomic data. The Aerometric Information Retrieval System administered by the EPA has hourly readings of ambient concentrations of seven pollutants. An unpublished compilation of annual means of each pollutant from thousands of monitors,[18] revealed that the most complete coverage of the U.S. exists for total suspended particulates (TSP). This is fortunate because TSP, as the by-product of burning fossil fuels and several other industrial activities (Goldsmith and Friberg, 1977) is, of the available pollutants, the most closely related to industry output and contributes directly to health problems, like bronchitis, that effect many working adults every year in addition to the elderly.

3.2 IS INCOME EXOGENOUS?

To carry out the Granger test and establish the direction of dynamic causality between income and pollution it is necessary to randomly select one monitor for each county and to match that series of annual observations up with real per capita income or real manufacturing income per worker in that county (REIS, 1991). This pooled time series-cross

[18]The compilation of hourly data was undertaken specifically for this research project. I am grateful to EPA employees, David Hunt for writing the Ad Hoc report that generated the data, and to Tom Link for troubleshooting the running of the report. The report gives annual simple averages for ambient concentrations of seven different pollutants, measured as the density of the pollutant per volume of air.

section data is suspected of having fixed county effects, confirmed in subsection 3.3.

3.2.1 A NEW GRANGER TEST FOR PANEL-DATA

Granger's (1969) causality test involves simply testing the significance in a time-series of lagged values of a variable, in a regression of a current left-hand side (LHS) variable on lagged values of the LHS variable. The intuition is that if only the lagged values of the LHS variable are significant, then the other variable does not Granger cause the current LHS variable. This idea is extended to panel-data by specifying a linear model, and testing the restricted model with lagged values of the left-hand side (LHS) variable against the unrestricted model with lagged values of both the right-hand side (RHS) and LHS variables.

$$y_t = \sum_{i=1}^{K_1} y_{t-i}\alpha_i + \sum_{i=1}^{K_2} x_{t-i}\beta_i + u_t \tag{4}$$

where $i=1,\ldots,n$, and u_t satisfies the classical zero conditional mean, no serial correlation, and homoskedasticity assumptions. If the RHS variable, x_t, "Granger causes" the LHS variable, it will be possible to reject the restricted model, H_0: $\beta=0$, and not to reject the unrestricted model, H_1: $\beta\neq0$ in (1), where $\beta=(\beta_1,\ldots,\beta_n)'$.

The problem in estimating this model with pooled time series-cross section data is that fixed effects panel-data model specifications with lagged dependent variables yield inconsistent results because "the within transformation induces a correlation of order 1/T between the lagged dependent variable and the error" (Ahn and Schmidt, 1992). Once the individual fixed effects are removed by the standard technique of first-differencing (Keane and Runkle, 1992) two-stage least squares (2SLS) is consistent, if not efficient, and the Granger test on the nested models i.e. $\beta=0$ vs. $\beta\neq0$ in (1), can be carried out by the procedure in Wooldridge (1990).

Instruments are selected for the RHS variables in the first stage of 2SLS that are uncorrelated with the error in the equation. Since the data is first-differenced, the first lag of the first variable on the RHS, y_{t-1}, does not have itself as a good instrument. To avoid this problem, all of the y_{t-i}'s with $i\geq2$ are used as instruments for each t. All of the other RHS variables (i.e. the x_{t-i}'s), have themselves as instruments, because they are uncorrelated with the LHS, and a perfect fit is obtained for each x_{t-i} instrument in the first stage.

For 2SLS, the standard sum of squared residuals (SSR) form of the F-statistic has an unknown distribution, even asymptotically (Wooldridge, 1990). To test the joint significance of the β's, the Lagrange multiplier test statistic for the restricted vs. the unrestricted model is computed. This statistic has a χ^2 limiting distribution, with degrees of freedom equal to the number of β's (i.e. K_2). Results of this test are in Tables

2.1 and 2.2.

Table 2.1

χ^2_{K2} Statistics for Tests of Granger Causality Between Real Per Capita Income and Total Suspended Particulates (TSP) in a Panel of U.S. Counties 1970–1984[19]

Number of lags (K_2)	One (7.88)	Two (10.60)	Three (12.84)	Four (14.86)	Five (16.75)
of TSP	10.03	13.08	13.94	20.19	35.91
of Income	1265	2758	3664	4322	4603

[19]All numbers have been rounded to the fourth significant digit, and are significant at the ≥½% level, with critical values in parentheses at the top of each column.

Table 2.1 should be read as follows. As explained above, the Granger test involves testing the significance of lags of a variable. The variable tested can be any panel that is not on the LHS, i.e. the x's in (4). The first column in Table 2.1 has TSP in a row when TSP is the x, and income in a row when it is the x variable. The columns that are each headed by a different number of lags, refers to a regression with that many lags of the variable in the first column. Table 2.1 then refers to ten regressions, five for each x variable, and allows the reader to compare the joint significance of the variable that does not appear on the LHS of each regression, or the Granger causality for that variable, with different numbers of lags.

Table 2.1 shows that lagged real per capita income is significant in explaining TSP and an aggregate form of conceptual model (1) is correct when using these macroeconomic variables. There exists a production relationship where income production also generates pollution. Income is said to "Granger cause" TSP. If past levels of income in a county had been different, then the current level of TSP, the measure of pollution used in the paper, will be different in that county.

It is not as clear from Table 2.1 if air pollution causes income. The second conceptual model (3), says that pollution is an externality, and that the ambient level of pollution effects output. This second model is intuitively appealing, but it is only Table 2.2 that bears this story out.

The χ^2_{K2} statistics for income in Table 2.1 tell a different story. By far the strongest signal is from income to pollution, indicating that once a past series of income is different, the current level of pollution produced as a result is different. The χ^2_{K2} statistics are between 126 and 263 times greater for income than pollution, and pollution is barely significant at the ≥½% level. This may indicate that there is very little feedback from pollution to income, and the signal is being picked up because of the large sample used.[20] The sample size is around 7000, because each of the over 550 counties used in the sample has a time series of observations between 1969 and 1984.[21]

Two things can be done as a result of these findings. It may be the case that gross income is contemporaneously exogenous, and results from a static fixed effects panel-data structural model can be reliably interpreted. This is the first set of results in subsection 3.3. First, it is prudent to test whether these relationships hold for a finer measure of income. If income is strictly exogenous, the results in Table 2.1 should be the same, for the same tests with manufacturing income in place of gross income. Manufacturing income comes from industrial activity

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[20]The degrees of freedom corrected version of the test statistic is approximately $F_{K2,N-K}$ where N is the size of the sample and $K=K_1+K_2$ (Wooldridge, 1990). This corrected statistic gave the same results for TSP as were obtained with the χ^2_{K2} statistic. All lags are significant at the ≥½% level.

[21]The sample is unbalanced with some counties having more of the years between 1969 and 1984 than other counties. Within each county series, very few missing observations were encountered.

alone, and may help to solidify the connection between gross income and TSP. These results are in Table 2.2.

Table 2.2

χ^2_{K2} Statistics for Tests of Granger Causality Between Real Manufacturing Income Per Employee and Total Suspended Particulates (TSP) in a Panel of U.S. Counties 1970–1984[22]

Number of lags (K_2)	One (7.88)	Two (10.60)	Three (12.84)	Four (14.86)	Five (16.75)
of TSP	4047	4628	6619	6646	6570
of Manufacturing	2710	3765	4204	4889	4814

[22]All numbers have been rounded to the fourth significant digit, and are significant at the ≥½% level, with critical values in parentheses at the top of each column.

Table 2.2 should be read in the same manner as Table 2.1. Here manufacturing income is one of the x's in (4) as indicated in column one. Once again, each block presents a significance test of either TSP or manufacturing income, or a separate Granger Test, at a different number of lags.

The results in Table 2.2 indicate that bidirectional dynamic causality can not be rejected between manufacturing income and TSP, the pollution measure. Aggregate forms of the conceptual models (1) and (3) both apply. In a reversal of the results in Table 2.1, the χ^2_{K2} statistics for pollution are between 1.2 and 1.6 times greater than the manufacturing statistics. This indicates that an even stronger argument for causality from manufacturing income to pollution exists in Table 2.2, than from pollution to manufacturing income. In Table 2.1, the results indicate that most of the relationship goes from pollution to gross income.

3.3 A COMPARISON OF SINGLE EQUATION AND SIMULTANEOUS EQUATIONS PANEL-DATA MODELS WITH FIXED EFFECTS

The results of subsection 3.2 indicate two directions for further analysis. The weak indication of dynamic causality from pollution to income in Table 2.1, may indicate that a linear panel-data model can be consistently used to estimate the aggregate form of the structural equation (1), because it may be that pollution is exogenous. The results in Table 2.2 indicate that a simultaneous model is required with aggregate forms of both structural equations (1) and (3), when a model with manufacturing income and pollution is estimated.

3.3.1 A SINGLE EQUATION TWO-WAY FIXED EFFECTS PANEL-DATA MODEL

The marginally significant test statistics in Table 2.1, together with the large sample used in this study, may indicate that this new Granger test for panel-data is picking up an economically unimportant dynamic causality signal. In addition, this Granger test says nothing about contemporaneous causality. Both may be absent, indicating that income is strictly exogenous. If this is true, a static two-way fixed effects panel-data model for structural equation (1), i.e. one with both county and time dummy variables, will yield consistent parameter estimates. Results are in Table 2.3.

Table 2.3

Two-way Fixed Effects Panel-Data Results With Gross Per Capita Income and Total Suspended Particulates (TSP) in U.S. Counties 1970–1984

Dependent variable	Constant term[a]	Income coefficient[a]	County dummy test[b]	Period and county effects[b]
TSP	60.859 (2.242)	0.00054471 (0.000139)	34.24204 ≥0.0000%	6.62245 ≥1.0070%

R^2: .7367

[a]Numbers in parentheses are standard errors.
[b]The Hausman (1978) statistic, presented with the level of significance below, argues for fixed effects over random effects.

Table 2.3 presents the results of estimating the aggregate form of a single structural equation from the conceptual model. Equation (1) is estimated because the Granger test using (4) indicates that income is exogenous from Table 2.1, once it is assumed that dynamic causality implies the same thing about contemporaneous causality. The positive income coefficient in Table 2.3 indicates that higher income leads to higher pollution, and there is no evidence of benefits from pollution control. If the U.S. decides to reduce pollution, the cost is reflected in reduced income.

Grossman and Krueger (1991) found in an international panel of 36 cities in 17 countries (in 1982) that "ambient levels of ... dark matter suspended in the air increase with per capita gross domestic product (GDP) at low levels of income," and decrease with high levels. To test for the relationship found by Grossman and Krueger in this U.S. panel, the counties were divided into three groups:

1. Counties with real per capita income (RPCI) less than or equal to the RPCI at one standard deviation below the mean of all counties. This group includes 767 observations;

2. Counties with RPCI greater than or equal to the RPCI at one standard deviation below the mean of all counties. This group includes 6552 observations, and;

3. The complete group of all 7319 observations in the original sample.

The structural equation (1) is re-estimated with the static two-way fixed effects panel-data model, for each of the sub-samples described by 1. and 2. above. The model is estimated for the complete sample in Table 2.3, and so is not re-estimated for this test. The Chow test for structural change, failed to reject the null hypothesis of no structural change.

Even though Grossman and Krueger fail to test the exogeneity of their RHS variables, the present study indicates from Table 2.1, that income may indeed go on the RHS of a single equation system, as Grossman and Krueger assumed. In contrast to Grossman and Krueger's international results, it does not appear that the relationship between pollutants and per capita income that has been blamed for the high levels of pollution in developing countries (Steer, 1992) exists in the present U.S. data.

3.3.2 A SIMULTANEOUS EQUATIONS PANEL-DATA MODEL WITH FIXED EFFECTS

The results in Table 2.3 may lead to incorrect conclusions regarding the existence of benefits from pollution control, because it may have been a mistake to ignore the weak causal relationship in Table 2.1, from pollution to income. It is clear from Table 2.2 that neither manufacturing income nor pollution is exogenous and so a simultaneous model is necessary to estimate the structural equation system of (1) and (3).

A simultaneous panel-data model allows the estimation of the model with manufacturing income, and testing the conjecture that results are different when bidirectional causality in the data is exploited. 2SLS by demeaning, i.e. doing the within transformation that subtracts the mean from each variable may be inconsistent when fixed individual effects are present. It has been established that 2SLS can be done on panel-data if the effects are random (Hsiao, 1986). Fixed individual effects are clearly present in this data and are first-differenced away. Then 2SLS is done on both structural equations (1) and (3), along with a dummy variable for each year. The dummy variables together take account of the fixed time effects.

In order to do 2SLS appropriate instruments for manufacturing income and pollution are required. An instrument for manufacturing income is manufacturing employment, and for pollution is total population, both available on a county basis. These are good instruments because it can be shown using the technique in subsection 3.1, that manufacturing income does not dynamically cause manufacturing employment, and that pollution does not dynamically cause manufacturing employment. Even though this test does not indicate the absence of contemporaneous causality directly, it gives an indication that contemporaneous causality is not important, so that current as well as lagged values of the exogenous variable can be safely included in the instrument set.[23] The Granger test with panel-

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[23] χ^2_{K2} statistics for first-differenced manufacturing employment with manufacturing income, and population with pollution are available from the author on request.

indicates directly that lagged values can be included in the instrument set.

Table 2.4

Simultaneous Linear (2SLS) Fixed Effects Panel-Data Results With Real Manufacturing Income Per Employee and Total Suspended Particulates (TSP) in U.S. Counties 1970-1984

Dependent variable	TSP	Manufacturing income
Constant	16.436 (11.07)	0.78822** (0.07015)
Coefficient of fitted variable[a]	-17.273+ (7.965)[b]	0.062502* (0.02574)
Effect of 1970 (compared to 1969)	6.5106 (5.093)	0.33699* (0.1402)
Effect of 1971 (compared to 1969)	2.5995 (5.827)	0.73007** (0.1777)
Effect of 1972 (compared to 1969)	3.3213 (7.130)	0.92925** (0.1900)
Effect of 1973 (compared to 1969)	4.3703 (5.598)	0.61121** (0.1213)
Effect of 1974 (compared to 1969)	7.4258 (8.346)	0.88748** (0.1330)
Effect of 1975 (compared to 1969)	13.030 (12.82)	1.2832** (0.1435)
Effect of 1976 (compared to 1969)	16.998 (11.97)	0.89362** (0.08976)
Effect of 1977 (compared to 1969)	3.0193 (4.337)	0.48352** (0.1093)
Effect of 1978 (compared to 1969)	3.5812 (5.020)	0.56752** (0.1157)
Effect of 1979 (compared to 1969)	0.31588 (2.086)	0.22824* (.09695)
Effect of 1980 (compared to 1969)	0.74435 (1.506)	-0.12628 (0.09224)
Effect of 1981 (compared to 1969)	-4.9067* (2.467)	0.63686** (0.2147)
Effect of 1982 (compared to 1969)	-14.285** (2.375)	0.58221 (0.3133)
Effect of 1983 (compared to 1969)	4.4716 (4.457)	0.41512** (0.09194)

Note: Numbers in parentheses are standard errors
[a]The fitted value from the first stage, has first-differenced manufacturing employment (for manufacturing income) or population (for TSP), and their lags, and the time dummy variables as instruments.
[b]This standard error is robust to heteroskedasticity and the almost certain serial correlation introduced by first-differencing the data. See Wooldridge (1989a) for details of the calculation for ordinary least squares (OLS).
**Significantlydifferent from zero at the ≥1% confidence level.
+ Significantly different from zero at the ≥2.5% confidence level.
* Significantly different from zero at the ≥5% confidence level.

Table 2.4 shows the 2SLS results of the estimation of the aggregate form of structural equations (1) and (3) simultaneously. In the second column TSP is on the LHS and in the third column manufacturing income is on the LHS. Each of the annual fixed effects are in rows 4 to 17. Comparison of structural estimation when gross income is assumed to be exogenous, as in Table 2.3, to structural results when manufacturing income, which is not exogenous, is included in a simultaneous fixed effects panel-data model, as in Table 2.4, shows that very different results are found. The assumption about the causal relationship between variables in panel-data models with fixed effects, significantly affects the results. The coefficient on one of the simultaneous variables, manufacturing income, is negative when the 2SLS specification is used. In the single equation model the coefficient on gross income is positive.

This difference in signs is crucial. The negative coefficient on the fitted value for real per capita manufacturing income in the regression with TSP on the LHS, indicates a negative effect of income on pollution.[24] This argues for human benefits from pollution control, even

[24]The 2SLS standard error of this coefficient is robust to heteroskedasticity and the serial correlation induced by first-differencing the data to remove the fixed individual effect. The individual effect had to be removed because the within estimator is inconsistent when the RHS variable is not strictly exogenous. See Keane and Runkle (1991) and discussion. The computationally simple method for correcting the 2SLS standard error involves running auxiliary regressions with the fitted values from the first stage, and manipulating the reserved residuals (Wooldridge, 1989b).

though they may be small. As the level of pollution falls, the income in counties across the U.S. in one of the structural equations (1), actually rises in real per capita terms. The higher level of income reflects increased productivity and investments in human capital, leading to improved worker health and well-being. These macroeconomic benefits can also come from increased activity from non-polluting firms, having the same affect on work related illness.

These results indicate why opposition exists to the 1990 Clean Air Act. In the present setting, the evidence of macroeconomic market benefits from pollution control is small, explaining why environmental and economic growth policies are in conflict. Economists have argued for weighing the costs and benefits of the Clean Air Act (Portney, 1990). The results of this subsection show that even though the effects are subtle, pollution control can increase income, and environmental and general economic policy become important complements. More research into the nature of the benefits from pollution control is needed before specific policy recommendations can be made, but Table 2.4 indicates that these benefits may indeed exist.

4. CONCLUSIONS

This paper has presented a novel method for testing Granger causality in panel-data. A recent literature has established how to avoid inconsistency when estimating panel-data models with lagged dependent variables and fixed effects (Ahn and Schmidt 1992, Keane and Runkle 1991). Omitted variables and individual coefficient significance tests in these 2SLS specifications have been worked out by Wooldridge (1990, 1989b). Two types of analyses are undertaken. The Panel-data literature is extended to include a Granger test of causality. These dynamic tests show that income causes TSP, the measure of pollution in the paper, but not necessarily vice versa. The same tests indicate that manufacturing income causes TSP, and that TSP also causes manufacturing income. This result is consistent with the conceptual framework of section 2. Manufacturing income and the air pollution from industrial activity are closely associated with each other, whereas gross income and pollution are further removed.

In contrast to the time-series type Granger tests of causality between two variables, the second set of empirical results are from static structural panel-data models. The formulation of the two structural panel-data models relies on information from the Granger tests. In the first structural model, the absence of dynamic causality from TSP to gross income is interpreted as indicating the absence of contemporaneous causality, and the exogeneity of gross income. Utilizing this information, a static two-way fixed effects panel-data model can be reliably interpreted using pollution as the dependent variable, in the structural equation (1). The period effects indicate the importance of technological change in the macroeconomy, and fixed individual county effects are shown to exist. The positive coefficient on income indicates that macroeconomic market benefits from pollution control and the reduction of ambient TSP, are not evident in this formulation. The Granger test, however indicates a weak causal relation that it may not be appropriate to ignore.

The presence of dynamic causality from TSP to manufacturing income and vice versa, indicates bidirectional contemporaneous causality, and the need to specify a different structural model for these variables. The technique is the same as that used for the Granger test, now carried out on the structural equations (1) and (3). The county level panel-data is first-differenced to remove the fixed individual effect, then 2SLS is done on both structural equations including time dummy variables for each year. The dummy variables control for fixed period effects. Since both the pollution and manufacturing income series appear to be stationary from their plots, first-differencing introduces some serial correlation, so the standard error on the manufacturing income coefficient is recalculated in robust form so the estimated coefficients can be reliably interpreted.

In this second structural model the manufacturing income coefficient in the first structural equation has the negative sign that indicates the presence of macroeconomic benefits. The evidence for the existence of these benefits is not overwhelming because the sign on the pollution coefficient in the other structural equation is positive, but it is remarkable that evidence of this subtle characteristic of the U.S. macroeconomy exists at all.

In the current framework, examples exist where benefits from pollution control are not captured because they offset the market benefits indicated by the income variable. Air pollution control, for example, reduces maintenance costs; air filters do not need to be replaced as often and paint lasts longer, lowering production costs. This represents a decrease in expenses to one firm, but a reduction in revenue to the maintenance company, with an ambiguous affect on income. This paper represents a first step in tying macroeconomic and environmental factors together empirically. Some sources of benefits are not captured by the present technique.

The hint at the existence of macroeconomic benefits from pollution control found in Table 2.4 suggests that more complete structural models with data on individual firms and their location choices that obviously effect regional pollution should be investigated. The present model is sensitive to unobserved effects, and this problem may be alleviated with micro pollution and production data. Within the present structure it is wise not to draw policy conclusions on the basis of these few results.

Extensions to the present research could include the same tests with different pollutants and measures of income, even different macroeconomic variables and pollution. As an example of the former, ambient sulphur dioxide concentrations are available from the same AIRS database, and so is income from electric and gas public utilities. The causal connections between these additional variables may provide a better indication of the macroeconomic market benefits to health and welfare from the control of pollution. In the future, results from more detailed structural models may be available.

LIST OF REFERENCES

REFERENCES

Ahn, Seung C. and Peter Schmidt. 1992. "Efficient Estimation of Models for Dynamic Panel Data," unpublished manuscript, Michigan State University.

Becker, Robert A. 1982. "Intergenerational Equity: the Capital-Environment Trade-Off." Journal of Environmental Economics and Management, 9:165-185.

Broder, Ivy E. 1986. "Ambient Particulate Levels and Capital Expenditures: An Empirical Analysis." American Statistical Association Proceedings: 288-293.

Goldsmith, John R. and Lars T. Friberg. 1977. "Effects of Air Pollution on Human Health." in Arthur C. Stern, ed., Air Pollution, Volume 2, The Effects of Air Pollution, New York: Academic Press

Granger, C. W. J. 1969. "Investigating Causal Relations by Econometric Models and Cross-Spectral Methods." Econometrica 37(3):424-438.

Grossman, Gene M. and Alan B. Krueger. 1991. "Environmental Impacts of a North American Free Trade Agreement," unpublished manuscript Princeton University.

Hausman, John A. 1978. "Specification Tests in Econometrics." Econometrica 46(6):1251-1271.

Hsiao, Cheng. 1986. Analysis of Panel Data, Cambridge University Press, Cambridge, The United Kingdom.

John, Andrew, Rowena Pecchenino, David Schimmelpfennig and Stacey Schreft. 1991. "Short-lived Agents and Long-lived Environment." Michigan State University, Department of Economics, Econometrics and Economic Theory Paper No. 8903.

Keane, Michael P. and David E. Runkle. 1992. "On the Estimation of Panel-Data Models With Serial Correlation When Instruments Are Not Strictly Exogenous." Journal of Business & Economic Statistics, 10(1):1-9.

MacAvoy, Paul W. 1987. "The Record of the Environmental Protection Agency in Controlling Industrial Air Pollution," in Richard L. Gordon, et al, eds., Energy: Markets and Regulation, Essays in honor of M.A. Adelman, The MIT Press, Cambridge, Massachusetts

Mendelsohn, Robert. 1992. "Macroeconomic Assessments of Environmental Regulations: Comprehensive or Deceptive?" Essay in AERE Newsletter 12(1):9-10.

Portney, Paul R. 1990. "Policy Watch: Economics and the Clean Air Act." The Journal of Economic Perspectives, 4(4):173-181.

Regional Economic Information System (REIS). 1991. CD-ROM database. The Bureau of Economic Analysis, U.S. Department of Commerce.

Sargent, Thomas J. 1981. "Interpreting Economic Time Series." Journal of Political Economy 89(2):213-248.

Steer, Andrew. 1992. "The Environment for Development." Finance and Development: A Quarterly Publication of the International Monetary Fund and the World Bank 29(2):18-21.

U.S. Environmental Protection Agency (EPA). 1990. Verification of Simplified Procedures for Site-Specific SO2 and NOX Control Cost Estimates. Washington, D.C.: National Technical Information Service.

Wooldridge, Jeffrey M. 1990. "A Note on the Lagrange Multiplier and F-statistics for Two Stage Least Squares Regressions." Economics Letters 34:151-155.

Wooldridge, Jeffrey M. 1989a. "A Computationally Simple Heteroskedasticity and Serial Correlation Robust Standard Error for the Linear Regression Model." Economics Letters 31:239-243.

Wooldridge, Jeffrey M. 1989b. "Regression-Based Inference in Linear Time Series Models with Incomplete Dynamics," unpublished manuscript, Michigan State University.