VALUING ENVIRONMENTAL SERVICES:

A SHADOW PRICE FOR NET PRIMARY PRODUCTION

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The "Holy Grail" for environmental economists would include objective prices for environmental services. Such prices are warranted because the environment contributes to economic well-being in ways that extend well beyond aesthetic amenities (Marc L. Imhoff et al., 2004; William A. Brock and Anastasios Xepapadeas, 2003; Gretchen C. Daily et al., 2003; Robert J. Costanza et al., 1997; Peter M. Vitousek, 1994). Contributions include the production of natural resources, the dilution and detoxification of wastes, the provision of a hospitable climate, and biodiversity. These services usually are not provided through the market and therefore, rarely are assigned a price. Without a price, the market cannot allocate environmental services efficiently. Such inefficiency leads to environmental degradation. Much of this degradation could be avoided using economically efficient market based mechanisms if prices were available for environmental services.

Here, we estimate a shadow price for environmental services that is based on an ecologically meaningful measure of their flow, net primary production. We use annual values for net primary production, along with capital and labor, to estimate a production function from an international panel. Results indicate that net primary production makes a statistically measurable contribution to GDP. This contribution can be used to calculate a shadow price. This price goes beyond previous estimates because it is objective and consistent with basic economic axioms regarding economic production. As such, this estimate may prove useful in linking economic and ecological activities.

I. Previous Approaches to Valuing Environmental Services

Economic valuation of environmental services attempts to assign a monetary value to an environmental amenity whose use or destruction would deprive others of its future availability (Walter A. Rosenbaum, 2002). Economists have made significant progress towards valuing environmental services using three general approaches (1) direct valuation; (2) indirect valuation; or (3) contingent valuation (Rudolf S. de Groot et al., 2002).

Direct market valuation is the exchange value that ecosystem services have when traded. This approach uses a production function to estimate the contribution that ecosystem services make to the production of some market good or service (e.g. drinking water or fish harvest). This approach has been used to value ecosystem services rendered by tropical wetlands (Edward B. Barbier, 1994) and the provision of mangrove habitat to fish farming (Barbier, 2000; Barbier and Ian Strand, 1998). Results are limited by the availability of data and the lack of a clear understanding of how the ecosystem, the service being valued, and the marketed commodity are linked (Yung En Chee, 2004; Daily et al, 2000).

When no explicit markets exist for environmental goods and services, several techniques are used to generate indirect market values. Avoided costs value environmental services based on the replacement costs of human infrastructure. For example, wetlands are valued based on the avoided costs of human infrastructure for flood control. A similar technique, replacement/restoration cost, values ecosystem services based on the cost of market services that achieve the same utility. The factor income approach values

ecosystem services based on their contribution to individual and commercial incomes (de Groot, 2002). For example, reducing water pollution increases fish populations and thereby increases income generated by the fishery. Travel cost methods value ecosystem services based the money and time that people spend on travel to an environmental service. Finally, hedonic pricing values ecosystems services based on the price that consumers are willing to pay for associated goods (David A. King and Jack A. Sinden, 1988).

Contingent valuation determines the price people are willing to pay for an environmental service based on surveys that pose hypothetical scenarios involving a valuation of alternatives. Survey techniques create a hypothetical market in which people are asked to create their demand function for an environmental good or service (Yung En. Chee, 2004). The ability of these methods to measure the value of environmental resources is limited because consumers (and natural and social scientists) do not fully understand the myriad of ways in which environmental services contribute to economic wellbeing. Other problems include analyzing the vast quantity of data obtained from survey techniques (William D. Nordhaus and Edward C. Kokkelenberg, 1999). Finally, contingent valuation has several well documented shortcomings (Peter A. Diamond and Jerry A. Hausman, 1999; Micheal W. Hanemann, 1999) the most prominent being that consumers' answers to a survey are different from what they would actually pay.

II. An Objective Measure of Ecosystem Services, Net Primary Production

Many of the techniques described above are hamstrung by the lack of an objective measure for ecosystems services. From an ecological perspective, nearly all ecosystem

services are powered by net primary production. On land, net primary production is the amount of energy fixed by plants beyond their needs for maintenance. This difference represents the amount of energy that is used to increase plant biomass and ultimately power the rest of the food chain. All actions by terrestrial plants and animals that contribute to economic well being ultimately are derived from net primary production. For example, the global distribution of biodiversity, and all the services it provides, depends in part on local rates of net primary production (Kevin J. Gaston, 2000). Similarly, soil quality depends in part on soil organic carbon, which is derived ultimately from net primary production.

Until recently, it has been very difficult to measure net primary production over time and space. This limit has been alleviated by satellite remote sensing and computer simulation models. Satellite remote sensing allows scientists to proxy biological activity with the normalized difference vegetation index (Robert K. Kaufmann et al., 2004). We calculate net primary production from NOAA/AVHRR satellite data (Liming Zhou et al., 2001) using a production efficiency model. The production efficiency algorithm includes three components: (1) leaf area index and a fraction of absorbed photosynthetically active radiation; (2) daily climate data (e.g. incident radiation, air temperature, and precipitation) and; (3) a biome specific parameterization that converts absorbed photosynthetically active radiation to net primary production (Ranga B. Nemani *et al*., 2003).

III. Methods

We use data on terrestrial net primary production to represent the amount environmental services available (Figure 1a). To test whether these environmental services contribute to economic production and whether this contribution can be used to estimate an objective shadow price, we expand a traditional economic production function to include terrestrial net primary production as a factor of production. The expanded version of the Cobb-Douglas production function is given by:

$$Y_{it} = A_i \, L_{it}^{\alpha} K_{it}^{\beta} N_{it}^{\varphi} \qquad (1)$$

in which Y is real GDP in real 1996 dollars for nation i at time t, L is the number of workers, K is the capital stock in real 1996 dollars, N is net primary production within the geographical borders of nation i in year t (kg/carbon/year), A is a technology scalar, and α, β, and φ are regression coefficients that represent the output elasticities of labor, capital, and net primary production respectively. Data for real GDP, labor, and capital are from the Penn World Tables (version 6.1; Alan Heston Robert Summers and Aten Bettinal, 2002). A perpetual inventory method is used to construct real capital stocks K_t. The accumulation of capital is related to the real investment rate i_t and the depreciation rate of capital δ (assumed to be 0.07 as in William Easterly and Ross Levine, 2001). Capital accumulation is given by: $K_{t+1}=i_t + \delta(K_t)$, where the initial estimate of capital K_0 is equal to the initial investment I_0 divided by the growth rate of capital (g_K) plus the depreciation rate of capital. It is assumed that each country is at its steady state, such that the growth rate of capital is

approximately equivalent to the growth rate of real output ($g_K \approx g_Y$) (Ian Sue Wing and Lars E. Steifert, mimeo).

Data for labor, capital, and net primary production are compiled for seventy two nations between 1982 and 2000[1]. This period is determined by the availability of satellite data. The sample includes nations for which a complete set of economic data are available. These nations include twenty developed nations and fifty one developing nations.

Equation (1) is estimated by taking the logarithm of both sides:

$$\ln Y = \ln(A_i) + \alpha \ln(L_{it}) + \beta \ln(K_{it}) + \phi \ln(N_{it}) + \mu_{it} \qquad (2)$$

Equation (2) can be specified using a variety of assumptions about international variations in the slopes and intercept. We chose among pooled OLS, fixed effects, random effects, and random coefficient models using F tests (Chao Hsiao, 1986). We test for cointegration using tests developed by Peter Pedroni (1999). The panel and group ADF test statistics indicate that the variables cointegrate, therefore equation (2) does not include a deterministic trend as a proxy for technological change. To ensure that this omission does not affect our results, we estimate equations (3) and (4):

[1] Argentina, Austria, Australia, Burundi, Belgium, Benin, Burkina Faso, Bangladesh, Belize, Bolivia, Brazil, Canada, Switzerland, Chile, China, Cameroon, Colombia, Costa Rica, Denmark, Ecuador, Egypt, Ethiopia, Spain, Finland, France, Gabon, Ghana, Guinea, Gambia, Greece, Guatemala, Honduras, Hungary, India, Ireland, Iceland, Italy, Japan, Kenya, Lesotho, Morocco, Madagascar, Mexico, Mali, Mozambique, Malawi, Malaysia, Niger, Nigeria, Netherlands, Norway, Nepal, Pakistan, Panama, Peru, Philippines, Portugal, Romania, Sweden, Chad, Thailand, Turkey, Tanzania, Uganda, Uruguay, USA, Venezuela, South Africa, Zambia, Great Britain.

$$LnY_{it} = A_i + \alpha \ln(L_{it}) + \beta \ln(K_{it}) + \varphi \ln(N_{it}) + \gamma Time + \mu_{it} \quad (3)$$

$$LnY_{it} = A_i + \alpha \ln(L_{it}) + \beta \ln(K_{it}) + \varphi \ln(N_{it}) + \gamma \ln(Time) + \mu_{it} \quad (4)$$

where technical change is a linear or logarithmic value of a deterministic trend, which has a value of 1 in 1982 and 18 in 1999.

IV. Results

Cointegration also implies that the test statistics used to chose among potential estimation techniques can be evaluated reliably against an F distribution. The F-tests reject the null hypothesis that the slopes and intercepts are the same across nations ($F(284,1008) = 1543.6$, $p < .001$) and the null hypothesis that only the intercepts vary across nations ($F(213,1152) = 18.4$, $p < .001$) therefore, we estimate equations (2-4) using the random coefficient model (P.A.V.B Swamy, 1970). We apply the random coefficient model estimator to data from which the individual means are removed because preliminary results indicate that international differences in the technology scalar (A_i) do not vary randomly around a constant mean.

Estimation results reject ($p < .01$) the null hypothesis that the regression coefficient associated with capital, labor, or net primary production is zero (Table 1). Rejecting $\varphi = 0$ indicates that net primary production makes a statistically measurable contribution to GDP. *Ceteris paribus*, high rates of net primary production generate environmental services that increase real GDP relative to nations with similar amounts of capital and labor, but lower rates of net primary production. We also reject the null hypothesis that $\varphi = 1.0$ ($t = 56.7$, p

< .001), which indicates that NPP does not act as a scalar. The size of φ (0.15) implies that a one percent increase in net primary production increases real GDP by 0.15 percent. The results do not change significantly if another estimation technique is used to estimate equation (2) (Table 1) or if a deterministic trend is included as in equations (3) or (4) (Table 2). Nor do the results regarding the contribution of net primary production change if the production function (with or without the time trend) is expanded to included commercial energy consumption, as measured by the heat equivalents of coal, oil, natural gas, and primary electricity.

Empirical estimates of production functions generally assume constant returns to scale. This assumption $\alpha+\beta+\varphi = 1$ is strongly rejected ($\chi^2(2) = 51.93$, $p<.0001$), which implies that the production function shows increasing returns to scale. On the other hand, we barely reject ($\chi^2(1) = 4.05$, $p < .046$) the null hypothesis $\alpha+\beta = 1$, which may indicate that priced inputs show constant returns to scale.

V. Discussion

We calculate a shadow price for net primary production based on the economic axiom that the price for a factor of production equals its marginal product. The marginal product of net primary production is the partial derivative of equation (1) with respect to N:

$$\frac{\partial Y}{\partial N} = \varphi A_i L_{it}^{\alpha} K_{it}^{\beta} N_{it}^{\varphi-1} \qquad (5)$$

The shadow price (1996$/kg carbon/year) generated by equation (5) may still understate the economically efficient price for net primary production because some contributions of net primary production to GDP are not priced via the market. In addition, this estimate does not include the value of aesthetic environmental amenities, such as existence values.

International differences in the shadow price for net primary production are consistent with both the ecological availability of net primary production and economic factors that determine their contribution to GDP (Figure 1b). The shadow price for net primary production generally is higher in developed nations than in developing nations because the shadow price for NPP is influenced by the technology through which ecosystem services contribute to economic production. Where technology is most efficient (developed countries), each unit of net primary production generates more activity.

This effect on shadow prices is reinforced by diminishing returns. Developed nations generally use small amounts of net primary production relative to capital and labor, which increases the marginal product of net primary production. On the other hand, developing nations use large amounts of net primary production relative to capital, which reduces the shadow price of net primary production. Consistent with this notion, the rate of technical substitution, which can be measured by the amount of net primary production that is needed to replace a unit of capital, tends to be greatest in developing nations.

From an ecological perspective, net primary production occurs in space, therefore ecosystem services can be measured by economic output per area (Figure 1c). At the margin, the value of ecosystem services per unit area is the product of the shadow price and the rate of net primary production, which varies by biome. In general, biomes near the

equator such as tropical rainforests have the highest rate of net primary production while biomes at high latitude, such as boreal forests have lower rates of net primary production. This latitudinal distribution coincides with the distribution of developing nations at low latitudes and developed nations at high latitudes. High rates of net primary production in developing nations offsets some of the international differences in the shadow price for net primary production, nonetheless, the greatest prices occur in developed nations.

The methodology used to estimate a shadow price for a large component of environmental services has several advantages relative to previous efforts. Estimating a production function from observations provides an objective estimate for the shadow price of environmental services. Estimates based on willingness-to-pay or contingent valuation methodologies depend in part on the degree to which consumers understand the way in which environmental services support economic activity. If consumers do not understand the benefits generated by environmental services, they are likely to understate their value.

The use of a production function also ensures that estimates for the shadow price of net primary production are consistent with economic theory. Diminishing returns imply that the shadow price for environmental services should increase as economic development or environmental degradation reduces net primary production. These reductions imply that there is a limit on the ability to substitute capital and/or labor for environmental services—the so-called economic Plimsol line (Herman E. Daly, 1977). Our results indicate that capital and/or labor can substitute for environmental services, but the rate of substitution increases as the climate and ecological systems that generate these services are degraded. This degradation may raise the shadow price to a point at which it is no longer

economically feasible for humans to replace environmental services with capital and/or labor. This point could represent an upper bound on the scale of economic activity.

Objective estimates for the shadow price of ecosystem services may have important empirical applications, such as assessing the economic effects of environmental challenges. For example, integrated assessment models for global climate change simulate economic losses with a damage function that represents a hypothetical relationship between temperature and the fractional reduction in GDP (Nordhaus, 1992). This method could be improved by linking the shadow prices developed here to changes in net primary production that are forecast by ecological models, which are driven by climate scenarios simulated by coupled atmosphere-ocean general circulation models.

In addition, the shadow price for net primary production could be used to modify national accounts for the effects of environmental degradation. For example, GDP includes economic activity that results from converting natural ecosystems to economic purposes, such as residential housing or manufacturing infrastructure. Such land use changes reduce environmental services, and so represent a depreciation of natural capital. The economic value of this depreciation could be valued by calculating the quantity of capital (K) that is required to replace environmental services that are lost due to land use change. This quantity of capital could then be subtracted from gross investment to calculate a measure for net national investment that accounts for environmental degradation.

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Figure Caption

Figure 1a Global distribution of net primary production. Values are an average of yearly values from 1982-1999. NPP 10^6 Kg Carbon / year. **(1b)** The shadow price for NPP (US 1996 $ per Kg /Carbon) as calculated from equation (5). Values are an average of yearly values from 1982-1999. **(1c)** Marginal value of the annual net primary production that is generated by average square kilometer of land.

Figure 1a

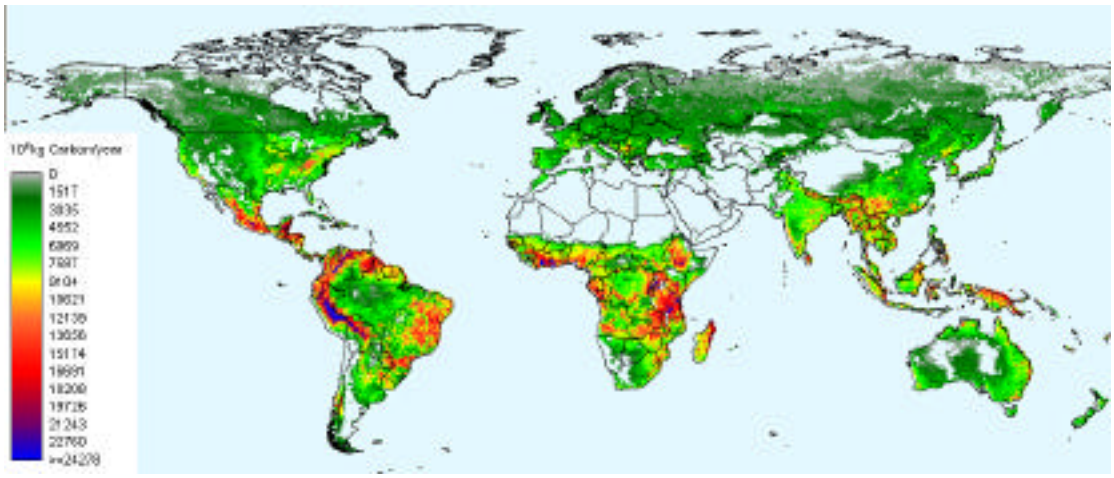

Figure 1b

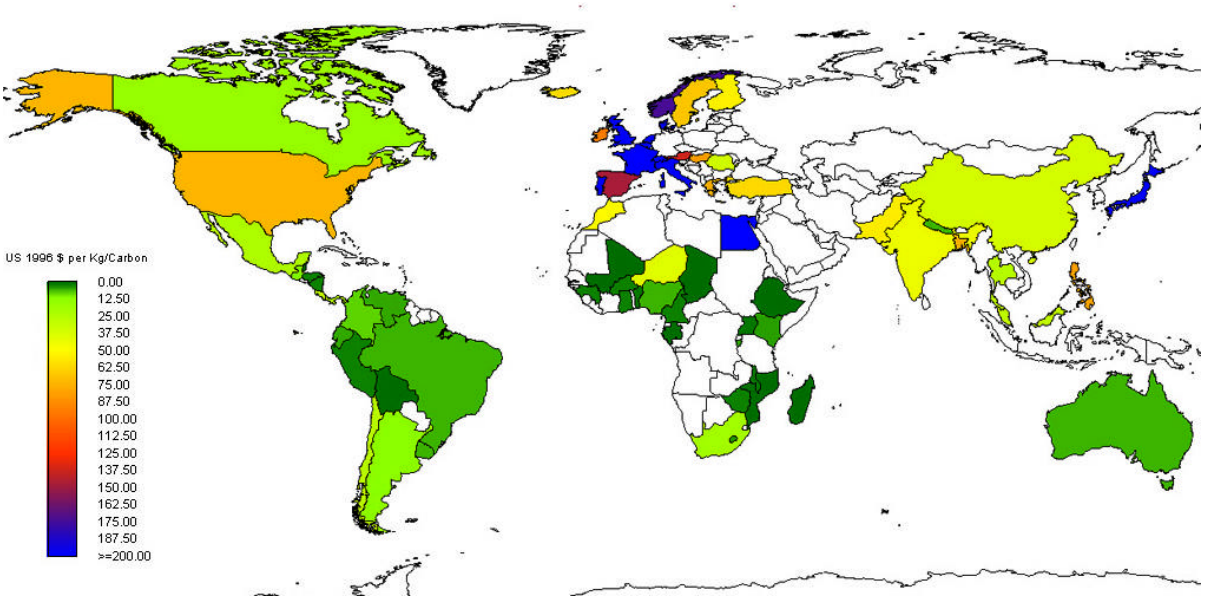

Figure 1c

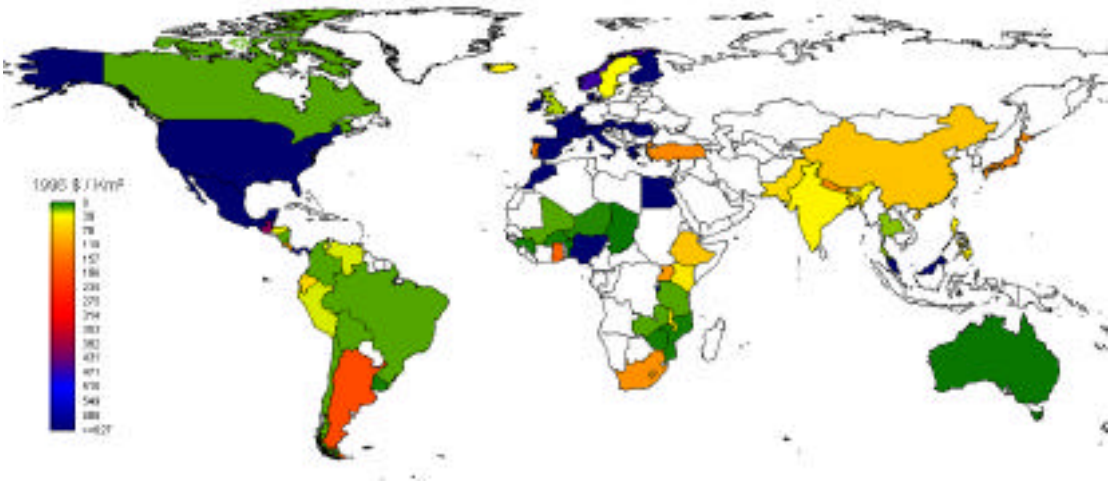

Table 1. Regression results for Equation 1

	OLS	**Fixed Effects**	**Random Effects**	**RCM**	**RCM** $\alpha+\beta+\varphi=1$	**RCM** $\alpha+\beta=1$
NPP (φ)	0.126** (0.02)	0.135** (0.05)	0.11** (0.04)	0.151** (0.02)	0.139** (0.02)	0.149** (0.02)
K (β)	0.673** (0.02)	0.45** (0.02)	0.46** (0.02)	0.648** (0.02)	0.696** (0.01)	0.675** (0.01)
L (α)	0.062** (0.03)	0.54** (0.03)	0.52** (0.03)	0.538** (0.11)	0.164** (0.02)	0.325** (0.01)
Constant	-2.06** (0.35)		-3.14** (0.58)			
R-squared	0.73	0.70	0.69	0.64		
Panel ADF				-4.00**		
Group ADF				-5.86**		
Test on Restriction					12.66**	4.03*

Coefficients are statistically significantly different from zero at the: **1%, *5%, +10%. Standard Errors in parenthesis. Panel and Group ADF statistics test the null hypothesis that the residual contains a unit root. They are modified so that they can be evaluated against the negative tail of a normal distribution.

Table 2: Regression Results for Equations 3 & 4

	OLS	Fixed Effects	Random Effects	RCM	OLS	Fixed Effects	Random Effects	RCM
	Linear Technical Change				Logarithmic Technical Change			
Tech (γ)	0.007	0.02**	0.01**	0.02**	0.48	0.07**	0.07**	0.05**
N (φ)	0.16**	0.03	0.07+	0.07**	0.16**	0.06**	0.08+	0.12**
Capital (β)	0.67**	0.30**	0.33**	0.33**	0.67**	0.36**	0.38**	0.61**
Labor (α)	0.06*	0.18**	0.22**	0.11	0.06**	0.33**	0.33**	0.19
Constant	-2.1**		5.13**		-2.13**		2.08**	
R-squared	0.73	0.70	0.74	0.64	0.73	0.73	0.72	0.68
Slopes & intercepts equal	F(355,936) = 1814.4**				F(355,936) = 1763.8**			
Intercepts equal	F(284,1080) = 22.4**				F(284,1080) = 21.8**			
Panel - ADF	-4.00**				-2.01*			
Group - ADF	-5.86**				-5.05**			

Coefficients are statistically significantly different from zero at the: **1%, *5%, +10%. . Panel and Group ADF statistics test the null hypothesis that the residual contains a unit root. They are modified so that they can be evaluated against the negative tail of a normal distribution.