SUSTAINABLE DEVELOPMENT IN AN N-RICH/N-POOR WORLD

Charles Perrings[1], Ann Kinzig[2] and George Halkos[3]

1. School of Life Sciences, Arizona State University, PO Box 874501, Tempe, AZ 85287-4501, USA. Charles.Perrings@asu.edu

2. School of Life Sciences, Arizona State University, PO Box 874501, Tempe, AZ 85287-4501, USA. kinzig@asu.edu

3. Department of Economics, University of Thessaly, 43 Korai Str, 38333 Volos, Greece. halkos@uth.gr

Address for correspondence:
Charles Perrings
ecoSERVICES Group
Arizona State University
PO Box 874501
Tempe, AZ 85287-4501
Charles.Perrings@asu.edu

Charles Perrings and Ann Kinzig acknowledge the Biodiversity and Ecosystem Services Research Training Network (BESTNet) research coordination grant, number 0639252, from the National Science Foundation

1. The two faces of the nitrogen problem

From an economic perspective, the sustainability of any development strategy is best tested by whether the per capita wealth it generates—the sum of produced, human and natural capital—is maintained over time (Dasgupta 2001). Development strategies that depend on the extraction of earth resources or that damage functioning ecosystems may still be sustainable, in this sense, providing that the profits generated (what economists refer to as the resource rents) are used to create renewable capital stocks of equivalent value (Dasgupta and Maler 2000; Hartwick 1977; Hotelling 1931; Solow 1974). To test the sustainability of natural resource-based development strategies, economists have developed measures of inclusive wealth that take account of changes in at least some environmental stocks (Arrow et al. 2012; Dasgupta and Mäler 2000; UNU-IHDP and UNEP 2012; World Bank 2006; World Bank 2010). Using one such measure of inclusive wealth, we consider the sustainability of development strategies that affect one of the most important of all environmental stocks—nitrogen.

Nitrogen is essential for all life, and yet only a handful of microorganisms are capable of using it in its dominant form—dinitrogen (N_2). Until relatively recently, all other species relied primarily on these microorganisms to convert N_2 to the more usable ammonium (NH_4^+) through the process of nitrogen fixation. (Other microorganisms convert ammonium to nitrate (NO_3^-) through nitrification, and a small amount of dinitrogen is converted directly to nitrate via non-biological means, primarily lightning-induced atmospheric fixation.) For much of its history, agriculture depended on husbandry of the soil nitrogen necessary for plant growth—returning nutrients to the soil in the form of crop waste, planting nitrogen-fixing legumes, using mulches or plant cover to protect the soil from erosion or nutrient leaching, or letting land lie fallow. In the early 1900's, however, the Haber-Bosch process was developed, allowing humans to convert atmospheric dinitrogen to ammonium (and hence to nitrate) on industrial scales. Since that time, use of the nitrogen-bearing fertilizers that result from this process has risen steadily until humans now exceed microorganisms in their capacity to fix nitrogen. Galloway and Cowling (2002) and Galloway et al. (2004) estimated that by the end of the last century humans fixed just under 150 trillion grams of nitrogen Tg(N) per year—approximately 86 Tg(N)/yr from fertilizer production, 31 Tg(N)/yr from the expansion of nitrogen-fixing crops (via nitrogen-fixing microorganisms), 13 Tg(N)/yr from other products, and 21 Tg(N) per year from fossil fuel consumption. By comparison, the total nitrogen fixed by both cyanobacteria and bacteria, which includes the 40 Tg(N)/yr from nitrogen-fixing crops, was only 108 Tg(N)/yr. Moreover, the rate of anthropogenic nitrogen growth is still accelerating. By the middle of this century, nitrogen fixed by humans is expected to be on the order of 267 Tg(N)/yr compared to 224 Tg(N)/yr fixed through natural processes (Galloway et al. 2004; Howarth et al. 2005). A more recent study by Townsend and Howarth (2010) argues that humans are now fixing nitrogen at twice the rate of natural processes.

The Haber-Bosch process has underpinned virtually every successful development strategy over the last century. The growth of agricultural productivity allowed by the process has directly increased agricultural incomes by increasing yields on existing agricultural lands, and by allowing expansion of agriculture into areas previously deemed too infertile. It has made possible the replacement of nitrogen stocks lost through the conversion of forests and grasslands to agriculture. It has shortened fallow periods, and increased the number of crops taken from individual fields each year. Indeed, wherever nitrogen has been the limiting factor in crop growth, accelerating nitrogen applications have increased agricultural productivity. This increased agricultural productivity has sustained the dramatic growth of the human population and allowed diversion of human resources to a range of non-agricultural activities—the underpinning of all successful development strategies. The expansion of commerce and industry, the development of public and private services, the development of science and technology and the strengthening of the institutions of government have all been made possible by the growth of agricultural productivity (Perrings 2014).

The treatment of nitrogen stocks has not been the same in all countries, however. Nor has it been neutral in its effects on species other than the targeted crops. A relatively small proportion of the nitrogen applied in fertilizers to agricultural systems is stored in the system—the rest is removed in the crop, leached into groundwater, carried away in surface run-off, volatilized to the atmosphere, or converted to other gaseous forms that escape to the atmosphere (Vitousek et al. 1997). Of the total quantity of reactive nitrogen added to farmland, one estimate is that around 50% is removed in the crop, 25% is emitted to the atmosphere, 20% runs off into aquatic systems, and only 5% is stored in the soil (Smil 1999). Later estimates confirm the relatively low rate of N-accumulation in the soil (Galloway et al. 2004; Schlesinger 2009; Van Breemen et al. 2002). While the proportion removed in the crop is sensitive to the level of nitrogen applications (Stevens et al. 2005) as well as other inputs (Vanlauwe et al. 2010), almost all applications are associated with some losses to the atmosphere and water.

In particular circumstances losses to the atmosphere and water can have undesirable effects. Nitrates in water, for instance, can compromise the blood's ability to transport oxygen, affecting the young of many species aside from humans—including cattle, horses, sheep, pigs, and chickens (Kinzig and Socolow 1994). Excess nitrogen in one form or another has contributed to respiratory ailments, cardiac disease, and several cancers, and has altered the dynamics of several vector-borne diseases (Townsend et al. 2003). Changes in nutrients have affected the abundance of pathogens by altering the relative density of hosts and vectors, host distribution, infection resistance, as well as pathogen virulence or toxicity (Johnson et al. 2010). Nitrogen-containing compounds carried away in surface runoff can enter coastal waters and have caused coastal eutrophication—characterized by excessive algal blooms, algal die-offs, and oxygen depletion. In the most severe forms, coastal eutrophication has led to extensive 'dead zones'—areas so depleted of oxygen they are incapable of supporting any life (Diaz and Rosenberg 2008). Excess fertilizer applications have also led to the conversion of ammonium or nitrate into nitrous oxide—an important greenhouse gas (Galloway and Cowling 2002).

There are, in fact, two quite different dimensions to the nitrogen problem. On the one hand, failure to replace nitrogen released when relatively intact forests and grasslands are converted, or lost through erosion and harvesting on agricultural lands, leads to declining stocks of soil nitrogen, and declining crop yields (Liu et al. 2010)(see Figure 1). On the other, excess application of fertilizers has given rise to several forms of nitrogen pollution (see Figure 2). Globally, 93% of all fertilizer applications occur in Asia, Europe and North America. Sub-Saharan Africa accounts for only 3% (Galloway et al. 2004). The problem of excess reactive nitrogen is overwhelmingly a problem of high and middle-income countries, nitrogen depletion is overwhelmingly a problem of poor countries, and specifically of sub-Saharan Africa (Liu et al. 2010).

The mechanisms underlying nitrogen losses are reasonably well understood. In the late 1990s Vitousek *et al* estimated that 40 Tg(N) per year was being lost from the burning of forests, grasslands, and wood fuels, while 20 Tg(N) per year was being lost when land was cleared for crops (Vitousek et al. 1997). Such losses tend to occur in poor countries where agricultural growth depends on expansion of the area under cultivation rather than enhanced productivity on existing agricultural land. The net rate of nitrogen loss in such countries is a function of the rate at which nitrogen stocks are replaced through fertilizer applications. Since fertilizer applications also tend to be lower in poorer countries, and that is where the nitrogen depletion problem is most acute. Regionally, Sub-Saharan Africa is affected more than other developing areas. Net nitrogen losses in dominant cropping systems in Kenya in the late 20th century, for example, were estimated to be between 67 and 147 kg per ha per year compared to 3 and 32 kg per ha per year in Costa Rica (Stoorvogel and Smalling 1998). Indeed, soil fertility depletion has long been considered one of the main biophysical barriers limiting food production in Sub-Saharan Africa (Drechsel et al. 2001). It is estimated that the region lost 4.4 million tons of nitrogen between 1980 and 2004, the major contributor to annual losses of soil nutrients valued on the order of $4 billion (International Fertilizer Development Center 2006).

The magnitude of the N-depletion problem largely reflects the failure of the markets to signal the true scarcity of nitrogen—to record the externalities of land-clearance or nutrient runoff. The proximate cause of N-depletion is loss of soil nutrients from land converted to agriculture that is uncompensated by either fallows or fertilizers. Loss of nutrients may be due both to cropping and soil erosion (Montgomery 2007). Absent fertilizer applications, this leads to the overexploitation of existing nutrient stocks, declining yields, and land abandonment (as 'waste' or 'barren' lands) (Pimentel et al. 1995). In many cases it is associated with the fact that converted lands are not subject to well-defined property rights. Many converted lands are common pool resources to which access is only weakly regulated, if at all, being occupied by "squatters" with little or no security of tenure (Alston et al. 1996; Barbier and Burgess 2001; Niazi 2003). In countries where a significant proportion of the population produces their own food, population growth translates into increasing pressure on common pool resources. While these are not the only drivers of land use in developing countries (see, for example, Lambin et al. 2001), they have a fundamental role to play in the N-depletion problem. The impact of declining nutrient stocks increases with the share of the population that depends directly on agriculture. At the same time, nutrient replacement is least likely in countries where farmers lack the resources to maintain soil fertility or have little incentive to do so given the lack of secure land tenure. The lack of well-defined rights to converted land ensures that resource users have very weak incentives to invest in the conservation or replacement of nutrient stocks, even when they have the resources to do so.

In much the same way, the N-pollution problem reflects the failure of markets or regulations to signal the cost of excess nitrogen (see, for example, Hanley 1990; Horner 1975; Moxey and White 1994; Semaan et al. 2007). If farmer's are not faced with the costs of the off-site impacts of nitrogen runoff, they may over-apply nitrogen-containing fertilizers on cropland.

This problem is exacerbated by government subsidies for fertilizer purchases and applications (Tilman et al. 2002).

As a broad generalization, poor countries suffer more from N-depletion and rich countries from N-pollution, but there are exceptions. In this paper we focus on the relationship between nitrogen replacement, income and wealth. We do this against the background of a long-standing, but ambiguous, literature on the relation between income and environmental change more generally. A number of cross-sectional and longitudinal studies of the relationship between income and a range of pollutants have found that, in many cases, pollution has an inverted U-shaped relation to per capita income—the so-called Environmental Kuznets Curve. That is, emissions of air- and water-borne pollutants frequently increase with per capita incomes at low levels of income, and decrease with per capita incomes at high levels of income (Cole et al. 1997; Seldon and Song 1994; Shafik 1994; Stern 2004; Stern and Common 2001). However, the relation is not consistent. For some pollutants, carbon dioxide and municipal solid waste for example, the relation with per capita income has been found to be monotonically increasing. For others, fecal coliform in drinking water for example, it has been found to be monotonically decreasing. For others still it has been found to have more than one turning point (Carson 2010; Cole et al. 1997).

The implication of this literature is that in the initial stages of growth people elect to deplete environmental assets in order to build up produced assets, but as their income rises they reverse the process. Since the nitrogen content of soils is an important component of their value, the depletion of nitrogen stocks implies a reduction in the value of soil as an asset. Other things being equal, therefore, it implies a reduction in wealth. In this paper we first consider the relationship between income growth and changes in N-stocks. We then consider the relationship between N-replacement and national wealth—where wealth is taken to be inclusive of all forms of capital, including natural capital. That is, we ask whether there is evidence for a trade-off between income and N-stocks, and if so how it is associated with changes in inclusive wealth.

Current estimates of changes in inclusive wealth show that low-income countries tend to be affected more by losses of natural capital than rich countries (UNU-IHDP and UNEP 2012; World Bank 2006; World Bank 2010). The measure of change in inclusive wealth used by the World Bank is the adjusted net savings rate. This is a record of changes in the value of assets that involves four adjustments to the measure of gross national savings recorded in the national income accounts: deduction of the depreciation of produced assets; addition of current expenditures on education (a proxy for investment in human capital); deduction of the depletion of selected natural resources (a proxy for depreciation of natural capital due to extraction); and deduction of damages due to selected emissions (a proxy for the depreciation of human and natural capital due to pollution) (World Bank 2010). If adjusted net Savings are negative, it indicates that the loss of capital through depreciation exceeds the level of new investment. We consider the relation between changes in stocks of nitrogen and changes in this measure of inclusive wealth.

2. Measuring N-replacement

There have been a number of attempts to measure anthropogenic effects on the nitrogen budget at global, regional, national and landscape scales. At global and regional scales, the focus has been on developing broad brush estimates of changes in the aggregate contribution made by major sources of reactive nitrogen: lightning, natural and anthropogenic bacterial and cyano-bacterial fixation, fossil fuel combustion and fertilizer production (Galloway et al. 2004). At the national scale (Howarth et al. 2002) studies have focused on anthropogenic changes in the nitrogen budget, including changes in NOx emissions from fossil-fuel combustion, but excluding natural sources of reactive nitrogen. Most studies at the landscape scale have similarly focused on anthropogenic effects. The Net Anthropogenic Nitrogen Input (NANI) mass-balance model introduced by Howarth et al. (1996) has been applied to a number of watersheds at a variety of scales (Hong et al. 2012; Howarth et al. 2011; Swaney et al. 2012). The NANI is calculated as the sum of four components: atmospheric N-deposition, fertilizer N-application, agricultural N-fixation and N in net food and feed imports. Negative fluxes remove N from watersheds, positive fluxes add N to watersheds (Hong et al. 2011).

At the sectoral level, (Liu et al. 2010) estimated total nitrogen input in agriculture at the turn of the century to have been approximately 136.6 (Tg)N per year, half deriving from mineral nitrogen fertilizer, 16% from biofixation, manure, recycled crop residues, and atmospheric deposition accounting for 8–13% of the total input. Since our concern is with the effect of anthropogenic N fluxes on the value of land as an asset we focus on only those components of the global nitrogen budget that are a direct consequence of land management decisions: the conversion of land to agriculture, fertilizer applications, and the production of crops and livestock. We do not include industrial emissions. Nor do we take account of the fate of N-exports. Where crops or livestock exports are disposed of affects the international distribution of nitrogen, but does not affect the nutrient content of the farmland from which exports derive.

We make a number of simplifying assumptions. First, we assume that the proportion of N added through fertilizer application or leguminous crops, and that is stored in agroecosystems, is the same for all countries. Although denitrification rates are likely to vary with climatic and other conditions (Galloway et al. 2004), we have insufficient information to correct for this. Second, we assume that the loss of nutrients through soil erosion due to land use change is the same for all countries. Once again, although there is evidence that soil erosion may be greater in some countries and some bioclimatic zones than in others (Stocking 2003), we do not have sufficient evidence to correct for this across our sample.

Our measure of N-loss consists of three indexes for 68 countries[1] (those countries where we had sufficient data to calculate the index) over the period 1964-2008. The first index is based on land use change. Nitrogen can be lost when forests or grasslands are cleared for other uses because soils are exposed, allowing faster decomposition, nitrogen cycling, and nitrogen losses to both air and water. We therefore calculated the annual change in arable plus permanent cropland. Additions to cropland can come from any biome, but in a majority of cases they derived from conversion of forests, grasslands, or savanna ecosystems. Data on land conversions were taken from the World Resources Institute (World Resources Institute 2011).

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[1] Albania, Argentina, Australia, Austria, Bangladesh, Brazil, Bulgaria, Cote d'Ivoire, Cameroon, Canada, Chile, China, Colombia, Costa Rica, Cuba, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Finland, France, Germany, Greece, Guatemala, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Jordan, Kenya, Lebanon, Libya, Mexico, Morocco, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Pakistan, Peru, Philippines, Poland, Portugal, Romania, Senegal, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Thailand, Tunisia, Turkey, UK, USA, Uruguay, Venezuela, Vietnam, Zambia, Zimbabwe.

The second index is based on crop production. Nitrogen is lost from cropping systems due to its removal in crops, but can be replaced due to planting of pulses (legumes). We took the average annual total cereal production for each nation (representing N-loss), subtracted from that the average annual total pulse production for (N-gain), and divided that by the average area under crops for each nation for the period 1964-2008. The index was normalized to 100 by dividing through by the country with the greatest output of non-nitrogen fixing crops per hectare of cropland. Data on crop production and crop production area also derived from the World Resources Institute Earth Trends (World Resources Institute 2011).

The third index captures the relative intensity of N-loss from livestock. Nitrogen is lost to the system through the export of livestock and livestock products. Data on livestock were obtained from the Statistics Division of the FAO (Food and Agriculture Organization 2012), while estimates of N-consumption per head were obtained from Hong et al. (2012). This was then used to calculate aggregate relative N-loss from livestock production and export per unit of land area, by taking tons of nitrogen lost per hectare and normalizing in the same way.

Our overall measure of N-loss was the normalized sum of these three sub-indexes. Figure 3 reports the overall N-loss index for each country, averaged over the period 1964-2008, the countries being ranked (low to high) by per capita gross national product. To see the relative importance of each of the two crop-related causes of N-loss across the sample, Figure 4 reports these two N-loss indices together. It shows that average N-Loss due to cropping dominated N-loss due to land conversion in cases such as Nepal, Egypt, The Netherlands, Japan and the USA, but that N-loss due to land conversion dominated in countries such as Nigeria, Cameroon and

Cuba. Whereas N-loss due to cropping bears a U-shaped relation to per capita GDP, N-loss due to land conversion increased with per capita gross national income up to around USD 2500, and then decreased.

Our measure of N-gain is the relative intensity of fertilizer use and livestock excretion (both measured in kg of N applied per hectare). Data were obtained from the World Resources Institute Earth Trends (World Resources Institute 2011) and the Statistics Division of the FAO (Food and Agriculture Organization 2012). Data on excretions per head for the livestock species included derive from (Hong et al. 2012). The two indexes were summed, and then normalized by dividing through by the greatest intensity of fertilizer use plus livestock excretion in each year, and then by multiplying by 100. The data on relative N-gain across the sample are summarized in Figure 5. The figure reports the average N-gain index for each country over the period 1964-2008, the countries being ranked (low to high) by per capita gross national product. The curve is again U-shaped, the most highly ranked countries in terms of N-gain being at either end of the income spectrum (Bangladesh and the Netherlands).

To calculate a measure of average net N-replacement during this time period, we then took the ratio of our N-gain and N-loss indexes. In a particular year this measure denotes the relative ranking of the country in that year with respect to net N-replacement. Changes from one year to the next are changes in the rank of the country, and not necessarily changes in the measure. A country could, for example, record an increase in N-loss without affecting our measure of net N-replacement as long as other countries were behaving similarly. Over the whole period we found that very low-income countries typically ranked low for N-gain and high for N-loss, middle-income countries ranked somewhat higher for both N-loss and N-gain, and high-income countries ranked high for both N-loss and N-gain. Net N-replacement bears an inverted U-shaped relation to per capita GDP (Figure 6).

We are unable to identify the value of the net N-replacement index that indicates exact replacement (given the nature of its construction), and we note that it is constructed at the country rather than the landscape level given the constraints on available data. Nonetheless, the probability that nitrogen stocks are declining is greater the larger the value of the N-Loss index, and the smaller the value of the N-gain index. Symmetrically, the probability that a country suffers from excess nitrogen is greater the larger the value of the N-gain index, and the smaller the value of the N-loss index. Figure 6 distinguishes between observations on net N-replacement by region. The countries of Sub-Saharan Africa had the lowest relative levels of net N-replacement, and were most at risk of net N-depletion. Mean net N-replacement in Asia, and in Central and South America was higher, but for some countries was still consistent with positive rates of net N-depletion. Mean net N-replacement was highest for the countries associated with intensive agriculture in Europe, Oceana and the Middle East, but the range of net N-replacement in Europe and Oceana was also greater than elsewhere. One other striking regional pattern is that the countries of North Africa and the Middle East typically had higher levels of nitrogen gain and lower levels of N-loss than elsewhere and, independent of their income level, had higher levels of net N-replacement. Libya, Lebanon and Israel, with extremely different per capita gross national income levels, all had amongst the highest levels of net N-replacement recorded. Such countries were most likely to experience N-pollution.

3. Analyzing the sustainability implications of N-replacement

We approached our analysis of the sustainability of the processes behind these indexes in two steps. In a first step we explored the relation between net N-replacement and the three factors commonly implicated in resource depletion externalities: income, population pressure, and the effectiveness of institutions. For our measure of institutional effectiveness we elected to use the broad characterization of governance adopted by the Polity IV project (Societal-Systems Research Inc 2010). This measure summarizes a set of political conditions that are themselves correlated with the property rights, market structures, and regulatory conditions required for farmers to be able to capture the benefits of investments in soil condition. Rural population pressure was measured by the proportion of population in rural areas, obtained from FAOSTAT (Food and Agriculture Organization 2012). This measure reflects the effects both of national dependence on agriculture and of relative fertility, the two most important elements in rural population pressure on land resources. Finally, income was approximated by per capita GDP, the data again deriving from the World Resources Institute Earth Trends (World Resources Institute 2011).

The data for 67 countries were used to estimate a model of the form:

$$Y_{it} = a + g_{t} + d_{i} + X_{it} b_{it} + e_{it}$$

where Y_{it}, the dependent variable, denotes net N-replacement by country i in year t; X_{it} is a vector of independent variables, the components of which are per capita income, per capita income squared, rural population pressure and institutional effectiveness; the ε_{it} are error terms (unaccounted for contributions to the dependent variable) for $i = 1,2,\ldots M$ cross-sectional units in periods $t = 1,2,\ldots T$; and α, γ_t and δ_i represent the overall constant, period and cross-section specific effects (random or fixed) respectively.[2] The results are reported in Table 1 and Figure 7.

An orthogonality test for random effects was also applied, and a Hausman test was used to check for inconsistency in the random effects estimates,[3] since we considered it to be likely that the explanatory variables would be correlated with country specific characteristics contained in the error component, like climate and geography. The test rejected the null that the random effects model is preferred to the fixed effects model.

To see the link between N-loss and N-gain on changes in inclusive wealth, we then estimated OLS and FE models of adjusted net savings as a function of N-loss and N-gain separately. To control for non-observable specific effects of the drivers of net N-replacement on wealth, we also estimated a two stage least squares (2SLS) model of adjusted net savings, in which net N-replacement was treated as an endogenous explanatory variable instrumented on income,

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[2] Since heteroskedasticity of the data potentially compromises both fixed and random effects models Baltagi, B. H. 2001, Econometric Analysis of Panel Data. Chichester, John Wiley., we applied a Generalized Least Squares (GLS) specification, in which $\hat{b} = \left(X' \mathrm{F}^{-1} X \right)^{-1} X \mathrm{F}^{-1} Y$ and the block diagonal covariance matrix took the form $\mathrm{F} = \left[\left(m\text{Ä}\, j_T + e \right) \left(m\text{Ä}\, j_T + e \right)' \right] = I_N \text{ Ä } \mathrm{F}_i$ .The White cross-section method was used in which the pooled regression was treated as a multivariate regression, and White-type robust standard errors for the system of equations were computed. The estimator was found to robust with respect to cross-equation correlation as well as to different error variances in each cross-section.

[3] This test compares the slope parameters estimated for FE and RE models (a significant difference implying that the RE model is estimated inconsistently due to correlation between the independent variables and the error components). The FE model can, however, be estimated consistently although the estimated parameters are conditional on the country and time effects in the selected sample of data Hsiao, C. 1986, Analysis of Panel Data: Econometric Society monographs, v. 11. New York, Cambridge University Press..

institutions and rural population pressure. Because data on adjusted net savings were not available for all countries in our sample, we worked with a reduced data set of 58 countries.[4] Instrumenting the N-replacement index had the effect of increasing the magnitude of both coefficients.[5] These results are reported in Table 2 and Figure 8.

4. Results and Discussion

While the low R^2 values indicate a large amount of unexplained variance in the estimated models, the significance of the coefficients on the independent variables allows us to draw inferences about their impact on net N-replacement and inclusive wealth. To summarize, we found that the index of net N-replacement is extremely low at low levels of per capita GDP, and that it is increasing in per capita GDP up to a point, beyond which it declines. In the poorest countries, depletion of nitrogen from soils converted to agriculture is not compensated through fertilizer application, cropping with legumes, livestock excretion, or fallowing. However, we also found that the rate at which net N-replacement increases with per capita income slows as per capita incomes rise, eventually becoming negative. This effect was seen in all models estimated: ordinary least squares (OLS), fixed effects (FE) and random effects (RE). We found the fixed effects model to provide the best fit to the data, implying that country-specific characteristics significantly affect the relation between net N-replacement and the anthropogenic drivers of

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[4] Albania, Argentina, Australia, Austria, Bangladesh, Brazil, Bulgaria, Cote d'Ivoire, Cameroon, Canada, Chile, China, Costa Rica, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Finland, France, Germany, Greece, Guatemala, Hungary, India, Indonesia, Ireland, Israel, Italy, Japan, Jordan, Kenya, Mexico, Morocco, Nepal, Netherlands, New Zealand, Nicaragua, Pakistan, Peru, Philippines, Portugal, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Thailand, Tunisia, Turkey, UK, USA, Uruguay, Venezuela, Zambia, Zimbabwe.

[5] A Hansen test of overidentifying restrictions failed to reject the null that the instruments were uncorrelated with the error term and that the specification was correct at the 1% level. In addition, the Cragg-Donald F-statistic indicated that the group of instruments used was not weak.

changes in nitrogen stocks (Table 1). We found, in addition, that net N-replacement increased with the effectiveness of institutions, and decreased with the proportion of the population in rural areas in both random and fixed effects models. The effectiveness of institutions was measured by a broad index of governance and democracy and not a dedicated measure of land tenure, but we expect the two to be correlated.

We then considered the impact of net N-replacement on inclusive wealth using the ordinary least squares, fixed effects, and a two stage least squares model in which the first stage captured the indirect effects of the anthropogenic drivers analyzed earlier. We found that in countries with low levels of relative N-loss, land conversion and/or cropping intensity are positively correlated with adjusted net savings. That is, land conversion and productivity gains in agriculture are both consistent with increasing inclusive wealth in poor countries, implying that gains from the creation of productive lands more than offsets losses due to nitrogen released in conversion. However, in countries with high levels of relative N-loss, further land conversion or cropping intensity has the opposite effect.

The same basic relationship was observed in all three models (see Table 2, Figure 8a). In the OLS and RE models the effect was relatively weak. Once the indirect effects of the income and other drivers of N-loss and N-gain were taken into account in the two stage least squares model, on the other hand, we found a much stronger effect. Specifically, an increase in N-loss in poor countries is strongly associated with an increase in adjusted net savings (and hence inclusive wealth). As relative N-loss increases (in middle and high income countries), however, the effect switches from positive to negative. Beyond the turning point any further N-loss is associated with declining rates of growth in inclusive wealth. By contrast, increasing relative N-gain was positively associated with growing inclusive wealth at all levels of relative N-gain (Figure 8b). The effect attenuated in both the OLS and 2SLS models, but not in the FE model.

What does this finding mean? The stylized facts of the two sides of the nitrogen problem will be familiar to many. Few will be surprised by the fact that poor countries are generally characterized by N-depletion, or that rich countries are characterized by N-pollution. Indeed, the second problem has already attracted considerable attention. Most work has focused on establishing conditions in which farmers are confronted by the social costs of excessive nutrient applications—to internalize the external costs and benefits of N-application (Moomaw 2002). Amongst the most important issues to be addressed here are policies that drive down the private cost of N-fertilizers (i.e. that subsidize nitrogen application (Anderson et al. 2006; Barde and Honkatukia 2004; OECD 2003; Schmid et al. 2007).

What may be more surprising are the implications of these stylized facts for the sustainability of the associated development strategies. We might expect that the uncompensated loss of soil nitrogen in poorer countries would be associated with declining rates of growth of inclusive per capita wealth. That is what we find. What is less intuitive is that increasing fertilizer application in both rich and poor countries can increase per capita inclusive wealth.

Since N-gain can compensate for N-loss, the impact of changes in relative N-replacement depends on the factors affecting both land conversion and fertilizer use. These factors tend to depress fertilizer use in the poorest countries, but their effect weakens steadily as per capita incomes rise. This is consistent with the evidence that adjusted net savings have been lowest in the poorest countries, and especially in the countries (largely in Sub-Saharan Africa) in the International Monetary Fund's 'Heavily Indebted Poor Country' program.[6] But these are precisely the countries where enhanced fertilizer application could have the greatest positive impact on inclusive wealth. Specifically, increasing fertilizer application can increase wealth most in cases where relative N-replacement has been low (poor countries), but it still has a positive effect on wealth even in cases where N-pollution is substantial.

The impact of relative net N-replacement on wealth may not be large, but it is statistically significant. Its policy implications are therefore worth considering. Resolving the depletion problem in poor countries requires that the positive feedbacks between poverty, population, productivity and environmental change be broken. This in turn requires establishment of the conditions in which farmers are able to capture the benefits of investment in nutrient stocks. There are a number of elements to this, including the establishment of security of tenure and property rights, the enhancement of credit and insurance markets, together with the reestablishment of extension services (Barrett 2013).

In the poorest countries the majority of the population depends for its livelihood on agricultural and forest products and has little opportunity to engage in other activities. This effectively reduces the scope for substituting other assets for agricultural land or forest

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[6] Currently Afghanistan, Benin, Bolivia, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Comoros, Côte d'Ivoire, Democratic Republic of Congo, Eritrea, Ethiopia, Ghana, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Nicaragua, Niger, Republic of Congo, Rwanda, São Tomé & Príncipe, Senegal, Sierra Leone, Somalia, Sudan, Tanzania, The Gambia, Togo, Uganda, and Zambia.

resources, and so increases the importance of investment to maintain the productive capacity of those resources. To the question ‘does poverty hurt the environment?’ the answer in the case of N-depletion is ‘yes’. The fact the highly indebted poor countries make the least intensive use of N-fertilizers indicates that income is a constraining factor. The fact that their failure to use N-fertilizers locks them into low (and declining) yields indicates that the existence of a poverty trap. To the question ‘does environmental degradation hurt the poor?’ the answer is also ‘yes’. In fact there is a more direct relation between declining productivity, yields and income in the case of N-depletion than in most problems involving environmental degradation.

The growing awareness of the tight connections between poverty and at least some forms of environmental change is already driving a number of initiatives at the international level. The striking relation between N-replacement, dependence on agriculture and poverty is strongest in countries that are already being targeted for debt relief under the International Monetary Fund’s Heavily Indebted Poor Country program. That program has the potential to be helpful to the nitrogen problem. Debt relief under the program is conditional on the development of poverty reduction strategies. The resources freed up under the debt relief program and the poverty reduction strategy have the potential to help both conserve/rebuild environmental assets at risk from N-depletion, and to develop the institutional conditions required to encourage private investment in nutrient stocks. Given the social cost of the loss of assets on which as much as three quarters of the population in HIPC states depends, it would be worth considering the scope for targeting this problem in the HIPC program.

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Table 1 Results for ordinary least squares (OLS), random effects (RE) and fixed effects (FE) models of net N-replacement as a function of income, rural population pressure and institutional effectiveness

Model	OLS (1)	RE (2)	FE (3)
Log GDPc	1.712^{***}	1.482^{***}	1.591^{***}
	(0.211)	(0.569)	(0.564)
Log GDPc^2	-0.097^{***}	-0.066^{**}	-0.070^{**}
	(0.013)	(0.032)	(0.035)
Log institutions	0.259^{***}	0.104^{***}	0.095^{**}
	(0.018)	(0.038)	(0.018)
Log percentage of rural population	0.183^{***}	-0.396^{***}	-0.457^{***}
	(0.031)	(0.003)	(0.144)
Constant	-9.468^{***}	-7.366^{***}	-7.742^{***}
	(0.907)	(2.631)	(2.605)
R^2	0.094	0.031	0.209
F test	0.000		0.000
Wald		0.000	
Hausman FE v. RE			0.000
Nobs/Countries	3,015/67	3,015/67	3,015/67

Note: Robust standard errors are in brackets. All tests' values reported are probabilities.
*Significant at 10%.
**Significant at 5%
***Significant at 1%.

Table 2 Results for ordinary least squares (OLS), fixed effects (FE) and two stage least squares (2SLS) models of adjusted net savings as a function of net N-loss and N-gain

Model	Ordinary Least Squares		Fixed Effects		Two Stage Least Squares	
	(1)	(2)	(4)	(5)	(7)	(8)
	N-loss	N-gain	N-loss	N-gain	N-loss	N-gain
Index	0.146***	0.128***	0.009	0.381***	0.710*	0.640**
	(0. 017)	(0.015)	(0.042)	(0.108)	(0.335)	(0.001)
Index^2	-0.001***	-0.0005)***	-0.000	0.001***	-0.004*	-0.007**
	(0.0001)	(0.0001)	(0.0001)	(0.0004)	(0.002)	0.003
Constant	4.535***	6.993***	9.752***	-0.436***	-13.275	-6.604
	(0.666)	(0.476)	(1.227)	(2.662)	(11.271)	(4.890)
R^2	0.075	0.065	0.041	0.079	0.062	0.062
F test	0.000	0.000				
Wald test			0.795	0.000	0.104	0.003
Hausman FE v. RE			0.007	0.000		
Hansen J					0.120	0.529
Cragg-Donald F					11.08	87.27
Nobs/Countries	1197	1197	1197/57	1,197/57	1,197/57	1,197/57

* Significant at 10%.

** Significant at 5%

***Significant at 1%.

Figure captions

Figure 1

An algal bloom due to nitrogen pollution of the St. Johns River near million-dollar homes in Jacksonville, Florida.
Source: Ocean River Institute, www.oceanriver.org.

Figure 2

Land clearance for agriculture in the Mau Forest of Kenya (the largest indigenous forest in East Africa).
Source: Christian Lambrechts, United Nations Environment Program.

Figure 3

Index of average N-loss by per capita GDP. The figure reports average annual relative nitrogen loss from all sources by country 1964-2008. Countries are ordered in terms of per capita GDP. The solid line indicates the best line of fit to these data, not controlling for any other variables. Annual relative nitrogen loss is decreasing in per capita gross national income at low levels of income, but is increasing in income at intermediate and high levels of income.
Sources: Data were obtained from the World Resources Institute's Earth Trends database (World Resources Institute 2011) and FAOSTAT at Food and Agriculture Organization (2012).

Figure 4

Average N-loss indices for N-depletion from land conversion, and from cropping, by country, ranked by per capita gross national income. The figure reports average annual relative nitrogen loss by source and by country, countries being ordered in terms of per capita gross national income. The solid lines indicate the best line of fit to each series: a U-shaped curve for N-loss due to cropping, but an inverted U-shaped curve for N-loss due to land use change. Annual relative nitrogen loss from cropping first decreases and then increases as per capita gross national incomes rise. Annual relative nitrogen loss from land conversion is the opposite.
Sources: Data were obtained from the World Resources Institute's Earth Trends database (World Resources Institute 2011).

Figure 5

Index of average N-gain by per capita GDP. The figure average annual relative nitrogen gains from all sources by country 1964-2008 on a log scale, countries being ordered in terms of per capita GDP. The solid lines indicate the best line of fit to each series, not controlling for any other variables. Annual relative nitrogen gains first decrease and then increase as per capita gross national incomes rise.

Sources: Data were obtained from the World Resources Institute's Earth Trends database (World Resources Institute 2011) and FAOSTAT at Food and Agriculture Organization (2012).

Figure 6

Average relative net N-replacement by per capita GDP. The figure reports average annual relative net nitrogen replacement by country (and by region). Regions covered comprise: Sub-Saharan Africa (black), North Africa and the Middle East (red), Asia (orange), Central and South America, and the Caribbean (grey), Europe (dark blue), Oceana (green) and North America (light blue). The solid line indicates the best line of fit to the data, not controlling for other variables. Annual average relative net N-replacement is first increasing and then decreasing in income.

Sources: Data were obtained from the World Resources Institute's Earth Trends database (World Resources Institute 2011) and FAOSTAT at Food and Agriculture Organization (2012).

Figure 7

The relation between the net N-replacement index and per capita income. Net N-replacement initially increases rapidly with per capita gross national income but the effect weakens as per capita incomes rise further.

Sources: See text for data sources

Figure 8

The relation between adjusted net savings and N-loss in the OLS, RE and 2SLS models. Panel (a): Per capita inclusive wealth increases with net N-loss if initial levels of land conversion and cropping activity are low, but the effect is weaker if initial levels of land conversion and cropping activity are high. If the indirect effect of the anthropogenic drivers of N-loss is taken into account (2SLS models), the rate of growth of per capita inclusive wealth is negative at low levels of relative N-loss, becoming positive as the N-loss index increases, but falling again at high relative levels of N-loss. Panel (b): By contrast, per capita inclusive wealth increases monotonically with net N-gain. Whereas the rate of increase slows in both the OLS and 2SLS models, it accelerates in the FE model.

Figure 1

Figure 2

Figure 3

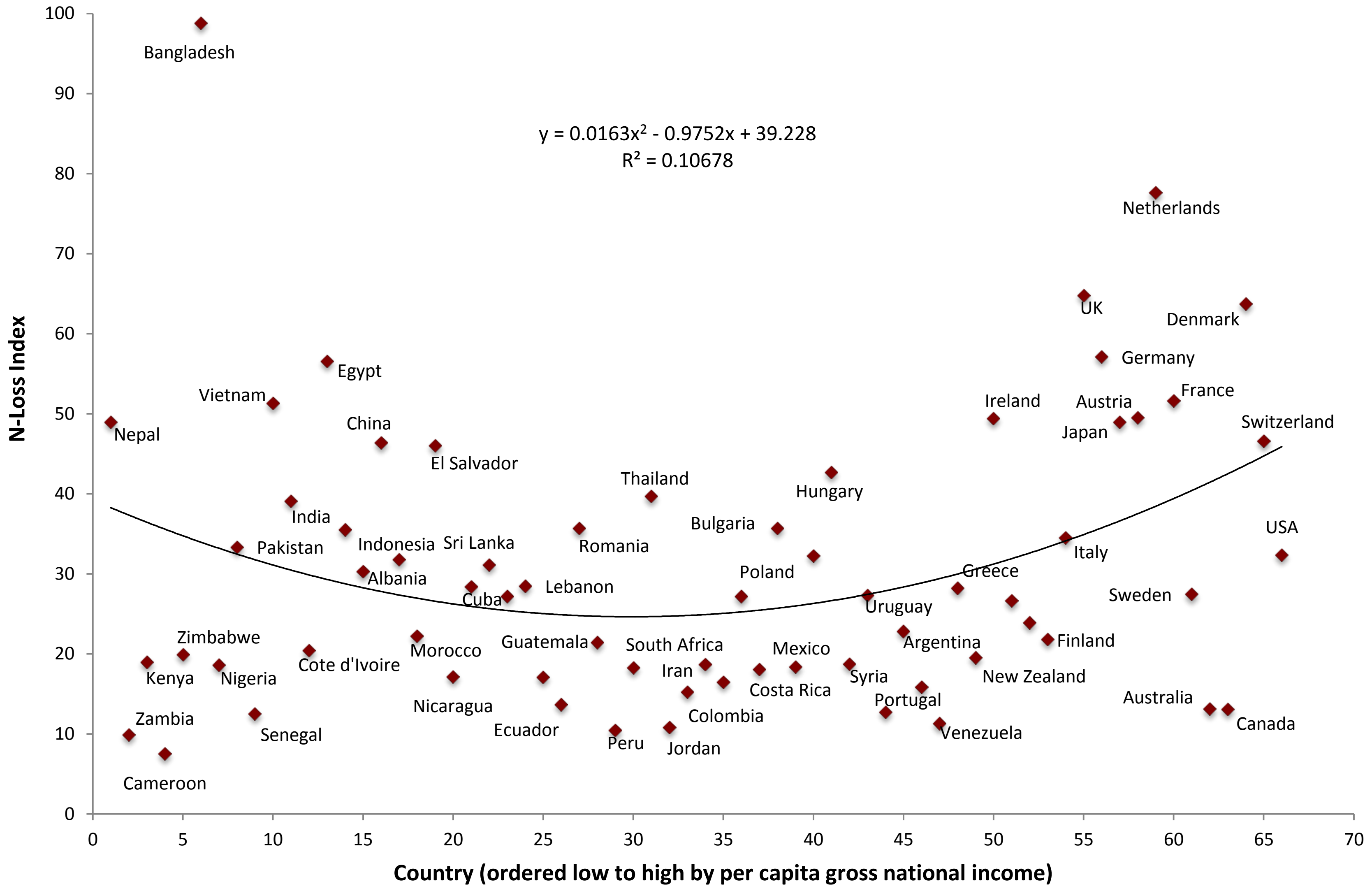

y = 0.0163x² - 0.9752x + 39.228
R² = 0.10678
N-Loss Index
Country (ordered low to high by per capita gross national income)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Bangladesh
Nepal
Vietnam
Egypt
China
El Salvador
India
Pakistan
Indonesia
Sri Lanka
Albania
Cuba
Lebanon
Romania
Thailand
Bulgaria
Hungary
Poland
Uruguay
Greece
Italy
Ireland
Austria
Japan
France
Germany
UK
Netherlands
Denmark
Switzerland
USA
Sweden
Finland
New Zealand
Argentina
Syria
Portugal
Venezuela
Mexico
Costa Rica
South Africa
Iran
Colombia
Jordan
Peru
Guatemala
Ecuador
Morocco
Nicaragua
Cote d'Ivoire
Zimbabwe
Kenya
Nigeria
Zambia
Senegal
Cameroon
Australia
Canada

Figure 4

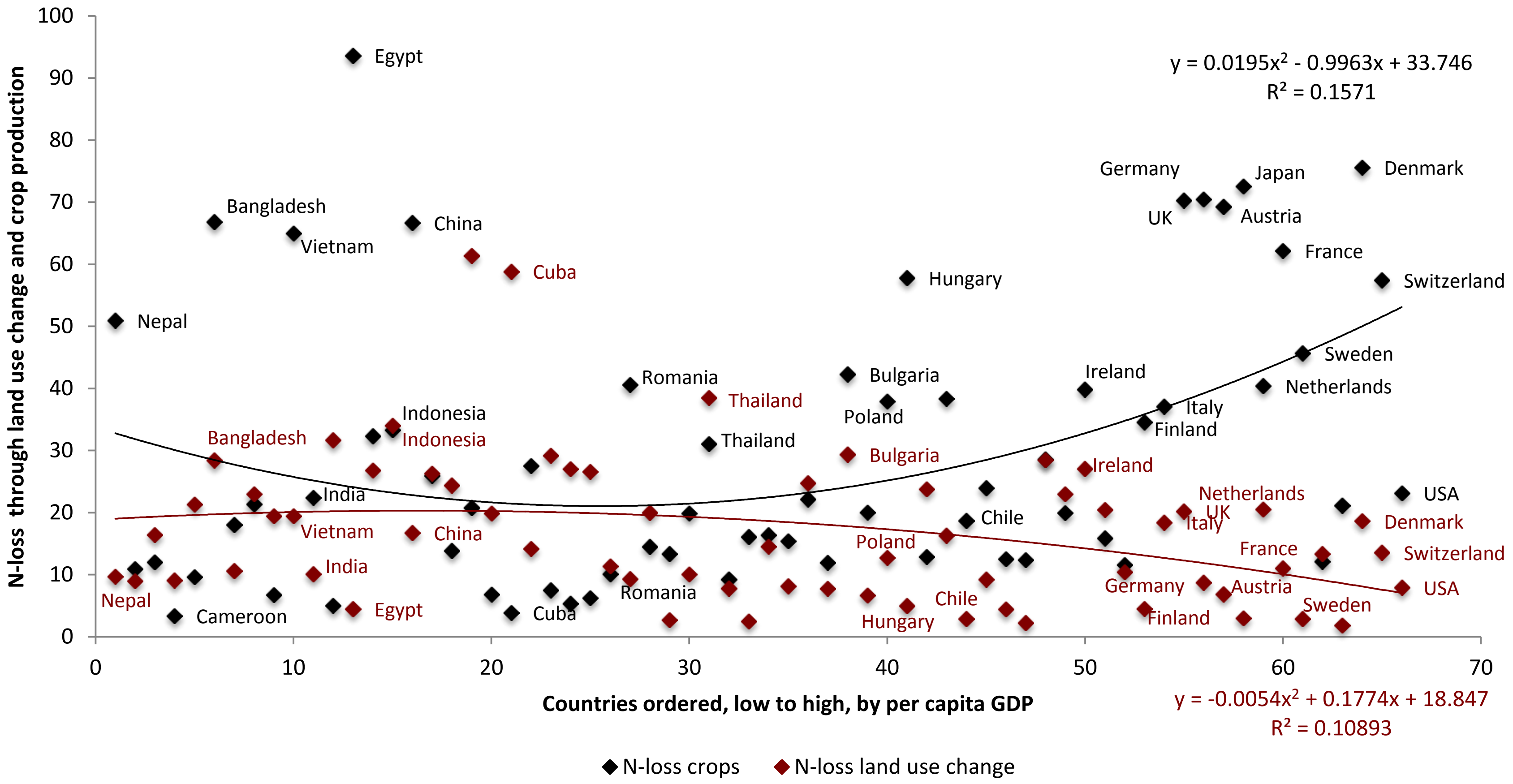
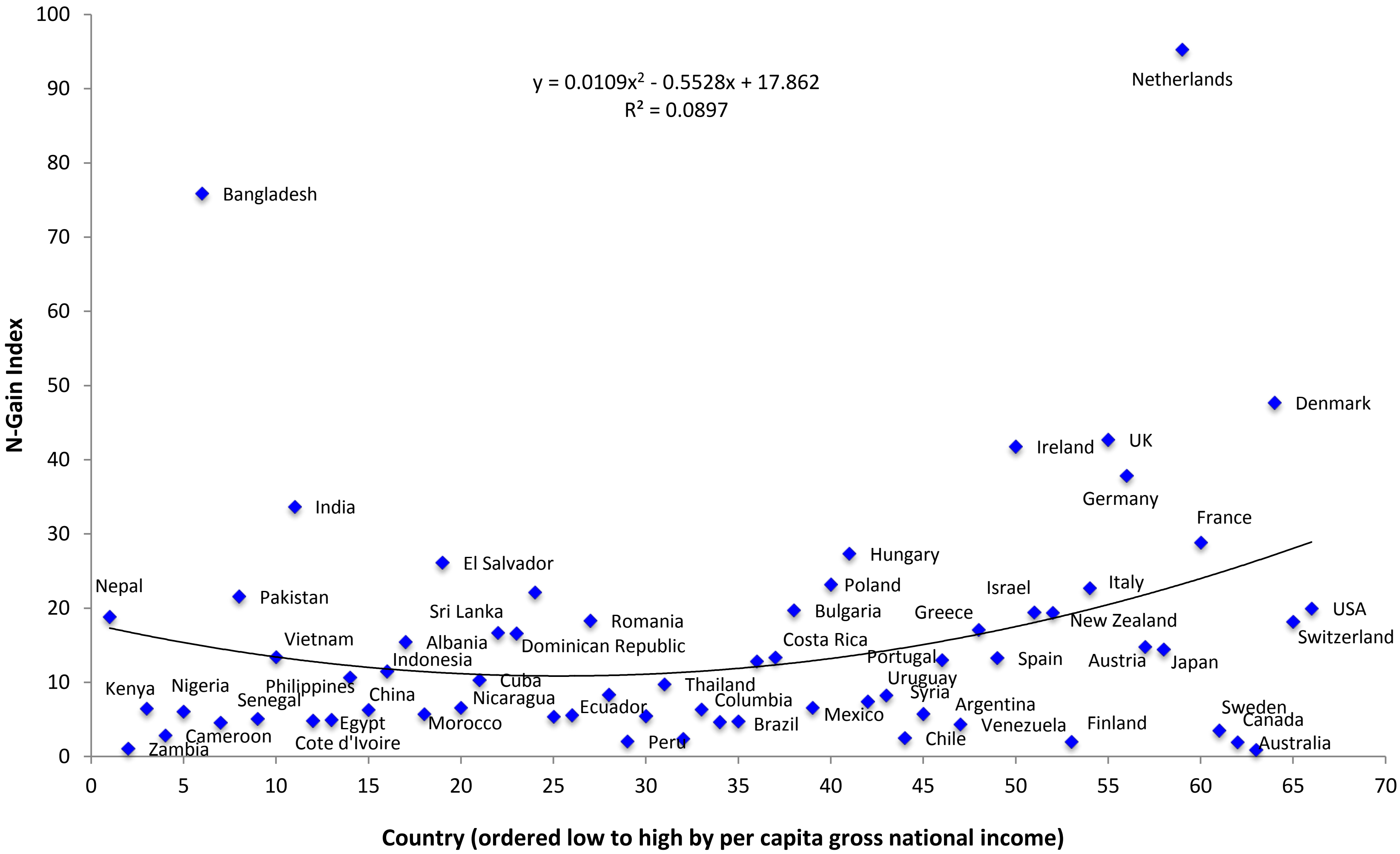

100
90
80
70
60
50
40
30
20
10
0
N-loss through land use change and crop production
Egypt
y = 0.0195x² - 0.9963x + 33.746
R² = 0.1571
Germany
Japan
Denmark
Bangladesh
China
UK
Austria
Vietnam
Cuba
France
Hungary
Switzerland
Nepal
Sweden
Romania
Bulgaria
Ireland
Netherlands
Thailand
Poland
Italy
Indonesia
Finland
Bangladesh
Indonesia
Thailand
Bulgaria
Ireland
India
Netherlands
USA
UK
Chile
Italy
Denmark
Vietnam
China
Poland
France
Switzerland
India
Romania
Germany
Austria
USA
Nepal
Chile
Sweden
Cameroon
Egypt
Cuba
Hungary
Finland
0
10
20
30
40
50
60
70
Countries ordered, low to high, by per capita GDP
y = -0.0054x² + 0.1774x + 18.847
R² = 0.10893
◆ N-loss crops
◆ N-loss land use change

Figure 5



y = 0.0109x² - 0.5528x + 17.862
R² = 0.0897
N-Gain Index
Country (ordered low to high by per capita gross national income)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Netherlands
Bangladesh
Denmark
Ireland
UK
Germany
France
India
El Salvador
Hungary
Nepal
Pakistan
Poland
Israel
Italy
Sri Lanka
Bulgaria
Greece
USA
Romania
New Zealand
Switzerland
Vietnam
Albania
Dominican Republic
Costa Rica
Indonesia
Portugal
Spain
Austria
Japan
Cuba
Uruguay
Kenya
Nigeria
Philippines
Thailand
Senegal
China
Nicaragua
Columbia
Syria
Ecuador
Argentina
Sweden
Mexico
Egypt
Morocco
Brazil
Venezuela
Finland
Canada
Cameroon
Chile
Zambia
Cote d'Ivoire
Peru
Australia

Figure 6

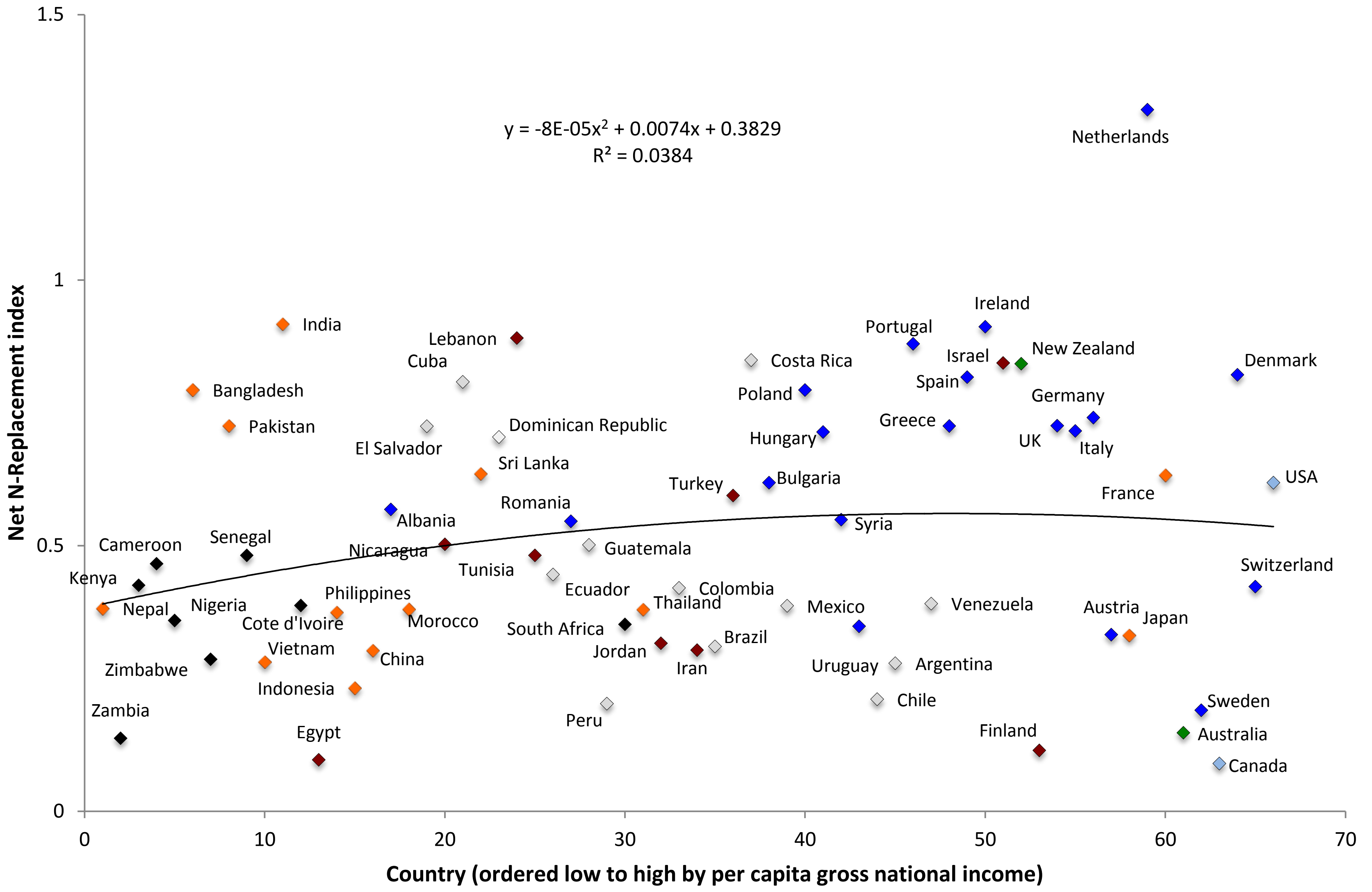

y = -8E-05x² + 0.0074x + 0.3829
R² = 0.0384
Net N-Replacement index
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Country (ordered low to high by per capita gross national income)
Netherlands
India
Lebanon
Cuba
Bangladesh
Pakistan
El Salvador
Dominican Republic
Sri Lanka
Albania
Romania
Cameroon
Senegal
Kenya
Nicaragua
Tunisia
Guatemala
Nepal
Nigeria
Cote d'Ivoire
Philippines
Morocco
Ecuador
South Africa
Thailand
Colombia
Zimbabwe
Vietnam
China
Jordan
Iran
Brazil
Indonesia
Zambia
Egypt
Peru
Costa Rica
Poland
Hungary
Turkey
Bulgaria
Portugal
Ireland
Israel
New Zealand
Spain
Greece
Germany
UK
Italy
Denmark
France
USA
Syria
Switzerland
Mexico
Venezuela
Austria
Japan
Uruguay
Argentina
Chile
Sweden
Australia
Canada
Finland

Figure 7

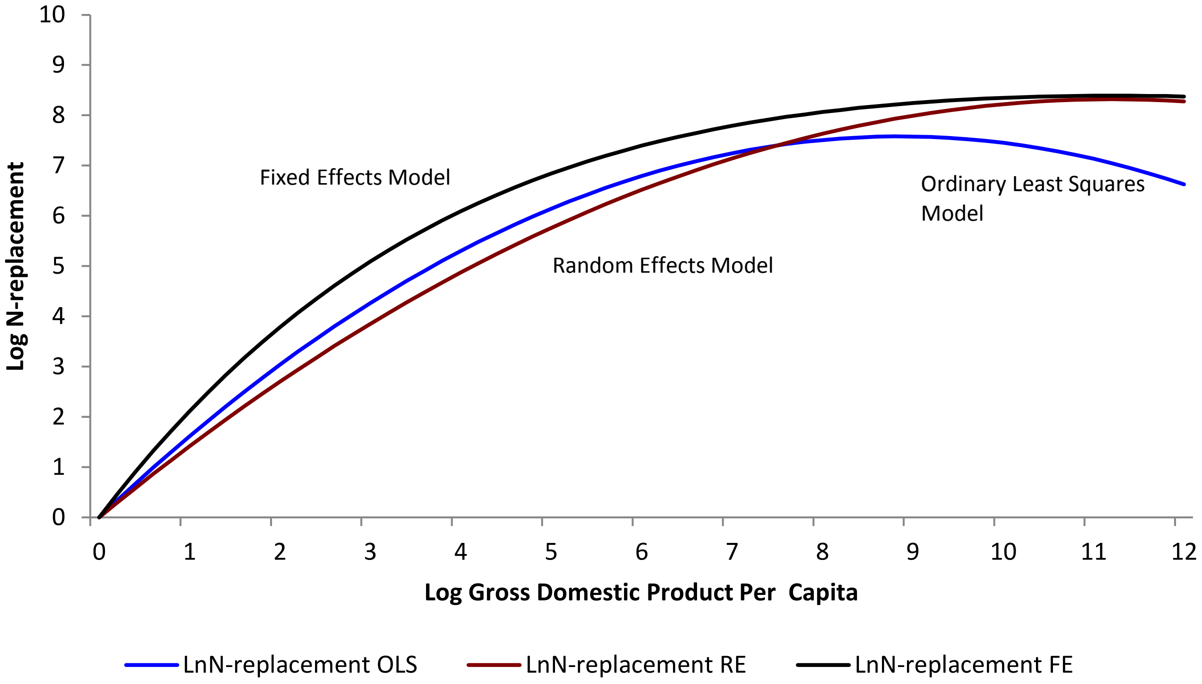
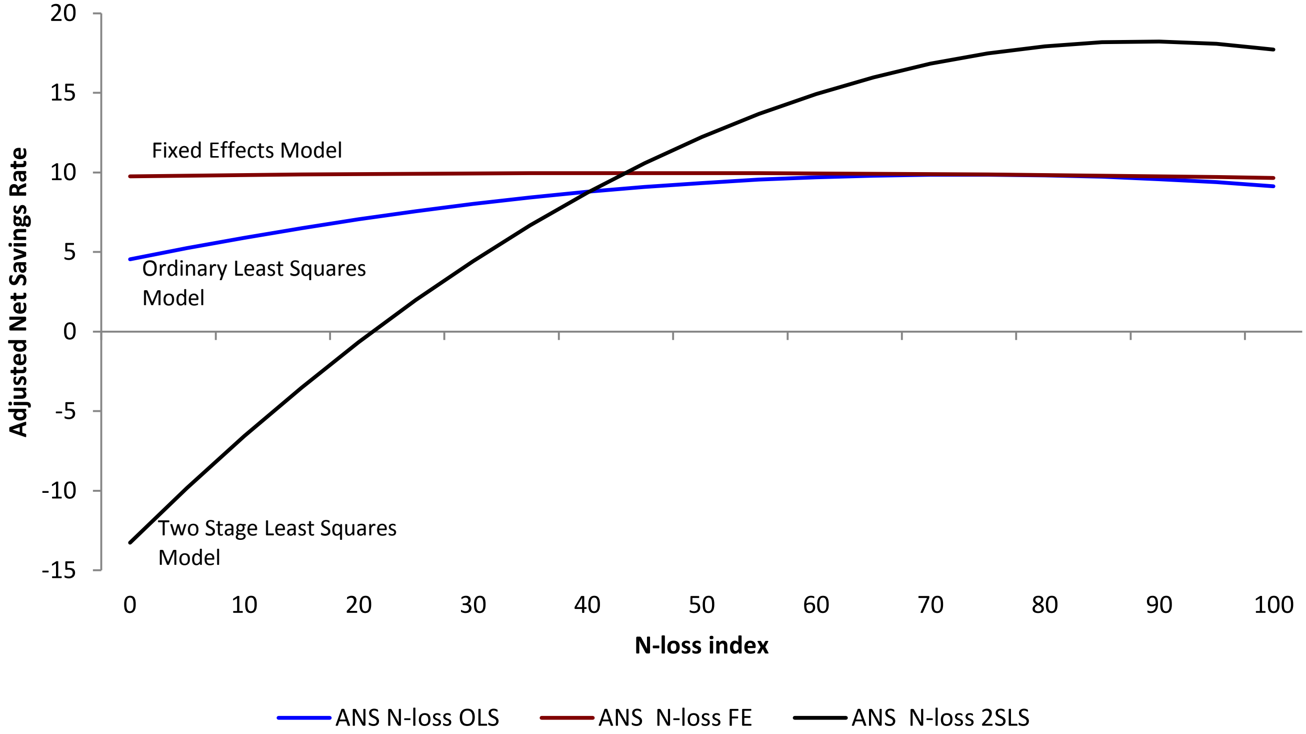
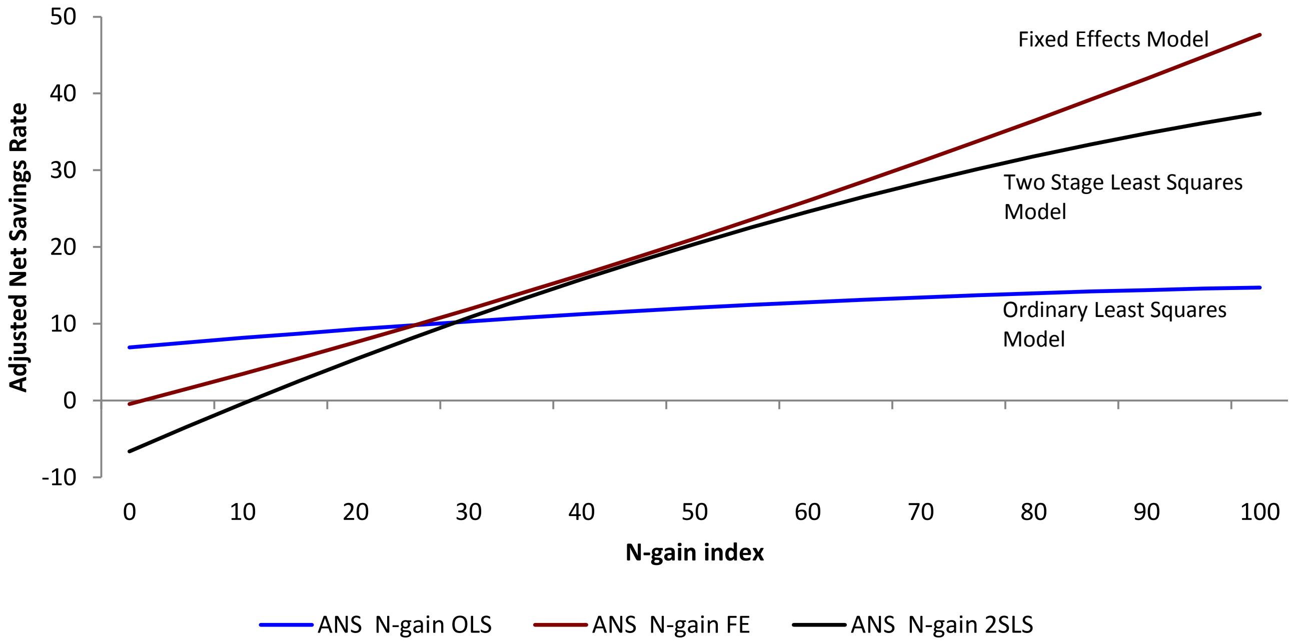

Fixed Effects Model
Ordinary Least Squares Model
Random Effects Model
Log N-replacement
0
1
2
3
4
5
6
7
8
9
10
Log Gross Domestic Product Per Capita
0
1
2
3
4
5
6
7
8
9
10
11
12
LnN-replacement OLS
LnN-replacement RE
LnN-replacement FE

Figure 8 (a)



20
15
10
5
0
-5
-10
-15
Adjusted Net Savings Rate
0
10
20
30
40
50
60
70
80
90
100
N-loss index
Fixed Effects Model
Ordinary Least Squares Model
Two Stage Least Squares Model
ANS N-loss OLS
ANS N-loss FE
ANS N-loss 2SLS

Figure 8 (b)


Adjusted Net Savings Rate
50
40
30
20
10
0
-10
0
10
20
30
40
50
60
70
80
90
100
N-gain index
Fixed Effects Model
Two Stage Least Squares Model
Ordinary Least Squares Model
ANS N-gain OLS
ANS N-gain FE
ANS N-gain 2SLS