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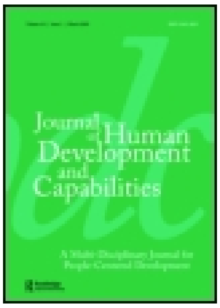

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A Model of Consumption and Environmental Degradation: Making the case for sustainable consumer behaviour

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A Model of Consumption and Environmental Degradation: making the case for sustainable consumer behaviour

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Abstract This paper develops and examines a model of the relationship between consumption and environmental degradation, using the per-capita Gross Domestic Product as the proxy for consumer behaviour and per-capita carbon dioxide emissions as the indicator of pollution. The time path of emissions and consumption are modelled within a dynamic framework, and the result is expressed as an optimization problem from which Hamiltonian conditions are derived. These conditions are analysed through the use of a phase diagram, and the empirical section of the paper reveals the relationship between carbon dioxide emissions and Gross Domestic Product values across nation-states as well as the United Nations classifications for development among countries. The paper closes with an examination of sustainable consumer behaviour that has global policy implications.

Key words: Consumption, Pollution, Environment, Economic models

Introduction

Our consumer world contains a cornucopia of material goods and services. As Ozanne *et al*. (1998, p. 185) suggest, "Open any glossy magazine, and see pictures of sumptuous foods, beautiful people, glamorous fashions, and possessions too many to mention. Turn to any television channel, and an unending series of consumption images pulse before the eyes." One outcome of the expanding influence of this consumer culture is the rise of globalization, which has altered societies throughout the world and created universal consumer market segments that associate similar meanings with people, places, and products (Alden *et al*., 1999). Together these segments form a transnational consumer culture (Ueltzhoffer and Ascheberg, 1999), which

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gives the appearance that consumer choice lacks constraints and "is depicted as a land of freedom in which everyone can be a consumer" within the larger human society (Slater, 1997, p. 27).

Indeed, consumer options and total consumption have expanded significantly during the previous 100 years. By the end of the twentieth century, consumption expenditures reached $24 trillion, twice the level of 1975 and six times that of 1950 (United Nations Development Programme [UNDP], 2001). Compared with real consumption expenditures in 1900 of $1.5 trillion, this figure represents an increase by a factor of 16. The impact upon the lives of consumers around the world has been nothing short of remarkable. The United Nations (UN) reports that: "Living standards have risen to enable hundreds of millions to enjoy housing with hot water and cold, warmth and electricity, transport to and from work — with time for leisure and sports, vacations and other activities beyond anything imagined at the start of this century" (UNDP, 1998, p. 1). Nonetheless, as demonstrated in the same report, this growth in consumption has been unevenly distributed, with 20% of the consumers living in the highest income nations accounting for 86% of all private consumption, while the bottom 20% consume slightly more than 1% (UNDP, 1998, p. 2).

These consumption inequities across nations, peoples, and regions of the world have resulted in widespread dissatisfaction, alienation, and concern (Hill and Dhanda, 1999). As Udombana (2000, p. 753) decries: "Four fifths of the world's population can no longer accept that the remaining fifth should continue to build its wealth on their poverty." Such criticisms go beyond typical concerns about negative influences of the larger material culture and include externalities of consumption that do ecological harm (Borgmann, 2000). Within this context all consumption-related activities, from production to usage to disposal, have environmental effects that are experienced throughout the world regardless of the physical location of the consumer. Thus, Ger (1997, p. 112) reflects: "Consumption and production patterns of affluent countries are responsible for most transboundary problems, such as ozone layer depletion, ocean pollution, and chemicalization of the habitat." Another concern is that the consumption causing most of this environmental damage is concentrated among richer nations, yet the actual damage falls hardest on poorer countries.

Research objective

The purpose of this paper is to model the relationship between consumption and environmental degradation, with a specific emphasis on carbon dioxide (CO_2) emissions. As Dhanda (1999, p. 258) asserts: "Not surprisingly, the world's dominant consumers are concentrated in the industrialized west, where high levels of consumption are matched with serious environmental damage. For example, the United States boasts one of the highest living standards in the world, as well as per capita carbon dioxide emissions that are uppermost across all countries." Much of the related previous scholarship involves the environmental Kuznets curve. This research reveals that income (a prerequisite for consumption) and pollution rise together until a nation reaches a certain level of prosperity, but these variables exist in an inverse relationship after that point (see Dasgupta *et al.* 2002; Yandle *et al.* 2002). Still others contend that previous research is inconclusive, and that more needs to be done before a clear understanding of this relationship is determined (Copeland and Taylor, 1995). The development and testing of this model may represent a significant step because of its explicit focus on consumption.

For the purposes of model formulation, consumption is operationalized as Gross Domestic Product (GDP) per capita and converted into US dollars based on the purchasing power of the focal nation's currency. As national income accounts reveal, roughly 67% of the GDP is private consumption. Therefore, the GDP is a plausible proxy for private consumption in the United States. This fraction may differ for other countries. However, macroeconomic models maintain that private consumption for all nations is a critical component of the GDP. Furthermore, it is commonly accepted that, at lower GDP levels, consumption as a fraction of GDP rises. Thus, it is safe to assume that for most nations GDP is an accurate proxy for consumption.

In order to maintain consistency across measures, CO_2 also is expressed in per-capita form. Data are used from a variety of global organizations including the UNDP and other UN-based agencies as well as the World Bank and the Carbon Dioxide Information Analysis Center.

In the next section of the paper, a model is developed and the results are analysed. Specifically, the time path of emissions and consumption are modelled within a dynamic framework, and the model is expressed as an optimization problem from which Hamiltonian conditions are derived that yield the differential condition for the state variable. Then, with the assistance of a simplifying assumption, the state variable and the current marginal valuation terms are derived. These conditions are analysed within a phase diagram.

The empirical section of the paper presents the relationship between CO_2 emissions and GDP values across nation-states. The GDP and the emissions data were taken from the UNSTATS database. These data are then broken into three segments — low-development, medium-development, and high-development countries — according to the classifications established by the UN. Regression analysis is performed on each of these categories to determine the steady-state path of nations within them. A discussion of the empirical results follows, and the paper closes with an examination of sustainable consumer behaviour that has global policy implications.

Model development and results

Theoretical model and Hamiltonian optimization problem

In this section, a theoretical model is developed that presents an optimization problem. The assumption is that consumers derive utility from consumption while simultaneously generating pollution. Hence, the model focuses on the trade-off between aggregate consumer behaviour and environmental degradation. The problem for global society, nations, or government-sponsored regulatory agencies, is to determine optimal consumption that takes into account the interaction of this trade-off. The theoretical model follows the treatment of Lambert (cf. 1985) wherein the production–consumption trade-off is modelled within an optimal control theory format. However, in our paper utility is multivariate in nature and is a function of consumption and emissions. Earlier, Forester (1973) modelled a similar problem that used the Pontryagin's Maximum Principle to solve for the optimal solution.

The optimization problem can be expressed as follows:

$$\underset{c}{Max}\int_{0}^{T} e^{-rt}U[C(t)-E(t)]dt$$

subject to: $\dot{E}=aC-bE$

$$E(0)=E_0, E(t)\leqslant E_T, 0\leqslant t\leqslant T.$$

The objective is to maximize the future utility discounted at rate r (constant exponential) where $C(t)$ represents the function for consumption over time and $E(t)$ denotes the function for emissions over time. The first constraint states that the change in emissions over time is a function of consumption and emissions. This constraint identifies the time path of the state variable, which is required for the existence of an optimal solution. This is a plausible condition for the time path, which shows that the rate of change of emissions has to decrease with rising emission levels if the terminal level of emissions is to be finite. The second constraint states the end-point conditions that govern the time-path for the build-up of emissions.

Alternatively, this Hamiltonian problem may be expressed as:

$$H=e^{-rt}\mu[f(C)-g(E)]+\lambda(aC-bE)$$

The next stage involves deriving the conditions that would solve the optimization problem. Following the standard assumption that andare concave and linear, respectively, the Hamiltonian conditions (explained later) are necessary and sufficient conditions for the existence of the solution to this optimization problem. The derivations are detailed in Appendix A and lead to the following differential equation for the state variable:

$$U'[\Phi(s)f'[C(s)]=a\int_{S}^{T} e^{-(b+r)(t-s)}U'[\Phi(t)]g'[E\{t\}]dt.$$

This equation is complex and rather cumbersome to interpret. Therefore, a simplifying assumption is made in the next subsection to improve its interpretability.

Steady state path and diagrammatic analysis

The Hamiltonian conditions determine the optimal control $\hat{u}(t)$ and the optimal path for the state variable $\hat{x}(t)$, which in this model is $\hat{e}(t)$. These conditions also determine the co-state variable $\hat{\lambda}(t)$, which is the marginal valuation at the moment of planning the state variable $\hat{x}(t)$ along the optimal path. These conditions also yield the current marginal valuation denoted by $m(t)$. For the problem at hand, a simplifying assumption is needed since simultaneous equations for E' and m' cannot be derived easily.

The optimization problem contains a present value integral that is being maximized. Now, $\lambda(s)$ denotes the marginal valuation at the moment of planning of the state variable at time $t=s$. In other words, this variable measures the effect at time $t=s$ discounted back to time $t=0$. However, it is more natural and intuitive to work with the current marginal valuation, denoted by $m(s)$. This variable $m(s)$ is obtained by taking forward from $t=0$ to $t=s$.

$$m(s)=e^{rs}\lambda(s) \tag{i}$$

Taking the first derivative yields:

$$m'(s)=re^{rs}\lambda(s)+\lambda'(s)e^{rs} \tag{ii}$$

Substituting the value for equation (i) into equation (ii) yields:

$$m'(s)-mr=e^{rs}\lambda'(s) \tag{iii}$$

Equation (iii) reveals the differential equation for the co-state variable λ (refer to equation (III) in Appendix A) of the Hamiltonian optimization, which is expressed in terms of m by combining it with the differential equation satisfied by $m(t)$.

From equations (II) and (III) in Appendix A and equation (iii), we get:

$$U'(\Phi)f'(C)+ma=0 \tag{iv}$$

$$U'(\Phi)g'(E)+m(b+r)=m'$$

From equation (IV) in Appendix A, we get:

$$E'=aC-bE \tag{vi}$$

$$aC=E'+bE \tag{vii}$$

$$C=\frac{E'+bE}{a} \tag{viii}$$

If $U(C)$ is linear, then $U'(C)=1$. Plug equation (viii) into equation (iv) to get:

$$f'\left(\frac{E'+bE}{a}\right)=-ma \tag{ix}$$

Also, if $U(C)$ is linear, then $U'(C)=$ 1and equation (v) takes the form:

$$m'=(b+r)m+g'(E) \tag{x}$$

These are the equations for E and that are required for the diagrammatic

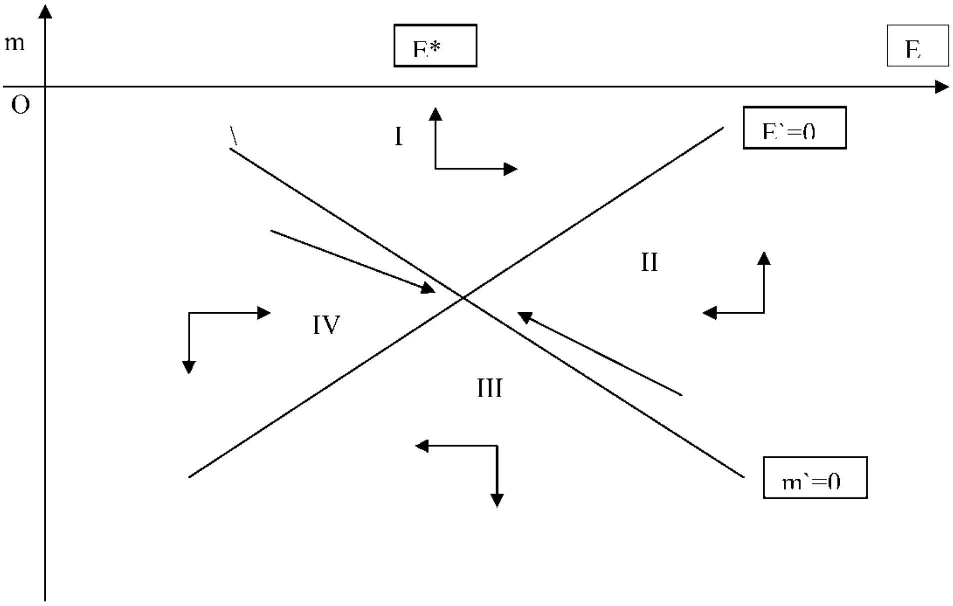

FIGURE 1. The steady state for emissions and consumption depends on the position of $E' = 0$ and $m' = 0$. Thus, there is no guarantee that the resulting steady state is necessarily ideal at any given time. Note that $m < 0$, which indicates a negative marginal value. Thus, m may be interpreted as the marginal pollution cost. The phase diagram corresponds to the Kuznets curve. For example, in the second quadrant, nations face high levels of emissions, perhaps because of advanced industrialization and high GDP. These nations may be able to reduce effluence through cleaner and more advanced production technology. The fourth quadrant depicts a symmetric case. In this quadrant, a nation with low emissions and low GDP is shown to move toward more economic development and higher external costs of pollution. A nation, perhaps a developing one such as China, incurs rising pollution costs and rising effluent emissions in its move toward economic development. Ironically, at emission levels closer to E^*, nations are more likely to move in either direction (i.e. to higher or lower emissions). The second and the third quadrants present these situations. For example, in the first quadrant emissions are rising as a nation improves its GDP, while in the third quadrant a nation curtails pollution at the cost of a decreasing GDP.

analysis of the steady state. Figure 1 is the phase diagram, which shows the time path for both E and m. In the following discussion we analyse time paths with varying levels of emission. Of particular interest are situations with low and high emission levels. Both low and high emission starting statuses could lead to steady-state equilibrium, to higher emission levels, and/or to lower levels of emission.

The steady state for emissions and consumption depends on the position of $E' = 0$ and $C' = 0$. Thus, there is no guarantee that the resulting steady state is necessarily ideal at any given time, due to the initial assumptions of the model and the reality of a dynamic marketplace and updated research data. For example, the optimal paths that seemed attainable 20 years ago are not deemed optimal given the recent information regarding the ozone layer or the consumption of fossil fuels.

To examine the existing steady-state path of consumption and emissions empirically, we propose several models. The objective is to test whether the actual international data corroborate any of the steady-state paths of consumption/emissions in reality. Figure 1 indicates that matters of emission and sustainable growth and consumption require continuous dialogue across nations. The figure shows that countries on the lower rungs of emission and consumption (Fig. 1, quadrant IV) could develop along paths that lead toward the steady-state equilibrium or away from it. To ensure that all nations remain on the path toward a steady state (justified by the latest scientific data), nations must have ongoing interactions.

All countries — developing and developed — contribute to emission levels. Figure 1 shows that every nation could deviate from the steady state toward higher and presumably unsustainable levels of emission. For example, a low emission society located in quadrant IV of Figure 1 could potentially move toward higher emission levels if the path of growth is not carefully determined. Similarly, advanced nations in quadrant II or quadrant I could be on a consumption path away from the steady state and toward higher levels of emission. The implication is that sustainable emission levels and steady-state equilibria are only possible if the entirety of the global community participates in a dialogue regarding sustainable consumption and emission standards.

Data analysis and results

For the empirical discussion, two models of the relationship between consumption and emissions (with consumption as a function of GDP levels) were estimated. The two empirical equations for emissions are as follows:

$$E = \alpha + \beta \mathrm{GDP} + u \tag{1}$$

$$E = \alpha \mathrm{GDP}^{\beta} eu \tag{2}$$

where u denotes the error term. Equations (1) and (2) were estimated using the entire dataset as well as data subsets for three development categories of nations. The objective was to examine the sign of the coefficient β for nations at various stages of economic development. Although these estimations do not correspond exactly to our findings from the phase diagram, they do suggest the tendencies of dynamic paths for emissions over time. For example, a consistently positiveindicates that emissions are moving toward a steady state that may exceed the environmental carrying capacity.

Table 1 presents the estimation results of equation (1) for all 212 nations, all available years (1990–1998), and pooled data for all nations and all years. The β coefficients are highly significant and consistently positive for all years as well as the pooled data. These findings indicate that emissions are positively correlated with GDP levels of nations. The values of the coefficient of determination for all years further indicate that an inevitable side effect of economic growth is effluent levels of emission and environmental degradation.

Estimation results based on equation (2) are presented in Table 2. These

Table 1. Estimation results of equation (1): autocorrelation–heteroscedasticity consistent estimates

Year	α	β	R^2	F
1991	21.34	0.0007***	0.75	548.92***
	(1.57)	(6.51)		
1992	38.89***	0.0004***	0.44	154.36***
	(2.83)	(3.93)		
1993	19.07	0.0007***	0.76	598.13***
	(1.51)	(7.08)		
1994	24.67**	0.0007***	0.73	524.63***
	(1.86)	(7.91)		
1995	25.04**	0.0007***	0.72	497.50***
	(1.84)	(8.25)		
1996	27.17**	0.0007***	0.71	467.54***
	(1.94)	(8.18)		
1997	19.01	0.0008***	0.78	648.31***
	(1.56)	(17.66)		
1998	−48.84	0.0007***	0.96	697.37***
	(−1.64)	(15.92)		
Pooled	21.13***	0.0007***	0.76	4381.17***
	(4.42)	(23.561)		

The Newey–West (1987) heteroscedastic–autocorrelation consistent estimation method is applied in order to obtain non-spurious variance covariance estimates. *t* statistics are reported in parentheses.
***Significant at 1% level.

verify the findings presented in Table 1. Thus, empirical results remain robust even under an alternative formulation of the functional relationship between emissions and GDP levels. The policy ramifications of the evidence reported in Tables 1 and 2 are compelling. Specifically, as nations achieve consumption levels and economic growth, they face a rising threat of environmental deterioration. In terms of Figure 1, we can assume that different stages of economic growth place nations in different quadrants of the phase diagram. Therefore, depending upon domestic environmental policies, continued economic growth may move a nation away from sustainable steady-state equilibrium over time.

To further investigate the relationship between economic growth, consumption, and emissions, data were separated into subsamples of low, medium, and high development categories as defined by the UNDP Human Development Index (HDI). Countries in the high human development category have an HDI rank of 0.800 and above, countries in the medium development category have an HDI value between 0.500 and 0.799, and countries in the low human development category have an HDI value of less than 0.500 (UNDP, 2001). The objective was to determine whether any of the categories of nations are reducing environmental deterioration through a more sustainable steady state of consumption and emissions. For example, a negative sign of coefficient β would be consistent with the notion that at some stage of economic growth nations allocate more resources for environmental protection. Additional information may de derived from the

Table 2. Estimation results of equation (2): autocorrelation–heteroscedasticity consistent estimates

Year	α	β	R^2	F
1991	-7.96^{***}	1.08^{***}	0.85	1016.61^{***}
	(-26.48)	(34.59)		
1992	-7.56^{***}	1.03^{***}	0.77	640.90^{***}
	(18.43)	(21.57)		
1993	-7.76^{***}	1.07^{***}	0.88	1320.76^{***}
	(-29.24)	(37.11)		
1994	-7.75^{***}	1.07^{***}	0.88	1472.65^{***}
	(-30.13)	(37.68)		
1995	-7.71^{***}	1.06^{***}	0.88	1346.93^{***}
	(-28.30)	(36.08)		
1996	-7.70^{***}	1.05^{***}	0.88	1363.17^{***}
	(-28.67)	(36.95)		
1997	-7.55^{***}	1.04^{***}	0.82	812.78^{***}
	(-26.11)	(31.83)		
1998	-5.44^{***}	0.85^{***}	0.78	99.35^{***}
	(-3.53)	(6.90)		
Pooled	-7.70^{***}	1.06^{***}	0.88	9579.25^{***}
	(-71.94)	(95.20)		

The Newey–West (1987) heteroscedastic–autocorrelation consistent estimation method is applied in order to obtain non-spurious variance covariance estimates. t statistics are reported in parentheses.
*** Significant at 1% level.

magnitude of the elasticity coefficient, or the percentage change in emissions with respect to the percentage change in GDP.

Tables 3 and 4 present estimation results necessary for this part of the analysis. Both tables indicate that the β coefficients are highly significant and positive. Therefore, at all stages of economic development, nations appear to be moving toward higher steady-state equilibrium levels of emissions and GDP over time. This finding is consistent with our phase diagram's (Fig. 1) quadrant I where economic development entails further degradation of environmental quality.

Table 3. Estimation results of equation (1): autocorrelation–heteroscedasticity consistent estimates

Category	α	β	R^2	F
Low	-2.88^{***}	0.001^{***}	0.67	491.19^{***}
	(-10.16)	(14.26)		
Medium	-27.03^{***}	0.003^{***}	0.68	1038.94^{***}
	(-2.70)	(7.63)		
High	-33.24^{***}	0.007^{***}	0.92	4105.89^{***}
	(-2.76)	(26.16)		

The Newey–West (1987) heteroscedastic–autocorrelation consistent estimation method is applied in order to obtain non-spurious variance covariance estimates. t statistics are reported in parentheses.
*** Significant at 1% level.

Table 4. Estimation results of equation (2): autocorrelation-heteroscedasticity consistent estimates

Category	α	β	γ	R^2	F
Low	-8.10^{***}	21.04^{***}		0.76	763.63^{***}
	(-25.44)	(26.14)			
Medium	-8.02^{***}	1.14^{***}		0.91	4744.01^{***}
	(-52.34)	(75.32)			
High	-5.26^{***}	0.83^{***}		0.83	1648.40^{***}
	(-21.81)	(42.20)			
Pooled					
Quadratic	-8.76^{***}	1.30^{***}	-0.01^{***}	0.87	4851^{***}
	(-30.89)	(20.80)	(-4.01)		

The Newey-West (1987) heteroscedastic-autocorrelation consistent estimation method is applied in order to obtain non-spurious variance covariance estimates. t statistics are reported in parentheses.
*** Significant at 1% level.

Table 4 presents the estimation results of equation (II). The β coefficients represent the percentage change in emissions with respect to percentage change in GDP. According to these estimates, the highest percentage contributors to emissions in the process of expanding consumption are countries in the low development category of nations (HDI values less than 0.05; e.g. Pakistan and Nigeria). This is followed by the medium development category of nations (HDI values between 0.5 and 0.8; e.g. China and Venezuela). The lowest percentage contributors are the countries in the high development category (HDI values greater than 0.8; e.g. Norway and the United States).

To test the Kuznets theory, we also estimated a quadratic relationship between effluent emissions and the GDP — expressed as:

$$E = \alpha + \beta \mathrm{GDP} + \gamma \mathrm{GDP}^2 \tag{3}$$

A statistically significant and positive γ supports the Kuznets curve.

Table 4 presents the estimates of equation (3). The coefficient of the quadratic term is positive and statistically significant, which validates the Kuznets curve. The intercept and the β coefficients are also statistically significant. Thus, the traditional parabola shape of the Kuznets curve is borne out by this sample.

The significant intercept indicates that, even at the lowest levels of GDP, emissions are not eradicated completely. It is common knowledge that low GDP nations have lower emissions standards. Furthermore, capital investments in emission controls and in the development of more environmentally friendly machinery and vehicles are also scarce.

To test the validity of the model estimated for the quadratic function versus the linear model in equation (3), we perform an F-test as follows:

$$F = [(\mathrm{RSSR} - \mathrm{USSR})/m]/[\mathrm{RSSR}/(n-k)],$$

where the RSSR and USSR are the sum of squared residuals from the linear (restricted) and the quadratic functional form (unrestricted) models. The number of restrictions ($\gamma = 0$ — one in this case) and n and k represent the number of observations and the parameters in the unrestricted model, respectively. The value of the *F* statistic is 55.59, which exceeds the critical value of χ^2 at a 1% significance level. Therefore, the restricted form of the model (i.e. the linear model) is rejected in favour of the quadratic formulation.

Two possible explanations emerge. First, at the lowest levels of economic development, nations may have fewer resources and therefore less ability to influence environmental quality as consumption expands. Second, at low levels of GDP. nations often grow at faster rates (e.g. double-digit growth rates), resulting in relatively higher emission levels as a by-product of expanding consumption. A logical inference is that, at the highest levels of economic development, nations have more resources to allocate to pollution control and environmental management. An example is the European Union enforcing strict controls on emissions. Furthermore, the rate of GDP growth in such countries usually does not exceed 2–5%, producing lower relative added emissions as a by-product of expanding consumption. These findings are consistent with the environmental Kuznets curve, which shows that the relationship between income and emissions has an inverted U shape. Our findings demonstrate that the marginal emissions rise initially with increases in GDP and subsequently fall as GDP advances beyond a certain level.

Conclusions and policy implications

Summary of findings

In this paper, theoretical models of the relationship between consumption as GDP and environmental degradation as CO_2 emissions are developed and examined. The models are expressed as a dynamic optimization problem that yields a set of differential equations for sustainable consumption and pollution. The graphic solution to these differential equations reveals that nations may take paths to a steady state that result in greater levels of emission as consumption increases.

The empirical section of the paper tests the relationship between CO_2 emissions and GDP across nation-states as well as within the UN categories of low, medium, and high human development countries. Results show that nations with rising GDP levels produce more environmental damage through greater CO_2 emissions. Additionally, countries with lower GDP levels produce emissions at a greater absolute rate than nations at higher GDP levels. One possible explanation is that developing countries do not have the resources necessary to control emissions in the face of economic development. An alternative explanation is that countries with lower GDP levels experience higher percentage growth rates in consumption, which in and of themselves are associated with greater rates of harmful emissions. Additional analysis using the environmental Kuznets curve also is supportive of these results.

Policy discussion

The consumer literature implicitly supports the belief that consumption choices are the sovereign domain of the individual and, therefore, should be subjected to limited interference (see Crane, 2000). However, while this perspective recognizes the benefits to consumers in particular exchange relationships, it fails to consider the impact of externalities on the larger society such as environmental degradation. Shultz and Holbrook (1999, p. 218) refer to this predicament as the commons dilemma, "a phenomenon in which the members of a social group face choices in which selfish, individualistic, or uncooperative decisions, though seeming more rational by virtue of short-term benefits to separate players, produce undesirable long-term consequences for the group as a whole."

As a result, recent scholarship has supported the generic idea of more sustainable consumption patterns (Borgmann, 2000), with market-based activities playing a key role in their continuing development and proliferation (Prothero and Fitchett, 2000). Even advocacy groups and regulatory agencies are beginning to realize the power of the marketplace to support environmental protection goals. For example, the UNDP (1998, p. 96) recommends "self-regulation through public disclosure of information on industrial pollution", whereby marketers may use their control and reduction of CO_2 as a competitive advantage in promotions. Additionally, eco-labelling and social labelling can be employed to alert consumers to the impact of their choices on others. Finally, consumer groups in developed countries have advanced a truth-in-advertising set aside that requires polluting firms to contribute to a fund that would be used to educate the marketplace to the externalities of their consumption.

While these tactics may have the desired effect, the magnitude of the problem suggests that their cumulative impact may not be enough to ensure a steady-state path of consumption and pollution. Thus, Dhanda (1999, p. 258) recommends three "policy options designed to reduce such environmental degradation based on the belief that pollution is a residual discommodity that is created concurrently with a valued commodity". The first option is command and control policies, which compel polluting firms to employ the best control and abatement technology that currently is available. The second is environmental taxes, which result in higher prices for goods and services that generate pollution such as CO_2 emissions. The third option is marketable pollution permits whereby a government agency establishes a cap on pollutants, and issues a fixed number of permits that can be traded freely and allow the bearer to pollute up to a defined limit.

Of course, a global solution must go beyond the confines of the developed world and take into account the resources and constraints of developing nations. The full implementation of the 1997 Kyoto Protocol would greatly enhance the opportunities that exist to transfer scarce resources between the developed and developing worlds. Such trading could result in the transfer of advanced environmentally friendly technologies from developed to developing and less developed nations that are estimated to exceed $100 billion annually, an amount that could not afford on their own (see Millock, 2002). Of course, this exchange of wealth depends upon the ratification of the Kyoto agreement by the most affluent countries including the United States, which has failed to do so at this point in time.

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Appendix A: Hamiltonian form of the optimization problem

The optimization problem when expressed in a Hamiltonian form is as follows:

$$\underset{C}{Max}\int_0^T e^{-rt}U[C(t)-E(t)]dt$$

$$\text{subject to: } \dot{E}=aC-bE$$

$$E(0)=E_0, E(t)$$

Alternatively, this Hamiltonian form may be expressed as:

$$\underset{C}{Max}\int_0^T e^{-rt}U[f(C)-g(E)]dt$$

$$\text{subject to: } E'=aC-bE$$

$$E(0)=E_0, E(t)\leqslant E_T, 0\leqslant t\leqslant T$$

Using the Hamiltonian conditions to solve problems

The optimization problem has the following Lagrangean function:

$$L=\int_0^T u(C(t)-E(t))+\lambda(t)[\dot{E}-(aC-bE)]dt$$

The Hamiltonian for the optimal control is therefore written as:

$$H=e^{-rt}u[C(t)-E(t)]+\lambda(aC-bE).$$

In general terms, given an optimization problem in the form:

$$\max_u\int_0^T f(t,x,u)dt$$

$$\text{subject to: } x'=g(t,x,u)$$

$$x(0)=x_0$$

and with an end-point condition of:

$$x(T)=x_T$$

the Hamiltonian conditions are:

$$\Phi = \frac{\partial \mathrm{H}}{\partial \mathrm{u}}$$

$$\lambda' = \frac{-\partial \mathrm{H}}{\partial \mathrm{x}}$$

$$\mathrm{x} = \frac{\partial \mathrm{H}}{\partial \lambda}$$

plus a transversality condition.

For the problem at hand, the control variable U is C and the state variable X is E. Hence, the Hamiltonian conditions can be derived as follows:

(I) $H\!:e^{-rt}U[f(C)-g(E)]+\lambda(aC-bE)$

(II) $\dfrac{\partial H}{\partial C}=0 \Rightarrow e^{-rt}U'(\Phi)f'(C)+\lambda a=0$

(III) $\dfrac{\partial H}{\partial E}=\lambda' \Rightarrow e^{-rt}U'(\Phi)g'(E)+\lambda b=\lambda'$

(IV) $E'=\dfrac{\partial H}{\partial L} \Rightarrow aC-bE=E'$

(V) $\lambda_{(T)} \leqslant 0,\ \lambda_{(T)}[\mathrm{E}_T-\mathrm{E(T)}]=0$ (the transversality condition)

Derivation of the optimal path

Refer to equation (III):

1. $e^{-rt}U'(\Phi)g'(E)+\lambda b=\lambda'$
2. $e^{-rt}U'(\Phi)g'(E)+\lambda'-\lambda b'$

(VI) $\lambda'-\lambda b=e^{-rt}U'(\Phi)g'(E)$

Multiply both sides by integrating factor to obtain:

(VII) $(\lambda'-\lambda b)e^{-bt}=\dfrac{d}{dt}[\lambda e^{-bt}]=e^{-(b+r)t}U'(\Phi)g'(E)$

Integrating from time $t=s$ to $t=T$ yields:

(VIII) $-\lambda(s)e^{-bT}+\lambda(T)e^{-bs}=\int\limits_{S}^{T} e^{-(b+r)t}U'(\Phi)g'(E)dt$

If $E(t)\neq E_T$ then $\lambda(T)=0$ from the transversality condition, and the first term disappears. Since the emissions are not reaching the end point state, it follows that the shadow price, $\lambda(T)$ is zero. Multiply both sides by $e^{(b+r)s}$:

$$\text{(IX)} \quad m(s) = -\int_S^T e^{-(b+r)(t-s)} U'(\Phi) g'(E) dt$$

$$\text{(X)} \quad m(s) = -\int_S^T e^{-(b+r)(t-s)} \left[\frac{\partial U}{\partial E}\right] dt$$

Now refer to equation (II):

$$\text{(XI)} \quad e^{-rt} U'(\Phi) f'(C) + \lambda a = 0$$

Multiply both sides by e^{rt}:

$$\text{(XII)} \quad U'(\Phi) f'(C) + ma = 0$$

Finally, substitute for m from equation (X):

$$\text{(XIII)} \quad U'[\Phi(s)] f'[C(s)] = a \int_S^T e^{-(b+r)(t-s)} U'[\Phi(t)] g'[E(t)] dt.$$

Equation (XIII) gives the differential equation for the state variable.

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