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ANALYSIS

Valuing ecosystem services: A shadow price for net primary production

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ABSTRACT

We analyze the contribution of ecosystem services to GDP and use this contribution to calculate an empirical price for ecosystem services. Net primary production is used as a proxy for ecosystem services and, along with capital and labor, is used to estimate a Cobb Douglas production function from an international panel. A positive output elasticity for net primary production probably measures both marketed and nonmarketed contributions of ecosystems services. The production function is used to calculate the marginal product of net primary production, which is the shadow price for ecosystem services. The shadow price generally is greatest for developed nations, which have larger technical scalars and use less net primary production per unit output. The rate of technical substitution indicates that the quantity of capital needed to replace a unit of net primary production tends to increase with economic development, and this rate of replacement may ultimately constrain economic growth.

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1. Introduction

The "Holy Grail" for environmental economists would include empirical prices for ecosystem services. Prices are warranted because ecosystems contribute to economic well being in ways that extend well beyond aesthetic amenities (Millennium Ecosystem Assessment, 2005; Imhoff et al., 2004; Brock and Xepapadeas, 2003; Daily et al., 2000; Costanza et al., 1997; Vitousek, 1994). Contributions include the production of natural resources, the dilution and detoxification of wastes, the provision of a hospitable climate, and biodiversity.

Many of these services are not provided through the market because the services and/or portions of the environment that provide them are non-appropriable. That is, they cannot be owned therefore access cannot be controlled. These conditions create an externality that prevents the market from allocating ecosystem services efficiently and the resultant inefficiency often reduces their provision. As an externality, degradation will continue without intervention.

The market cannot recognize the economic impact of environmental degradation if ecosystem services do not have a price. For example, existing technologies that reduce the environmental impact of human activity on ecosystem services are not fully implemented because the environmental services they preserve are free (Millennium Ecosystem Assessment, 2005). If empirical prices for ecosystem services were available, degradation could be reduced using economically efficient market based mechanisms.

Here, we evaluate two fundamental questions about ecosystem services: (1) do ecosystem services contribute to

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economic activity, as measured by traditional metrics, such as Gross Domestic Product, and (2) can this contribution be used to calculate a shadow price for ecosystem services? To answer these questions, net primary production is used as an ecologically meaningful measure for the ecosystem services that are rendered by natural capital. Using annual values for net primary production, along with capital and labor, we estimate a Cobb Douglas production function from an international panel. The positive output elasticity for net primary production probably measures both the market and nonmarket contributions of ecosystem services. We use the estimated output elasticities and technical scalars to calculate the marginal product of net primary production, which represents the shadow price for ecosystem services. The shadow price generally is greatest for developed nations, which have larger technical scalars and use less net primary production per unit output. We also calculate the rate of technical substitution. Our results indicate that the quantity of capital needed to replace a unit of net primary production tends to increase with economic development. This rate of replacement may ultimately constrain economic growth.

2. Ecosystem services and economic activity

2.1. *How do ecosystem services contribute to traditional measures of economic activity?*

The Millennium Ecosystem Assessment (2005) identifies three types of ecosystem services; provisioning services, regulating services, and cultural services. Provisioning services include food, fiber, freshwater, genetic resources, and chemicals. The economic value for many of these services, such as value added in agriculture, is included in the system of national accounts that is used to calculate Gross Domestic Product and other measures of economic activity. Despite inclusion, their importance may be understated. In several African, European, and Asian nations, the economic benefits of converting forests to pasture or using them as a source of timber and fuel wood are smaller than the loss of non-marketed services such as carbon sequestration, watershed protection, and recreation and hunting (Millennium Ecosystem Assessment, 2005).

These non-marketed services, along with the regulation of climate, erosion, pests, and natural hazards, are known as regulating services. Many of these services are not priced by the market, nonetheless, they contribute to economic output two ways. Some regulating services increase economic output directly. For example, mangrove ecosystems regulate water quality and control erosion, which allows the local ecosystem to support a larger population of fish. Higher densities increase the quantity of fish caught, which increase the value of output (Barbier, 2000; Barbier and Ian Strand, 1998). Efforts to calculate the direct market valuation of regulating services has been limited by a lack of data and a clear understanding of how the ecosystem, the service being valued, and the marketed commodity are linked (Chee, 2004; Daily et al., 2000).

Regulating services also increase output indirectly in ways that can be understood via the economic notion of opportunity costs. For example, natural wetlands purify drinking water and provide flood control. Although these services usually are not priced by the market, they increase economic output by increasing the availability of capital and labor that can be used elsewhere in the economy (Kaufmann, 1995). To illustrate, suppose that natural wetlands and the services they provide are destroyed. To maintain economic well-being, wetland ecosystem services would be replaced by a water filtration plant and a system of dams and levees. Their construction and operation would consume capital and labor that otherwise would be available to produce other goods and services. The value of these other goods and services, which are lost due to the construction and operation of the filtration plant, dams, and levees, are termed opportunity costs, and represent the economic value of the ecosystem services provided free by the wetlands.

These opportunity costs sometimes can be quantified using the concept of avoided costs, which are 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 environmental services based on the price of market services that provide the same utility.

The third type of ecosystem services is cultural services. These include spiritual and religious values, aesthetic values, and recreation and ecotourism. Many ecosystem services used for recreation and ecotourism are included in the system of national accounts. Their contribution often is measured using travel cost methods, which quantify the money and time that people spend on travel to an ecosystem service. Aesthetic values represent the quality of natural lands. A portion of their economic value is included by the higher rents that consumers are willing to pay for land with nice views, etc. This contribution has been measured using hedonic prices, which attempt to isolate the value contributed by a specific trait or aesthetic quality (King and Sinden, 1988). Finally spiritual and religious values can raise the value of particular landscapes, including those that will never be visited but which have an existence value. For example, many consumers in developed nations value tropical rainforests or polar bears even though they may never see either *in situ*.

2.2. *An empirical measure of ecosystem services*

Many provisioning and regulating services can be proxied by terrestrial net primary production. Terrestrial net primary production is the difference between the energy fixed by producers (largely plants), which is termed gross primary production, and the energy they use for maintenance. Net primary production represents the amount of energy used by plants for storage, growth, and reproduction. These energy flows support consumers and detritivores. As such, net primary production can be viewed as a flow that maintains the stock of natural capital that generates ecosystem services. This assumption is consistent with previous analyses—for example the value of services provided by the biomes listed in Table 2 of Costanza et al. (1997) is positively correlated with their relative rates of net primary production.

Net primary production is positively correlated with the flow of many provisioning and regulating services. In general, landscapes with high net primary production generate more food, timber, or fiber than less productive landscapes. The global distribution of biodiversity and the services it provides, such as the availability of genetic resources and biological chemicals, generally increases with net primary production (Gaston, 2000). Net primary production also is correlated with the fraction of a region's water supply that is generated by transpiration. Many regulating services also are positively correlated with net primary production. Carbon sequestration is directly related to net primary production. At the scale of biomes, net primary production is negatively related to the soil erosion protection factor listed by the International Geosphere–Biosphere Programme and is positively related to their relative rates of soil formation—soil formation is enhanced by high rates of net primary production.

Other provisioning services seem to be correlated with ecological stocks, such as biomass, but their contribution to current economic production, which is a flow, may be best represented by net primary production, which also are a flow. Old-growth forests with high biomass store more carbon than younger forests or tree plantations. But so long as biomass remains constant, the stock makes no contribution to current economic production. Changes in biomass, which are a flow that may be proxied by net primary production, contribute to economic production. Net primary production in young forests or tree plantations contributes to economic production by removing carbon, which would have altered climate and reduced economic activity.

Finally, net primary production probably is correlated with cultural services, such as recreation and ecotourism. Recreation and ecotourism occurs largely in highly productive ecosystems. Reductions in net primary production tend to reduce recreation and tourism. Conversely, net primary production probably is not related to aesthetic values or spiritual and religious values, although Odum (1971) argues that people are intrinsically attracted to highly productive ecosystems.

3. Methodology

We test the null hypothesis that ecosystem services do not contribute economic production by expanding a traditional economic production function to include terrestrial net primary production as a factor of production. An expanded version of the Cobb–Douglas production function is given by:

$$Y_{it} = A\ L_{it}^{\alpha} K_{it}^{\beta} N_{it}^{\lambda} \tag{1}$$

in which Y is real GDP in 1996 dollars for nation *i* at time *t*, *L* is the number of workers, *K* is the capital stock in 1996 dollars, *N* is net primary production within the geographical borders of nation (million kg carbon/year), *A* is a technology scalar, and α, *b*, and λ are output elasticities of labor, capital, and net primary production respectively. Output elasticities measure the percentage change in GDP that is generated by a one percent increase in the use of a factor input (holding other inputs constant). A positive output elasticity for net primary production would reject the null hypothesis by indicating that an increase in ecosystem services increases economic production.

We calculate net primary production from NOAA/AVHRR satellite data (Zhou et al., 2001) using a production efficiency model (Nemani et al., 2003). The model used here is based on the algorithm used to produce MODIS NPP products (Heinsch et al., 2003). We use NOAA/ AVHRR data because it covers a longer time period (1982–2000). The spatial resolution is 0.5°. The production efficiency algorithm includes three components:(1) leaf area index and a fraction of absorbed photosynthetically active radiation (APAR), which combines the meteorological constraint of available sunlight with the ecological constraint of leaf area index; (2) daily climate data (e.g. incident radiation, air temperature, and precipitation) and; (3) a biome specific parameterization that converts APAR to net primary production (Fig. 1). Values for vegetated pixels are converted to annual values and summed for individual nations in a geographic information system. The result is one value of net primary production for each nation per year.

Data for real GDP, labor, and capital are from the Penn World Tables (version 6.1; Heston et al., 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

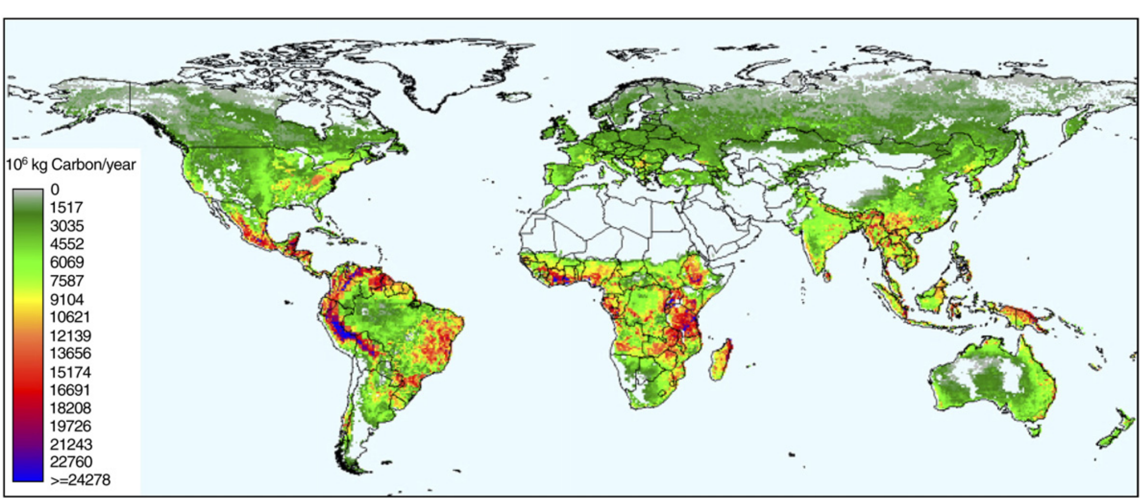

Fig. 1 – Global distribution of net primary production, as measured in millions of kilograms carbon per pixel per year. Values are an average of yearly values from 1982–1999. The size of pixels varies with latitude with the largest pixels near the equator.

and the depreciation rate δ (assumed to be 0.07 as in Easterly and Levine, 2002). 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. This method of calculating K_0 assumes that each country starts at steady state, such that the growth rate of capital is approximately equivalent to the growth rate of real output ($g_K \approx g_Y$) (Sue and Steifert, 2005). K_0 is calculated for 1960 and updated through the sample period, therefore, the initial value for capital stock probably has little effect on the value of capital stock in 1982, which is the first year of the sample period. Furthermore, international variations caused by the 1960 start date are eliminated by the fixed effect transformation that is used to estimate the production function with the cointegration/error correction approach.

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 that are used to calculate net primary production. Sample size is determined by the number of nations for which a complete set of economic data are available, which include twenty developed nations and fifty one developing nations.

Eq. (1) is estimated by taking the natural logarithm of both sides:

$$\ln(Y_{it}) = \ln(A) + \alpha\ln(L_{it}) + \beta\ln(K_{it}) + \lambda\ln(N_{it}) + \eta_{it} \qquad (2)$$

in which η is the regression error. Estimating Eq. (2) from an international panel raises two econometric issues; (1) do the regression coefficients vary among nations and (2) does simultaneous equation bias and econometric issues of identification confuse the interpretation of regression results? To evaluate these issues, Eq. (2) is estimated using two general approaches. Panel techniques are used to capture international variations in the technical scalar and output elasticities. Cointegration techniques are used to investigate the potential impact of simultaneous equation bias and the econometric conditions needed to identify statistical estimates of the output elasticities.

3.1. Panel methodology

Eq. (2) can be specified using a variety of assumptions to assess international variations in regression coefficients. We use F tests (Hsiao, 1986) to chose among specifications that assume that: (1) the technical scalar and output elasticities are the same among nations (pooled OLS estimator); (2) the technical scalar varies among nations but the output elasticities are the same among nations (fixed effects or random effects estimator); or (3) the technical scalar and the output elasticities vary among nations (random coefficient model).

[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.

We start with the least restrictive assumption, that the technical scalar and the output elasticities vary among nations. To test whether only the output elasticities vary among nations, we impose restrictions that equalize the technical scalar among nations. Rejecting this restriction would indicate that Eq. (2) should be estimated using the random coefficient model. Should this restriction not be rejected, we impose restrictions that equalize the output elasticities and technical scalar among nations. Failure to reject this restriction would indicate that Eq. (2) should be estimated using pooled OLS. Rejecting this restriction would indicate that Eq. (2) should be estimated using either the fixed or random effects estimator. As described below, tests indicate that Eq. (2) should be estimated using the random coefficient model, which lets the technical scalar and output elasticities vary among nations as given by Eq. (3):

$$\ln(Y_{it}) = \ln(A_i) + \alpha_i\ln(L_{it}) + \beta_i\ln(K_{it}) + \lambda_i\ln(N_{it}) + \eta_{it} \qquad (3)$$

3.2. Cointegration and error correction

To evaluate the potential effect of simultaneous equation bias, we use techniques that emphasize the time series properties of the data. Unit root tests developed by Levin et al. (2002) indicate that GDP (5.47), capital (8.30), and labor (6.42) have a stochastic trend (i.e. they are I(1)) while net primary production (−10.04) is stationary (i.e. it is $I(0)$). The panel ADF statistic developed by Pedroni (1999) indicates that GDP, capital, and labor cointegrate (Table 2). Cointegration implies that the long-run equilibrium relationship among GDP, capital, and labor can be estimated using the DOLS estimator (Stock and Watson, 1993) as follows:

$$\ln\tilde{Y}_{it} = \alpha\ln(\tilde{L}_{it}) + \beta\ln(\tilde{K}_{it}) + \sum_{i=-s}^{s} \delta\Delta\ln(\tilde{K}_{it-i}) + \sum_{i=-s}^{s} \theta\Delta\ln(\tilde{L}_{it-i}) + \mu_{it} \qquad (4)$$

in which Δ is the first difference operator (e.g. $Y_{it}-Y_{it-1}$) and the tilde represents the fixed effects transformation (This transformation is used because the fixed effect estimator indicates that the technical scalar varies greatly among nations). The leads and lag(s) are chosen using the Schwarz (1978) criterion.

By definition, there can be no long-run relationship between $I(1)$ variables and $I(0)$ variables, therefore, Eq. (4) does not include net primary production. To estimate the effect of net primary production on GDP, and to determine the causal relationship among variables, an error correction model is estimated as follows:

$$\Delta\ln Y_{it} = \pi + \rho\ln(\varepsilon_{it-1}) + \lambda\ln(\tilde{N}_{it}) + \sum_{i=1}^{s} \delta_i\Delta\ln(\tilde{K}_{it-i}) + \sum_{i=1}^{s} \theta_i\Delta\ln(\tilde{L}_{it-i}) + \sum_{i=1}^{s} \psi_i\Delta\ln(\tilde{Y}_{it-i}) + \xi_{it} \qquad (5)$$

in which ε is the residual from the cointegrating relationship estimated in Eq. (4). Eq. (5) is estimated using OLS because all variables are I(0). The Akaike (1973) information criterion is used to determine the number of lag(s).

The output elasticity for net primary production is given by λ. The effect of disequilibrium among GDP, capital, and labor, on the level of GDP is given by ρ. A negative value indicates the rate at which GDP adjusts to the long-run value implied by capital and labor. For example, if ρ has a value of -0.2, then 20% of the difference between the equilibrium value of GDP implied by capital and labor, and the previous year's value of GDP is eliminated in the current year.

Values of ρ also can be used to evaluate the degree to which simultaneous equation bias affects the results and evaluate econometric conditions of identification that may prevent interpreting α, b, and λ as output elasticities. To estimate the relevant values for ρ, we repeat the cointegration/error correction methodology with modified versions of Eqs. (4) and (5) in which capital or labor become the dependent variable and GDP becomes an independent variable.

3.3. *Sensitivity analyses*

To assess the degree to which the results are robust, we also estimate specifications that represent changes in the quality of the labor force, technical capabilities, and depreciation rates. Economists have made considerable efforts to quantify qualitative changes in the labor input (e.g. Barro and Sala-I-Marin, 2004). To evaluate this effect, we expand the production function to include an index of educational attainment for sixty-two of the seventy-two nations in our sample for which data are available (Barro and Lee, 2001). They report data for average years of schooling at five year intervals, 1960–2000. We interpolate linearly between values to generate annual values.

Cointegration among GDP, capital, and labor implies that the residual is stationary and that a deterministic trend is not needed to represent technical change over the nineteen year sample period. To ensure that this omission does not affect our results, a deterministic time trend is added to both Eqs. (3) and (4).

To assess the assumption of a constant depreciation rate, Monte Carlo techniques are used to generate 1000 experimental data sets in which the depreciation rate varies randomly around 0.07 ± 0.02 for each year and nation. Each data set is used to estimate Eq. (3) via the random coefficient model.

4. Results

4.1. *Panel estimation*

Cointegration among GDP, capital, and labor implies that the test statistics used to chose among potential estimation techniques can be evaluated reliably against an *F* distribution. Consistent with large differences among nations in the sample, test statistics reject the null hypothesis that the technical scalar and output elasticities are the same across nations and the null hypothesis that only the technical scalar varies across nations (Table 1). Based on these results, we estimate Eq. (2) using the random coefficient model (Swamy, 1970). The random coefficient model estimates a mean value for the output elasticities, around which the output elasticities for individual nations vary randomly. This specification is not appropriate for the technical scalar—results from the fixed effects estimator indicate that the technical scalar varies greatly among nations. To allow the technical scalar to vary freely among nations (as opposed to randomly around a common mean), we apply the random coefficient model estimator to data from which the individual means are removed (i.e. the fixed effects transformation).

Estimation results reject ($p<0.01$) the null hypothesis that the output elasticity for capital, labor, or net primary production is zero (Table 1). Rejecting $\lambda=0$ indicates that net primary production makes a statistically measurable contribution to GDP. *Ceteris paribus*, high rates of net primary production proxy ecosystem services that increase real GDP relative to nations with similar amounts of capital and labor, but less net primary production. We also reject the null hypothesis that $\lambda=1.0$ ($t=59.2$, $p<0.001$), which indicates that NPP does not act as a scalar. The size of λ (0.13) implies that a one percent increase in net primary production increases real GDP by 0.13%.

Empirical estimates of production functions generally assume constant returns to scale. An assumption that all output elasticities sum to one ($\alpha+\beta+\lambda=1$) is rejected strongly ($\chi^2(2)=10.1$, $p<0.0001$), which implies that the production function shows increasing returns to scale. On the other hand, we fail to reject ($\chi^2(1)=3.29$, $p<.07$) the null hypothesis

Table 1 – Regression results for panel estimate based on Eq. (2)

	Base case OLS	Base case fixed effects	Base case random effects	Base case RCM	RCM time trend	RCM education attainment	RCM GDP adjustment
NPP (λ)	0.06^{*}	0.16^{**}	0.07^{*}	0.13^{**}	0.08^{**}	0.17^{**}	0.13^{**}
K (β)	0.76^{**}	0.52^{**}	0.56^{**}	0.72^{**}	0.38^{**}	0.66^{**}	0.75^{**}
L (α)	0.16^{**}	0.49^{**}	0.43^{**}	0.44^{**}	0.16	0.20^{+}	0.56^{**}
Educ						0.15^{**}	
Time					0.02^{**}		
Constant	-4.44^{**}		-3.95^{**}				
R^2	0.96	0.76	0.78				
Z score					2.83^{*}	-1.78^{+}	0.04
$\alpha+\beta=1$	104.3^{**}	0.04	0.64	$3.29^{\#}$	$23.2^{**\#}$	$0.06^{\#}$	$11.2^{**\#}$
$\alpha+\beta+\lambda=1$	9.54^{**}	14.3^{**}	5.40^{**}	$10.11^{**\#}$	15.4^{**}	$5.35^{**\#}$	$21.8^{**\#}$
Slopes intercepts equal	201.4^{**}				218.9^{**}	188.8^{**}	116.7^{**}
Intercepts equal	12.5^{**}				11.8^{**}	15.4^{**}	12.3^{**}

Coefficients are statistically significantly different from zero at the: **1%, *5%, +10%. #Distributed as a chi-square with one degree of freedom—For the education model, the restriction tests whether the output elasticities for capital, labor, and education sum to 1.
Z score compares estimated values of λ as follows: $Z = \frac{\hat{\lambda}_{\text{Base case}} - \hat{\lambda}_{\text{Alternative}}}{\sqrt{\hat{\sigma}^2_{\text{Base case}} - \hat{\sigma}^2_{\text{Alternative}}}}$ in which $\hat{\sigma}^2$ is the variance of the estimated value $\hat{\lambda}$.

Table 2 – Regression results for cointegration (Eq. 4) and error correction approach (Eq. 5)

	Base case	Education attainment	Time trend	GDP adjustment
Eq. (4)				
Capital (β)	0.53**	0.51**	0.53**	0.62**
Labor (α)	0.42**	0.28**	0.41**	0.47**
Education		0.26**		
Time			1.51E-04	
R^2	0.65	0.69	0.65	0.60
$\alpha+\beta=1.0$#	0.64	1.24	1.61	2.33*
Panel ADF	−7.64**	−6.21**	−7.64**	−7.48**
Group ADF	−8.92**	−7.57**	−8.92**	−8.57**
Eq. (5)				
Net primary production (λ)	0.08**	0.09**	0.09**	0.09**
Error correction ρ	−0.27**	−0.10**	−0.27**	−0.26
R^2	0.17	0.24	0.17	0.15
Z score (relative to base case)		−0.32	−0.44	0.20
Z score (relative to panel result)	−1.47	1.78	−2.83*	0.04

Coefficients are statistically significantly different from zero at the: **1%, *5%, +10%. #Distributed as an F—For the education model, the restriction tests whether the output elasticities for capital, labor, and education sum to 1.

Z score compares estimated values of λ as follows: $Z=\frac{\hat{\lambda}_{\text{Base case}}-\hat{\lambda}_{\text{Alternative}}}{\sqrt{\hat{\sigma}^2_{\text{Base case}}-\hat{\sigma}^2_{\text{Alternative}}}}$ in which $\hat{\sigma}^2$ is the variance of the estimated value $\hat{\lambda}$.

that the output elasticities for capital and labor sum to one ($\alpha+\beta=1$), which may indicate that priced inputs show constant returns to scale.

4.2. Cointegration and error correction

The preceding results are confirmed by the regression results for Eqs. (4) and (5). The output elasticities of capital and labor from Eq. (4) are 0.53 and 0.47 respectively (Table 2). A restriction that imposes constant returns to scale ($\alpha+\beta=1$) cannot be rejected ($F(1,776)=0.64$ $p<0.43$), which again indicates that priced inputs show constant returns to scale. The regression coefficient associated with net primary production in the error correction model indicates that the output elasticity of net primary production is 0.09 ($t=2.82$ $p<.01$), which is not statistically different ($Z=1.47$, $p>0.14$) from the value generated by the random coefficient estimator.

Three aspects of the results suggest that simultaneous equation bias and the econometric conditions that would preclude the identification of the output elasticities do not confuse the interpretation of results. First, there is no indication of bias. We fail to reject restrictions that impose constant returns to scale on the priced inputs included in the production function, either capital and labor, or capital, labor, and educational attainment. Second, cointegration implies that any correlation between the regression error (μ) and capital and labor in Eq. (4) that would cause simultaneous equation bias is probably very small. GDP, capital, and labor are $I(1)$ while the regression error is $I(0)$ so any correlation would be very small. Thirdly, the negative value for ρ in Eq. (5) indicates that that GDP moves towards the equilibrium value implied by capital and labor, such that about 29% of disequilibrium is eliminated per year. When the cointegration/error correction methodology is repeated with capital as the dependent variable, the estimated value of ρ drops by an order of magnitude ($\hat{\rho}=-0.026$, $t=4.1$ $p<0.01$). The much slower rate of adjustment greatly eases concern that the cointegrating relationship that includes GDP, capital, and labor also represents the effect of GDP on capital. When the cointegration/error correction methodology is repeated with labor as the dependent variable, the relationship appears spurious (e.g. the panel ADF −1.34 does not reject the null hypothesis) and the coefficient associated with capital in the cointegrating relationship is not significant. This implies that labor does not respond to disequilibrium in the relationship among GDP, capital, and labor given by Eq. (4).

The slow rate at which capital adjusts to GDP, the lack of adjustment between labor and other inputs, and the

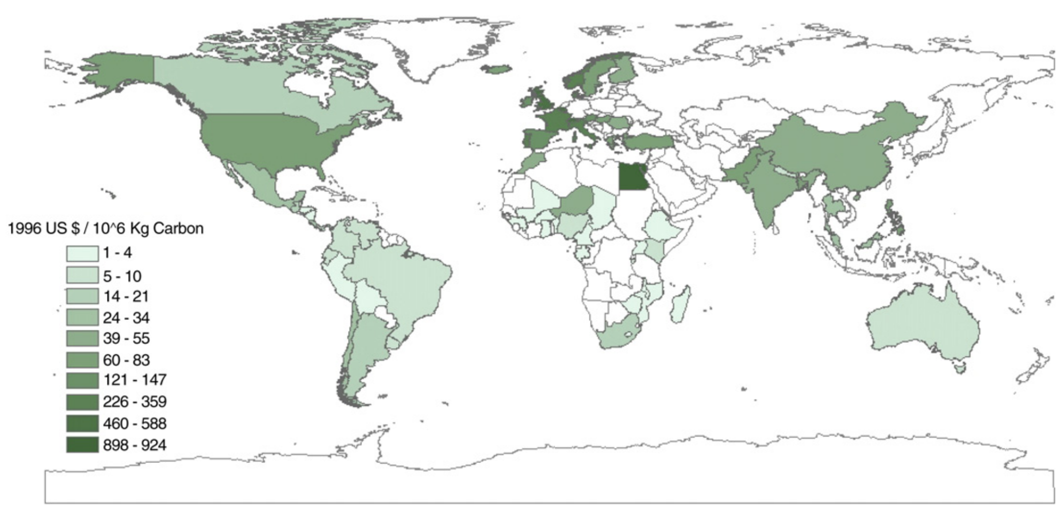

Fig. 2 – The shadow price for NPP (US$1996 per million kg/carbon) as calculated from Eq. (6). Values are an average of yearly values from 1982–1999. Values less than $1 appear blank.

international nature of the panel eases concerns about econometric conditions that would preclude identification of the output elasticities. When firm-level data are used to estimate a Cobb Douglas production function, the results may not be identified if inputs are collinear with productivity shocks. Such collinearity occurs if all firms face common input prices, if these prices are used to chose the optimal level of inputs, if the use of inputs is perfectly flexible, and if these adjustments does not incur any costs (Bond and Soderbom, 2005). For this international panel, none of these conditions are likely. Input prices probably vary considerably among nations. The very slow or lack of adjustment indicated by the error correction models imply that inputs do not vary immediately. These conditions reduce potential collinearity between productivity shocks and input levels relative to panels that consist of firm level data. As such, the regression coefficients estimated from Eqs. (3)–(5) probably can be interpreted as output elasticities.

4.3. *Sensitivity analyses*

The results described above are robust. Estimates for λ generated by the panel approach are not statistically different from those to those generated by the cointegration and error correction approach, except for the models that include a time trend (Table 2). Similarly, modifications to the base case do not change the estimate for λ in a statistically significant fashion, except for the addition a time trend when the model is estimated using a panel approach (Tables 1 & 2). Finally, allowing the depreciation rate to vary randomly has little effect on the estimate for λ. Each of the one thousand estimates for λ is statistically different from zero and they have a mean value of 0.136±0.015.

5. Discussion

5.1. *What does the relationship between net primary production and GDP measure?*

The positive output elasticity for net primary production indicates that ecosystem services contribute to economic activity, as measured by GDP. This contribution probably includes both marketed and non-market contributions. As described previously, many provisioning services contribute to GDP through the agriculture, fiber, and forestry sectors. As such, net primary production can be viewed as a determinant of rent that extends beyond location relative to economic activity. That is, net primary production can be viewed as a measurable determinant of a landscape's contribution to economic worth.

The output elasticity of net primary production likely goes beyond marketed contributions to GDP. Net primary production probably does not simply represent agricultural value added—empirical correlations between crop yield and satellite measures of net primary production tend to be weak (Zhang et al., 2005). Nor is the positive output elasticity for net primary production generated solely by international differences in the fraction of GDP generated in agriculture, fiber, or forestry—if present, this correlation is eliminated by the fixed effect transformation.

To test whether the output elasticity includes nonmarket contributions, GDP is reduced by the fraction that is generated in the agriculture, fiber, and forestry sectors, and the adjusted GDP data are used to estimate Eqs. (3)–(5). Although market contributions have been eliminated from GDP, the relationship between net primary production and the adjusted version of GDP remains—the estimated value for λ does not change in a statistically meaningful fashion (Table 1 & 2). This positive relationship indicates that net primary production contributes to GDP in ways that extend beyond sectors in which the products of net primary production enter the economy. Unfortunately, our analysis cannot separate marketed and non-market contributions of net primary production. Data are not available to separate net primary production in managed ecosystems from natural ecosystems nor are there data to subtract the capital used by these sectors from the national total.

Despite the inclusion of both marketed and nonmarketed contributions, this study does not measure contributions to human welfare that are not measured by GDP. For example our study would not be able to capture the value of ecosystem services to a hunter–gatherer society, which lives entirely from ecosystem services, but has no money or economy. Nonetheless, the contribution of these ecosystem services to human welfare would be high.

5.2. *A shadow price for net primary production*

Given the positive output elasticity for net primary production, we calculate its shadow price 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 Eq. (1) with respect to N:

$$\frac{\partial Y}{\partial N} = \lambda A_i L_{it}^{\alpha} K_{it}^{\beta} N_{it}^{\lambda-1} \tag{6}$$

Eq. (6) is used to calculate the shadow price ($1996/million kg carbon/year) for net primary production with the output elasticities and technical scalars that are estimated using Eq. (3) with the random coefficient model. This calculation may still understate the economically efficient price for net primary production because marketed contributions of net primary production to GDP may not be valued completely by the market. Furthermore, this estimate does not include aesthetic components of ecosystem services, such as existence values.

The shadow price for a million kilograms of carbon ranges from a low of $0.37 in Zambia (an average over all years) to a high of $924 in The Netherlands (Fig. 2). These international differences can be explained by economic axioms that focus on well understood differences between developed and developing nations. As such, our results are consistent with economic theory. One important difference between developed and developing nations concerns the level of technology, as represented by the technology scalar in Eq. (1). Developed nations generate more output per unit input because their technology is more effective than developing nations. Consistent with this differences, the shadow price for ecosystem services tends to be higher in developed nations where the technology scalar tends to be higher.

Economic theory also indicates that the relative price of factor inputs is determined by their relative value marginal product.

The relative marginal product of factor inputs depends in part on the combination of factor inputs used. In general, the relative marginal product tends to be greatest for factors in least supply. Such differences in factor endowments also contribute to differences in the shadow price for net primary production. After normalizing the use of factor inputs by GDP, developing nations use more net primary production per unit of output than developed nations. Under these conditions, the marginal product of net primary production will be smaller in developing nations.

Given this consistency with basic economic axioms, our method for estimating the shadow price for ecosystem services alleviates many of the fundamental contradictions with economic theory in the values reported by Costanza et al. (1997) that are described by critics (e.g. Bockstael et al., 2000). Bockstael et al. (2000) argue that it is incorrect to scale up values for ecosystem services estimated from small landscapes. Our production function and its implied shadow price is estimated at one consistent level of aggregation. The production function allows us to evaluate the value of ecosystem services at the margin (we explicitly avoid making any estimate for total value—due to increasing returns to scale it is incorrect to multiply net primary production by its shadow price to determine the total value of ecosystem services). This marginal estimate stands in stark contrast to the all-or-nothing assessment implied by the total value of ecosystem services reported by Costanza et al. (1997). Finally, the production function contains factor inputs and prices that are determined within each nation's economy. As such, the results provide a metric to express trade-offs (next section describes the trade-off between human capital and ecosystem services). Bockstael et al. (2000) note that such information, which lies at the heart of the economic definition of value, is absent from the estimate for the value of ecosystem services that are generated by Costanza et al. (1997).

5.3. *Economic growth: substituting capital for environmental services*

Economic theory generally attributes growth to the accumulation of capital, increases in human capital, and technical change (Barro and Sala-I-Martin, 2004). Discussion of the environment's contribution is limited and focuses mainly on natural resources (e.g. Wright, 1990; Stijns, 2005), especially the natural resource curse (e.g. Sachs and Warner, 1995).

Our results also suggest a relatively minor role. Although the output elasticity is positive, net primary production is stationary while GDP has a stochastic trend. From a statistical perspective, it is hard to argue that the stochastic trend in economic activity is generated by relatively stable rates of net primary production. It is possible that the fraction of ecosystem services used by the economy increases over time. If so, our analysis would attribute this contribution to technical change because the fraction of net primary production used as a factor of production remains constant (100%).

Instead, our results suggest that ecosystem services could eventually limit economic growth. Historically, growing economies are characterized by capital accumulation and changes in land-use that reduce net primary production. Capital infrastructure, such as houses, roads, factories etc. replace natural ecosystems with less ecologically productive landscapes. These changes alter the macroeconomic mix of factor inputs in favor of capital relative to ecosystem services.

The continued success of this strategy depends on the degree to which humans can substitute capital for ecosystem services. A limit on the ability to substitute capital for ecosystem services may imply an upper bound on economic activity—the so-called economic Plimsoll line (Daly, 1977). Evidence for an economic plimsoll line may be suggested by the rate of technical substitution, which is the quantity of one factor that is required to replace a unit of another factor while holding output constant. As indicated in Fig. 3, the rate of technical substitution of capital for net primary production becomes larger as the use of factors shifts from combinations dominated by ecosystem services (e.g. developing nations) to combinations dominated by capital (e.g. developed nations). At some point, economic growth may generate combinations at which it may not be economically viable to replace ecosystem services with capital and/or labor. That is, the cost of the capital needed to replace a unit of net primary production may be large relative to the gain

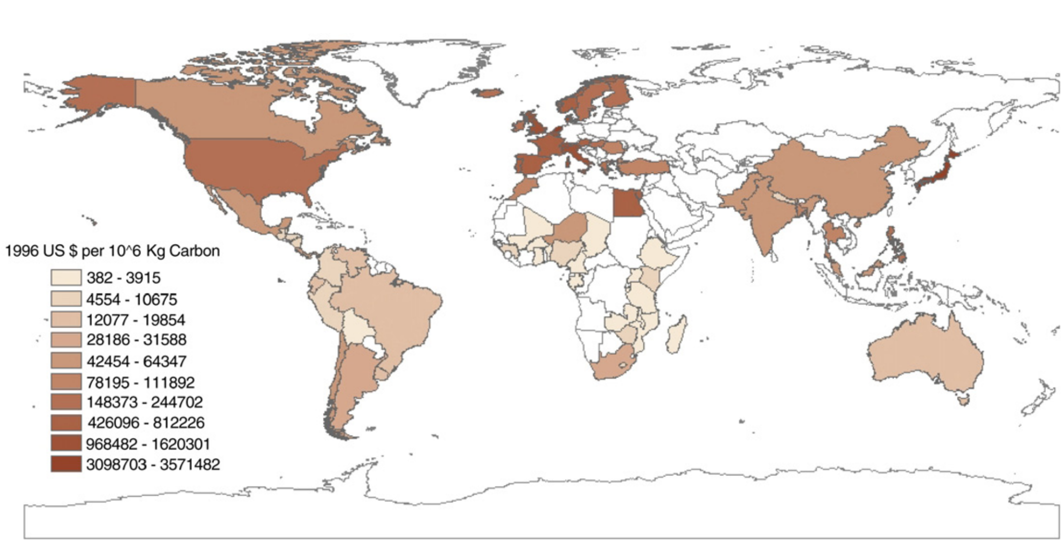

Fig. 3 – The Rate of Technical Substitution. The dollar value of capital stock that is needed to replace 1 million kg of carbon.

in economic activity associated with the increase in capital stock and reduction in net primary production.

Economic limits on the substitution of capital for net primary production may be illustrated by New York's City's efforts to maintain a clean water supply. For much of its history, water came from the Catskill Mountains, which are about 250 km north. Because of pollution in the Catskill region, water no longer met EPA standards for drinking. To comply with this standard, city managers determined that they needed a filtration system that would cost $6–$8 billion to build and $300 million a year to operate. Alternatively, they could purchase relevant areas of the Catskill region, slow polluting activities, preserve natural habitat, and allow ecosystem services to purify the water. This option cost between $1 billion and $1.5 billion, and had little in the way of annual costs. New York City chose not to substitute capital for ecosystem services because financial calculations indicated that purchasing land in the Catskills had a higher internal rate of return, 90 to 170% and a shorter payback period of 4–7 years, than the filtration system.

6. Conclusion

Empirical 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 the relationship between temperature increases and the fractional reduction in GDP (Nordhaus, 1992). To date, most of these efforts attempt to quantify the effect of climate change on managed ecosystems, such as agriculture or forestry.

In ongoing research, we attempt to expand climate change damage functions by linking the shadow prices developed here to changes in net primary production that are forecast by ecological models. Specifically, we use forecasts for climate coupled with atmosphere–ocean general circulation models to drive models of net primary production. Values for net primary production are coupled with forecasts for population growth and capital accumulation to generate forecasts of GDP. By comparing forecasts for GDP that are associated with competing climate scenarios, we hope to estimate the change in economic activity that is associated with climate driven changes in ecosystem services.

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