USING GROSS PRIMARY PRODUCTION TO MEASURE THE ECONOMIC BENEFITS OF ECOSYSTEM SERVICES AND THE ECONOMIC IMPACTS OF CLIMATE CHANGE

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Abstract

We explore the hypothesis that the incoming solar radiation fixed by the photosynthesis (gross primary production GPP) can be used to measure and aggregate different types of ecosystem services and that this aggregate contributes to market measures of economic well-being. Specifically, we include gross primary production in an expanded Cobb-Douglas production function and use estimation results to evaluate three fundamental questions: (1) does gross primary production contribute to Gross Domestic Product, (2) does this contribution go beyond the economic sectors where GPP generates biological resources included directly in GDP, and (3) how will anthropogenic climate change affect the provision of ecosystem services and macroeconomic activity? Estimates for the output elasticities associated with GPP indicate that GPP contributes to gross domestic product. This contribution remains after removing factor inputs and outputs that are associated with economic sectors that harvest biological resources. Climate change simulated by the RCP8.5 scenario alters GPP in ways that reduce the net present value of GDP by 3.8 percent relative to the RCP2.6 scenario.

Introduction

Economic systems are supported by two types of capital, produced capital and natural capital. People manufacture produced capital, which corresponds to the capital traditionally defined by economists and is included in the system of national accounts. Conversely, humans do not produce natural capital; it is the natural environment. Natural capital generates ecosystem services (ESS) that contribute to economic well-being, but natural capital or ESS are not traditionally included in national accounts (Millennium Ecosystem Assessment, 2005; Imhoff *et al*., 2004; Brock and Xepapadeas, 2003; Daily *et al*., 2000; Costanza *et al*., 1997). Although not priced by the market, climate change and other anthropogenic activities) may change in the availability of natural capital and ESS and therefore affect economic well-being as measured traditional measures of economic activity.

The Millennium Ecosystem Assessment (2005) recognizes four types of ESS; provisioning services, supporting services, regulating services, and cultural services. Provisioning services include goods that are obtained from ecosystems, such as food, fiber, raw materials, etc. Supporting services include ecosystem functions that enable other services to function, such as soil formation and nutrient cycling. Regulating services ensure long-term ecosystem functioning by maintaining ecosystem characteristics within a stable range, such as pest and disease control, water and air purification, waste decomposition, etc. Finally, cultural services include intangible benefits that enhance recreation, spiritual thought, cognitive development, etc.

The benefits generated by ESS usually are not priced because they are not supplied through the market. Instead, researchers price ecosystem using a variety of techniques. Costanza *et al.,* (1997) use a willingness to pay methodology to price 17 ecosystem services. Since then, analysts use a variety of techniques, such a system dynamic models, benefit transfer methodologies, frontier analyses, etc. to price a variety of ecosystem services at various geographic scales (for a review see Islam *et al*., 2019).

Analysts use these indirect measures because there seems to be no objective measure for natural capital or ESS and there seems to be no clear point at which the market prices their contributions. Consistent with the need for a common metric (e.g. Boyd and Banzhaf, 2006) we postulate that energy can be used as a common measure for natural capital and ecosystem services. Natural capital can be envisioned as the planet's ecosystems, which can be measured by the biomass (e.g. grams of carbon), and they render ecosystem services by metabolizing organic forms of energy, which are generated by converting inorganic forms of energy (i.e. solar insolation) to organic forms (e.g. sugars) via photosynthesis. This organic energy is measured by gross/net primary production. This production moves through the food chain powering the activities by all living organisms.

Viewing primary production as the source of energy for all ecosystem services springs from a biophysical perspective of economic activity, which defines economic production as a work process that uses energy to organize high entropy raw materials into low entropy final goods and services. The work needed to oppose the tendency towards disorder is powered by energy. Produced capital uses animate (e.g. labor and domesticated animals) and inanimate (e.g. wind, water, fossil fuels) forms of energy. Natural capital does this work by converting inorganic forms of energy (e.g. solar energy) to organic forms of energy (e.g. sugars) and metabolizing this organic energy to do work.

From this perspective, all ESS are powered by the energy fixed by primary production (European Commission). Provisioning services, such a food and fiber, represent biological materials produced from net primary production (e.g. agricultural yields). Supporting services, such as nutrient cycling, are supported by biological forms of energy that power the one or more nonspontaneous flows (e.g. nitrogen fixation) that are present in all biogeochemical cycles. Similarly, regulatory services are powered by biological forms of energy; transpiration, which is coupled directly to photosynthesis, initiates the transition from dry to wet seasons in the Amazon (Wright *et al*., 2017). Similarly, net primary production powers many of the of ecosystem services that are defined by Perevochtchikova *et al*., (2019), such as carbon capture (e.g. Chen and Yara, 2019), biodiversity (e.g. Costanza *et al*., 2007), and soil formation (e.g. Peterson and Lajtha, 2013).

Here, we explore the hypothesis that the biological energy fixed by the photosynthesis (grams of carbon) can be used to measure and aggregate ESS and that this aggregate contributes to market measures of economic well-being. Furthermore, we postulate that the contribution measured by the market goes beyond the provisioning services whose output is powered directly by primary production and is included in the value added by extractive sectors, such as agriculture. Finally, we postulate that the biological energy fixed by the photosynthesis can be used to assess how anthropogenic climate change will affect ecosystem services and ultimately economic activity.

To test these hypotheses, we evaluate three fundamental questions about ecosystem services: (1) does gross primary production contribute to economic activity, as measured by Gross Domestic Product, (2) does this contribution go beyond the economic sectors where gross primary production generates output included directly in GDP, and (3) how will climate change affect the provision of ecosystem services and macroeconomic activity? To answer these questions, we extend the relation between GDP and net primary production described by Richmond et al, (2007). First we estimate a Cobb-Douglas production function from a panel of 171 nations with an econometric technique that is designed to estimate cointegrating relations among nonstationary panel data. Second, we test whether the market values supporting, regulatory, and/or cultural services by excluding economic inputs and outputs associated with provisioning services. Finally, we quantify the macroeconomic impacts of changes in ecosystem services due to climate change by simulating the modified Cobb-Douglas production function with forecasts for gross primary production through 2100 that are based on two IPCC scenarios for the emission of carbon dioxide and other radiatively active gases.

Estimates for the output elasticity of GPP indicate that the biological energy fixed by the photosynthesis can be used to measure and aggregate ESS and this aggregate contributes to GDP. These output elasticities remain after we remove economic inputs and outputs that are associated directly with provisioning services such as agriculture and forestry. Simulating the production function through 2100 indicates that the higher rates of emissions associated with the IPCC RCP.5 scenario reduce the net present value of GDP by 3.8 percent relative to the RCP2.6 scenario.

Methods

To estimate the macroeconomic benefits of ecosystem services, we follow Richmond *et al.*, (2007) and expand the traditional two-factor Cobb-Douglas production functions as follows:

$$Y_{i,t} = A_i K_{i,t}^{\alpha} L_{i,t}^{\beta} E_{i,t}^{\gamma} \qquad (1)$$

in which Y is real GDP for nation i in year t, A is a technical scalar, K is capital stock, L is labor, E is ecosystem services, and α, β, and γ are output elasticities.

We estimate equation (1) from a panel that includes 18 annual observations (2000-2017) for 171 nations, which are chosen based on the availability of a full set of observations. These observations are used to create two balanced panels, one with 55 developed nations and another with 116 developing nations. These classifications are based on the Human Quality Index (UNDP, 2018). Observations for real GDP (*Y*), capital stock (*K*), which are measured in million 2011 US dollars (as converted by exchange rates), and labor (*L*), which is measured by millions of persons engaged, are compiled from the Penn World Tables (Feenstra *et al*., 2015). These values constitute the base case for developed and developing nations. We also compile observations for GDP that use PPP indices to convert local currency units to US dollars to test the degree to which the results are robust.

Data for gross primary production, which are used to proxy ecosystem services (*E*), are compiled from the NASA Land Processes Distributed Active Archive Center (LP DAAC). The data are generated by model MOD17A2H V6 Gross Primary Productivity (GPP) which is driven by a cumulative 8-day composite with a 500m resolution extending from 2000 to present. This model is based on the concept of radiation-use efficiency and its output also is used to calculate terrestrial energy, carbon, water cycle processes, and biogeochemistry of vegetation. Annual data for each nation are generated using the Google Earth Engine.

To test whether the market value of ESS extends beyond provisioning services, we modify the output and inputs from equation (1) as follows:

$$Y_t^* = Y_t * (100 - \%AgForFish) * .01 \quad (2)$$

$$K_t^* = K_t - \ Kagforfish_t \quad (3)$$

$$L_t^* = L_t * (100 - \%LAgForFish) * .01 \quad (4)$$

in which %AgForFish, the percent of GDP from ISIC divisions 1-5, which includes forestry, hunting, and fishing, as well as cultivation of crops and livestock production (World Bank; data for Taiwan https://statdb.dgbas.gov.tw/pxweb/Dialog/NI.asp), Kagforfish is the net capital stock (million US dollars) in agriculture, hunting, forestry, and fishing, in accordance with division 1 (ISIC 2) or categories A-B (ISIC 3) or category A (ISIC 4) (World Bank). Nominal dollar values for Kagforfish are converted to 2011 values using the implicit price deflator for US GDP (St. Louis Federal Reserve), and %LAgForFish is the percentage of total employment in the agriculture, hunting, forestry, and fishing, in accordance with division 1 (ISIC 2) or categories A-B (ISIC 3) or category A (ISIC 4) (World Bank). These revised data are used to estimate a revised version of equation (1) as follows:

$$Y_t^* = A K_t^{*\alpha} L_t^{*\beta} E^{\gamma} \qquad (5)$$

To estimate the modified production function from the historical observations, we take the log of both sides, which creates a linear relation between GDP and factor inputs as follows:

$$ln\,(Y_{it}) = ln\,(A_i) + \alpha Ln(K_{i,t}) + \beta Ln(L_{i,t}) + \gamma Ln(E_{i,t}) + \mu_{i,t} \quad (6)$$

To account for the likely presence of stochastic trends in the four time series, equation (6) is estimated using dynamic ordinary least squares (DOLS) for panel data (Mark and Sul, 2003). This technique estimates a homogeneous cointegration vector from a balanced panel of N individuals observed over T time periods. The number of lags and leads used by the DOLS estimator is chosen using the Schwarz Information Criterion (SIC).

To evaluate whether the cointegrating relation given by equation (6) represents a long-run relation for GDP, we estimate an error correction model (ECM), which is given by equation 7:

$$\Delta Y_{i,t} = \tau + \rho_1 \varepsilon_{i,t-1} + \sum_{j=1}^{s} \lambda_j ln\,(\Delta Y_{i,t-j}) + \sum_{j=1}^{s} \theta_j ln\,(\Delta K_{i,t-j}) + \sum_{j=1}^{s} \varphi_j ln\,(\Delta L_{i,t-j}) + \sum_{j=1}^{s} \delta_j ln\,(\Delta E_{i,t-j}) + \eta_{i,t} \qquad (7)$$

in which $\varepsilon_{i,t}$ is the disequilibrium in cointegrating relation ($\varepsilon_{i,t} = (Y_{it}) - (ln\,(\hat{A}_i) + \hat{\alpha} Ln(K_{i,t}) + \hat{\beta} Ln(L_{i,t}) + \hat{\gamma} Ln(E_{i,t}))$, $\widehat{\ }$ indicates the value estimated from equation (6), Δ is the first difference operator ($x_t - x_{t-1}$), $\tau,\ \rho,\ \lambda,\ \theta,$ and $\varphi, and\ \ \delta$ are regression coefficients, $\eta_{i,t}$ is the regression residual, and s is the lag length. A statistical estimate $-1.0 \le \hat{\rho} < 0$ indicates that real GDP adjusts towards the equilibrium value implied by the production function. This would suggest that the cointegrating relation can be interpreted as a production function that represents the conversion of economic inputs to GDP.

Estimating the ECM (equation 7) requires two pieces of information; the optimal lag length s and the estimation method; pooled OLS, fixed effects estimator, random effects estimator, or the random coefficient model. To choose, we estimate six error correction models; two values for lag length (one or two or lags) and three assumptions about the regression coefficients; the slopes and intercepts are equal across cells (pooled OLS), the slopes are the same across cells but the intercepts vary across cells (fixed effects estimator), or the slopes and intercepts vary across cells (random coefficient model). From these results, we chose the optimal lag length (using the Akaike information criterion) and choose among estimation techniques using test statistics (F tests) that evaluate the null hypothesis that the intercepts (τ) or the intercepts and slopes ($\tau,\ \rho,\ \lambda,\ \theta,$ $\varphi, and\ \delta$) are equal across cells (Hsiao, 1986).

The effect of climate change on GDP from 2018 – 2100 is quantified by simulating the production function with forecasts for GPP that are generated using two emission scenarios, IPCC RCP 2.6 and RCP8.5 (Eyring et al., 2016). RCP 2.6 is a 'very stringent' pathway that requires emissions of carbon dioxide (CO_2) start to decline by 2020 and go to zero by 2100. Similar restrictions are imposed on other gases such that RCP 2.6 is likely to keep global temperature rise below 2 °C by 2100. Although not a 'no climate change scenario' RCP 2.6 can be interpreted as a 'best case' scenario. Conversely, RCP 8.5 allows emissions to rise throughout the 21st century. As such, RCP 8.5 is used to simulate the most severe impacts of climate change. Forecasts for GPP that are associated with these two scenarios are obtained from the coupled model intercomparison project 6 MIP.CSIRO.ACCESS-ESMI-5 (Ziehn *et al*., 2019). Forecasts for GPP contain monthly values with a 250km resolution to 2100. We sum monthly values to create annual values. To create national values, annual values for individual cells are summed within national boundaries. To ensure consistency with the historical values used to estimate the modified production function, we update the historical observations for 2017 using the percent change in the forecast values.

For both climate scenarios, labor input (L) is forecast based on the percentage change in each nation's total population between the ages of 16 and 64 that is compiled for the medium variant projection generated by the United Nations (2019). The forecast for capital stock is generated endogenously by assuming a depreciation rate of 1 percent per year and an investment rate that is 15 percent of GDP. We recognize that this may not generate the optimal path for GDP. Future efforts will look to endogenize investment and use different scenarios for population growth.

For each scenario, we calculate the net present value (NPV) of GDP for the 156 nations for which forecasts for GPP are available as follows:

$$NPV_{2100} = \sum_{i=2018}^{2100}\left(\frac{GDP_i}{(1+r)^i}\right) \qquad (8)$$

in which r is the interest rate (1 percent). To evaluate the impacts of anthropogenic climate change on economic activity, we calculate the percent change in NPV_{2100} generated by the RCP 8.5 scenario relative to NPV_{2100} generated by the RCP 2.6 scenario for of the 155 nations for which forecasts of GPP are available.

RESULTS

Estimation results indicate that capital, labor, and GPP have a statistically measurable long-run relation with real GDP in both developed and developing nations (Table 1). For the base case, the output elasticities for GPP ($\hat{\gamma}$) in developed and developing nations are 0.18 and 0.14 respectively. Statistically significant measures for the output elasticity of ESS remain if we eliminate the economic inputs and outputs from sectors associated with provisioning services or convert local measures of GDP to US dollars using indices for purchasing power parity. Test statistics reject the null hypothesis of constant returns to scale ($\hat{\alpha} + \hat{\beta} + \hat{\gamma} = 1$) for all versions of equation 6 (Table 1). Despite this rejection, the totality of results suggest that GPP can be used to measure and aggregate ESS and that they enhance GDP.

All but one of the empirical estimates for the error correction models generate values for $\hat{\rho}$ that are between 0 and -1 (Table 1). This result indicates that disequilibrium in the revised version of the Cobb-Douglass production function moves Y towards the equilibrium that is implied by inputs of capital, labor, and GPP. This adjustment implies that equation (1) can be interpreted as a long-run relation for GDP.

We use the output elasticities and technical scalars estimated from the base case for the modified production function (equation 1) to generate empirical estimates for the macroeconomic value of ecosystem services as follows:

$$\frac{\partial Y_t}{\partial E_t} = \hat{\gamma}\hat{A}K^{\hat{\alpha}}L^{\hat{\beta}}E^{\hat{\gamma}-1} \qquad (9)$$

Equation (9) measures the change in GDP for a one unit change in GPP and so represents a shadow price for ecosystem services. Results for equation (9) indicate that a kilogram of carbon of gross primary production by natural ecosystems generates 0.09 – 3.91 million dollars of GDP (Figure 1). This wide range is associated with international variations in factors of production (capital, labor, and ecosystem services) and the technical scalar (A). Equation (9) implies that the shadow price for ecosystem services is greatest in large economies, which have large capital stocks and labor pools. We recognize the interpretation of equation (9) as the shadow price for ecosystem services is clouded by results indicate that the revised production function does not show constant returns to scale.

Discussion

Using GPP to measure and aggregate ESS and how are ESS included in GDP

The totality of results indicates that ecosystems services, as proxied by gross primary production, make a statistically measurable contribution to macroeconomic economic activity, as measured by GDP. Estimates for γ (and α and β) that are statistically different from zero and estimates for ρ between zero and negative one indicates that GDP is related to GPP (and capital and labor) and that GDP adjusts towards the equilibrium value that is implied by GPP (and capital and labor). This suggests that ecosystem services, as proxied by GPP contribute to the market value of economic activity, as measured by GDP, even though ecosystem services are not explicitly priced by the market. This contribution may be one reason that the output elasticities do not show constant returns to scale.

At first glance, a relation between GPP and GDP may simply represent the economic value of biological resources, such as agriculture, forestry, and fisheries, that are priced by the market and included in GDP. *Ceteris paribus*, nations with highly productive ecosystems can generate large amounts of value added in the agriculture, forestry, or fishery sectors, will have higher rates of GDP. But this explanation for a relation between GPP and GDP is not straightforward. Empirical analyses suggest a weak relation between net primary production and agricultural yield (e.g. Zhang *et al*., 2005). This relation may be weak because yield represents energy used for reproduction (seed) or storage (root crop), which is only one of the many biological uses of production (growth, maintenance, protection).

The hypothesis that the relation between GPP and GDP simply represents the economic value of biological resources, such as agriculture, forestry, and fisheries also is undermined by the results of equation (5). Removing the value added (equation 2), capital stock (equation 3), and labor input (equation 4) in sectors associated with provisioning services does not eliminate the statistically significant output elasticity for GPP (γ) or estimates for $\hat{\rho}$ that are between zero and negative one (Table 1). This suggests that supporting and regulating services (and maybe cultural services) can be measured and aggregated using GPP and their value is included in traditional measures of economic activity.

Nonetheless, our results do not describe how the market includes the economic benefits generated by ESS in traditional measures of economic activity such as GDP. We explain their contribution via the following thought experiment. Suppose two economic systems have identical endowments of capital (K) and inputs of labor (L). One economy (Economy #1) is located in the temperate forest biome that generates GPP at high rates and therefore renders ESS at high rates. The other economy (Economy #2) is located in the desert biome, which generates GPP at low rates and therefore renders ESS at low rates. Our results indicate that Economy 1 has a higher GDP than Economy #2.

Higher rates of GDP in Economy #1 may be generated by the higher productivity of provisioning services in Economy #1. That is, if Economy #1 and Economy #2 allocate the same amount of capital and labor to sectors associated with biological resources, these sectors are likely to be more productive in Economy #1 because the natural capital generates higher rates of gross primary production. This will allow Economy #1 to generate more economic output than economy #2, despite their identical endowments of capital and labor.

This increased output may be reinforced by the way in which Economy #2 allocates its capital and labor relative to Economy #1. Economy #2 likely allocates more of its capital and labor towards activities that are provided at little or no cost by the regulating and supporting services that are provided by the temperate forest. As such, less capital and labor is available to sectors that generate larger amounts of value added per unit input.

Measuring the Economic Impacts of Land-Use Change

The macroeconomic shadow price for GPP (equation (9)) can be used to price the environmental costs of development projects that convert natural ecosystems to human purposes, which is known and land use change. That is, replacing an area of natural ecosystem with a road or building reduces that parcel's production of GPP and likely the provision of ESS. Indeed, land use change is an important cause for the loss of ESS (Hasan *et al.,* 2020).

The resultant loss of ESS reduces economic activity by the shadow price for GPP. This shadow price varies over space, and these spatial variations can be used to calculate the value of ecosystem services lost by individual development projects. In general, productive biomes, such as temperate forests, generate more GPP and hence more ecosystem services than the desert biomes. Under these conditions, an economic project that converts one hectare of temperate forests reduces GPP, and hence the supply of ecosystem services by more than the conversion of a hectare of desert. Rates of GPP also vary across space within a biome such that converting a hectare of highly productive temperate forest reduces ESS more than the loss of a less productive hectare of temperate forest. Spatial variations in the productivity of land allows analysts to calculate the loss of productivity, and ultimately the value of ESS due to land conversions at a specific site relative. And the dollar value site-specific variations in GPP can be compared directly to the benefits of that conversion.

Measuring the Economic Impact of Climate Change

Climate change affects economic activity through many channels. Climate change has a direct effect on the productivity some economic sectors, such as agriculture, forests and fisheries (e.g.

Arneth et al., 2019). Higher temperatures associated with climate change also lower the productivity of labor and capital (e.g. Chavaillaz, *et al*., 2019; Petrakopoulou *et al*., 2020). Climate change also affects the stock of natural capital and its ability to render ESS.

We use the expanded production function (equation 1) to quantify the macroeconomic costs and benefits of changes in ecosystem services due to climate change. Anthropogenically induced changes in precipitation and temperature increase GPP in some areas and reduce GPP in other areas. In the RCP8.5 scenario, these changes shrink the aggregate NPV of GDP for 156 nations by 3.84 percent relative to the changes in GPP simulated by the RCP 2.6 scenario. For individual nations, changes in GPP due to the RCP 8.5 reduce the average net present value of GDP by 0.8 percent relative to the RCP 2.6 scenario.

But these averages hide large differences among nations. The blue bars in Figure 2 indicate that the net present value of GDP declines in 44 nations. But blue bars on the far left indicate that many nations have extremely large reductions (≈30-90%). Nations with the largest reductions are located in Africa (Egypt, Senegal, Mauritania, Gambia) and Kuwait (Figure 3). Conversely, the net present value of GDP increases in most (111) nations. For many of these nations, the increase is less than ten percent. Nations with the largest increases include Tunisia, Algeria, and the UAE.

The size of these climate related changes in ecosystem services is partially shaped by the measure, the net present value of GDP. By definition, discounting reduces the value of future gains and losses. This effect is reinforced by the timing of changes in climate; climate differences between the RCP8.5 and RCP 2.6 scenarios appear in the latter half of this century. For example, global temperature in the RCP 8.5 scenario starts to diverge from the temperature forecast by the RCP 2.5 scenario after 2050. As such, differences in GPP, ESS, and GDP emerge later in our sample period, which discounts their effects.

To assess the effect of discounting on our measure for macroeconomic impacts of climate-related changes in ecosystem services, we compare values of GDP in 2100 that are simulated using the RCP 8.5 and RCP 2.5 scenarios (Figure 2 red bars). Comparing the final value for GDP expands the range of effects. That is, changes in GDP in 2100 are more negative and positive compared to changes in the net present value of GDP.

Conclusion

Empirical estimates for the expanded Cobb-Douglas production function indicate that (1) gross primary production can be used to proxy a variety of ESS, (2) this common unit of measure can be used to aggregate a variety of ESS, and (3) this aggregate makes a quantifiable contribution to a market measure of economic well-being GDP. Furthermore, this contribution goes beyond provisioning services in which gross primary production supports biological activities that are included directly in GDP. Finally, anthropogenic changes in climate will affect the ability of natural capital to generate GPP, which will affect the provision of ecosystem services and macroeconomic activity.

Although these results are preliminary, their promise warrants further investigation. First, we specific a Cobb-Douglass production function (equation 1) because of its simplicity. But this simplicity embodies many restrictions. Future efforts will investigate whether econometric estimates for other production functions, such as a CES production function, generate output elasticities that indicate GPP makes a statistically measurable contribution to GDP. Second, we need to consider how to interpret output elasticities that do not show constant returns to scale. Specifically we need to investigate how does this inconsistency with basic economic theory affect the interpretation of the shadow price for GPP that is calculated using equation 9.

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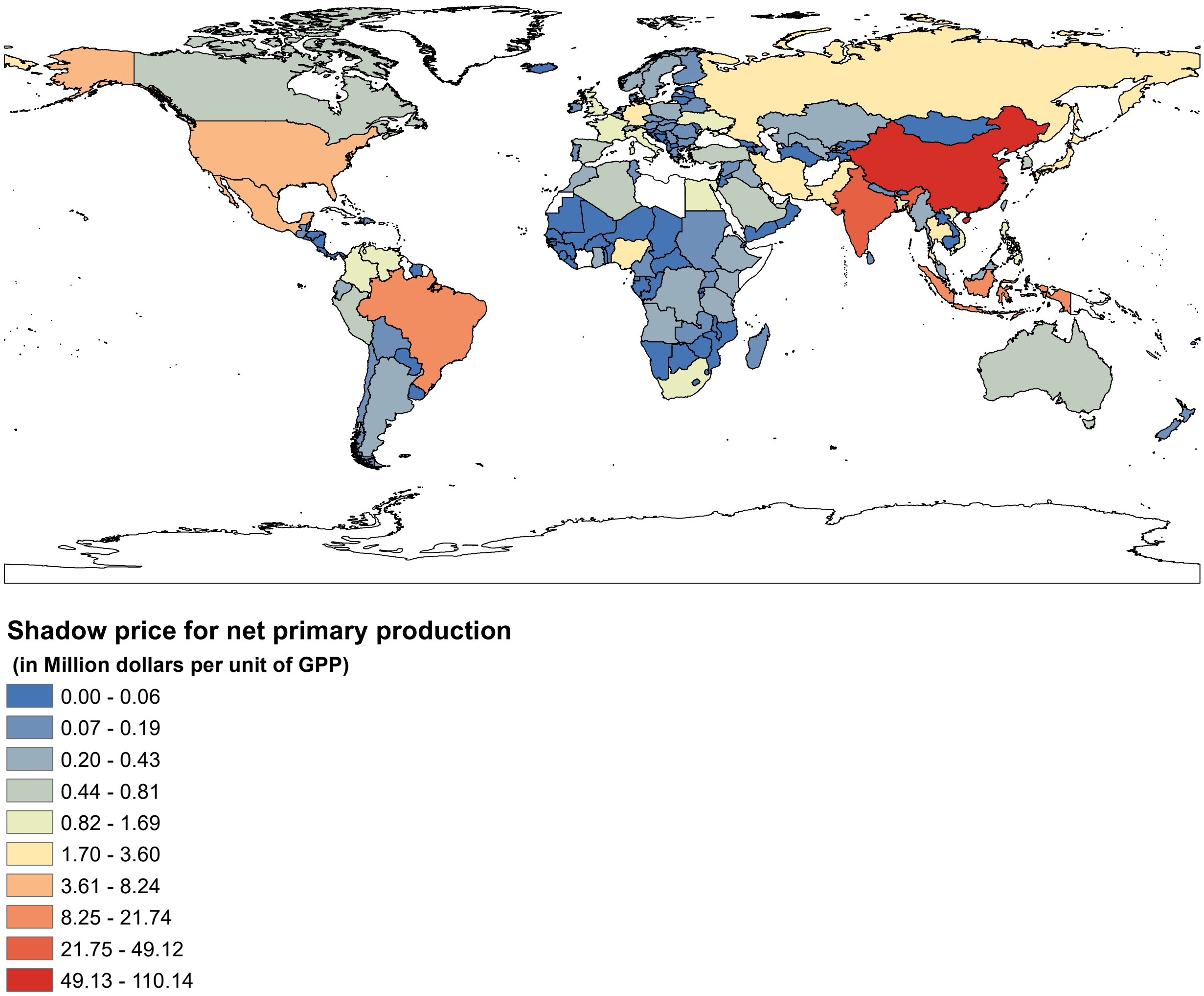
Figure Captions

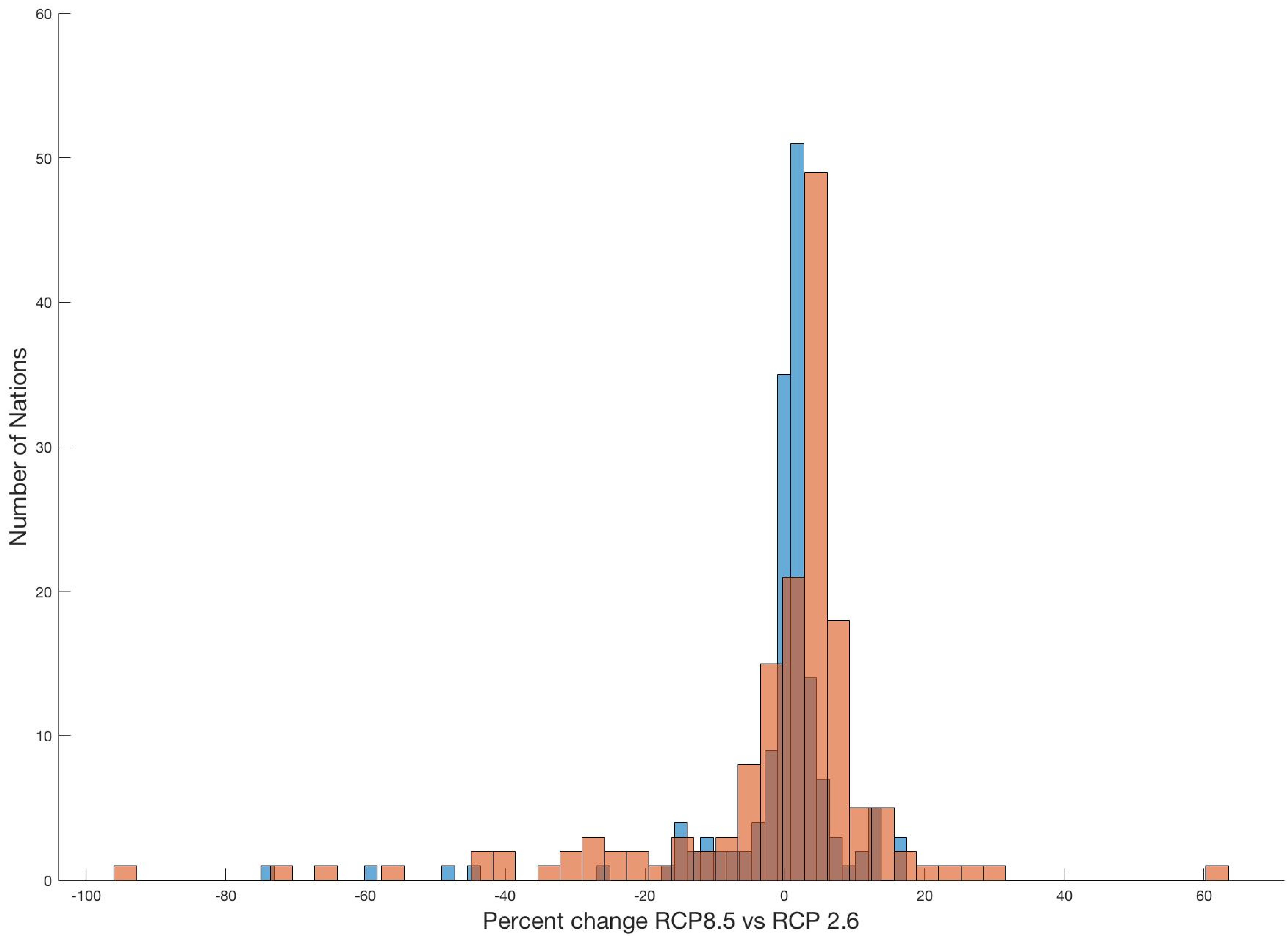
Figure 1 The macroeconomic shadow price for net primary productivity. Values are in millions of US Dollars (2011 prices) per kg. of carbon. Values represent an average of eighteen observations that is calculated using equation (5) with annual values (2000-2017) of K,L, and E for each nation.

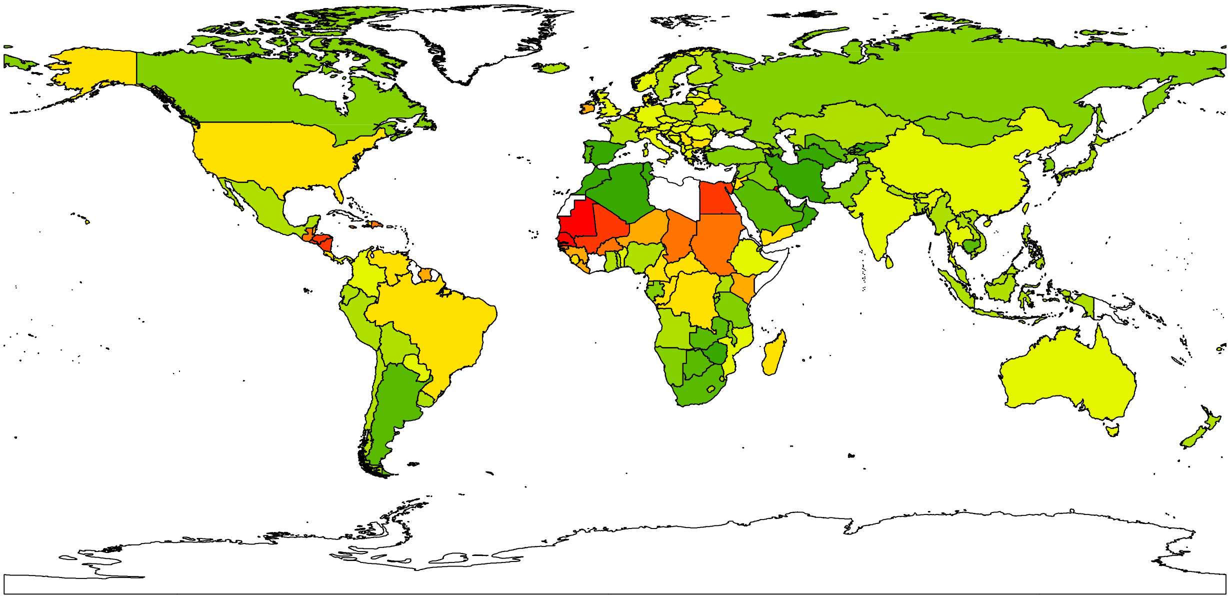
Figure 2 Histogram for the effect of climate change on economic activity via ecosystem services. Blue bars represent the percent change in NPV2100 generated by the RCP 8.5 scenario relative to the NPV2100 generated by the RCP 2.6 scenario. Red bars represent the percent change in GDP in 2100 generated by the RCP 8.5 scenario relative to GDP in 2100 generated by the RCP 2.6 scenario.

Figure 3 The effect of climate change on NPV2100 via ecosystem services. The percent change in NPV2100 simulated by the RCP 8.5 scenario relative to NPV2100 in 2100 generated by the RCP 2.6 scenario.



Shadow price for net primary production
(in Million dollars per unit of GPP)
0.00 - 0.06
0.07 - 0.19
0.20 - 0.43
0.44 - 0.81
0.82 - 1.69
1.70 - 3.60
3.61 - 8.24
8.25 - 21.74
21.75 - 49.12
49.13 - 110.14

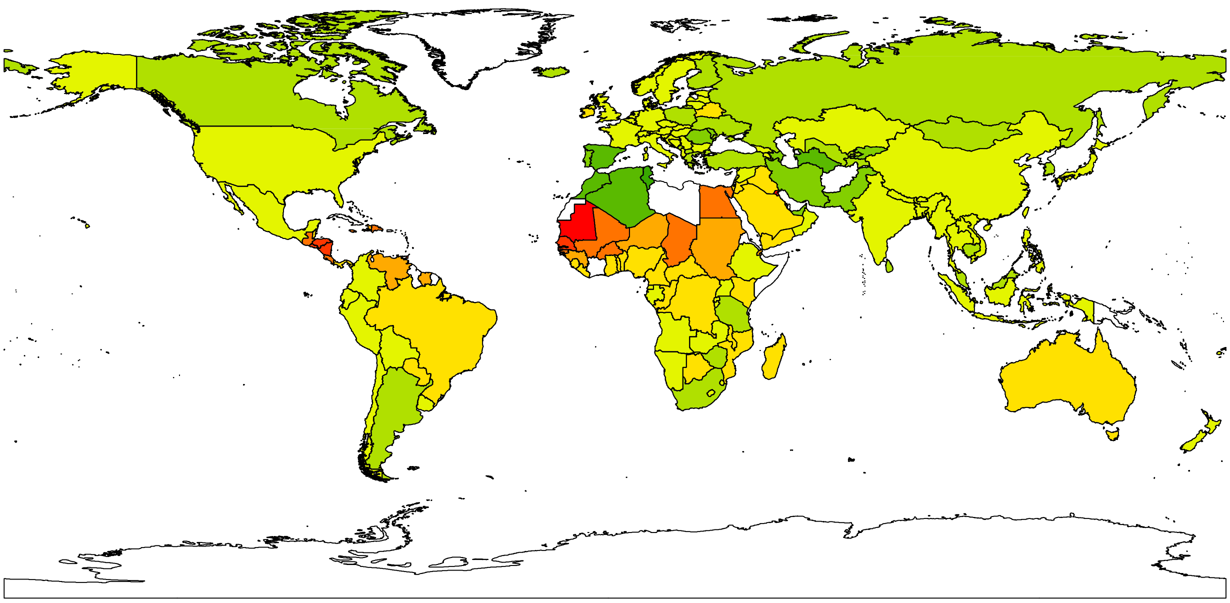

Number of Nations
60
50
40
30
20
10
0
-100
-80
-60
-40
-20
0
20
40
60
Percent change RCP8.5 vs RCP 2.6



The Change in the Net Present Value of GDP

NPV85/NPV26

- -74.49 - -45.10
- -45.09 - -15.08
- -15.07 - -9.85
- -9.84 - -3.71
- -3.70 - 0.00
- 0.01 - 1.16
- 1.17 - 2.64
- 2.65 - 4.82
- 4.83 - 8.37
- 8.38 - 17.37



The Change in the Net Present Value of GDP

GDP85/GDP26

-95.86 - -64.40
-64.39 - -39.19
-39.18 - -22.21
-22.20 - -10.97
-10.96 - 0.00
0.01 - 5.87
5.88 - 10.16
10.17 - 18.16
18.17 - 29.77
29.78 - 63.29

Table 1 Estimation results for Equation (6) and Equation (7)

	Developed Nations				Developing Nations			
	All Services		No provisioning		All Services		No provisioning	
Cointegrating relation								
	Exchange	PPP	Exchange	PPP	Exchange	PPP	Exchange	PPP
K	0.68^{***}	0.75^{***}	0.61^{***}	0.90^{***}	0.79^{***}	0.91^{***}	0.45^{***}	0.67^{***}
L	0.11^{***}	0.38^{***}	0.18^{***}	0.45^{***}	0.62^{***}	1.13^{***}	0.28^{***}	0.96^{***}
E	0.18^{***}	0.48^{***}	0.25^{***}	0.18^{***}	0.14^{***}	0.19^{***}	0.79^{***}	0.56^{***}
$\hat{\alpha}+\hat{\beta}+\hat{\gamma}$	0.97	1.61	1.04	1.53	1.55	2.23	1.52	2.19
$\hat{\alpha}+\hat{\beta}+\hat{\gamma}=1$	$\chi^2(1)=3.4E3$	$\chi^2(1)=2.4E4$	$\chi^2(1)=1.3E4$	$\chi^2(1)=1.8E4$	$\chi^2(1)=1.9E7$	$\chi^2(1)=5.1E7$	$\chi^2(1)=1.2E7$	$\chi^2(1)=1.3E7$
Error correction model								
$\hat{\rho}$	-0.10^{***}	-0.15^{***}	-0.11^{***}	-0.12^{***}	-0.08	-0.11^{*}	-0.10^{*}	-0.11^{*}