Vulnerability, Income Growth and Climate Change

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Abstract. Cross-country data on energy consumption, GDP and vulnerability are used to measure percentage changes in vulnerability associated with percentage changes in per capita GDP and per capita energy consumption. Energy consumption, through its nonlinear effects on per capita income, have the effect of reducing a country's overall vulnerability to climate change by a greater amount at moderate income levels than at low and high incomes. An implication is that country-specific climate change policies which emphasize carbon reductions through per-capita reductions in energy use, especially in developing regions of the globe, are unlikely to reduce vulnerability to climate change, especially at very low incomes.

JEL codes: I3, Q5, O2

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1. Introduction

In this paper we confront a basic tension in the ongoing debate regarding policies to reduce carbon emissions in industrialized and developing regions of the world. It is widely argued that greater climate variability will increase mankind's exposure to extreme events, among them intense rainfall (e.g., Diffenbaugh et al. 2005; Trapp et al. 2007), greater heat stress (e.g., Diffenbaugh et al. 2005; Diffenbaugh et al. 2007), and more violent storm events (e.g., Emanuel 2005). Moreover, such extreme events are forecast to occur disproportionately in areas populated by the world's poor [e.g., Allan and Soden (2008) predict that tropical precipitation is expected to increase in equatorial regions, while already arid subtropics should experience additional drying]. The poor are regarded as especially vulnerable to extreme weather events due to their low physical and financial capacity to withstand economic shocks, their disproportionate dependence on climate-sensitive sectors, and the inherently low capacity of developing country governments to provide social safety nets or invest in basic infrastructure aimed at disaster preparedness and relief (Fankhauser 1995; Morduch 1994; Parry et al. 2001; UNDP 2007). Even in the absence of anthropogenic warming, poor countries are afflicted with poverty-related pollution and resource degradation that they lack the financial or economic means to confront (Tobey 1989). For example, 1.2 billion people lack access to clean water, 2.6 billion people lack access to basic sanitation, and an estimated 1.6 billion have sub-standard or inadequate housing (UNDP 2006). Moreover, recent analyses of the world-wide population at high risk from climate change reveal a disproportionate share in low-income settings (IPCC, 2007).

At the same time, economic history suggests income gains throughout the world have risen largely in step with energy consumption and, therefore, carbon emissions. The basic pattern is a very high rate of marginal consumption at lower levels of income and declining marginal consumption at higher levels of income. What is less clear from these data is whether energy consumption produces higher incomes or whether higher incomes lead to greater energy consumption. Much empirical work in recent years has been dedicated to segregating and identifying the direction of causality between these two variables, using data over various time frames and from various countries. Investigations regarding the direction of causality have typically followed the familiar methods outlined by Granger (1969) and have proven inconclusive.[1] For example, evidence of unidirectional causality from income to energy consumption has been found for the US (Kraft and Kraft 1978; Yu and Hwang 1984), West Germany (Erol and Yu 1987), and France, Italy, and Japan (Lee 2006). In contrast, other studies for the US (Stern 1993, 2000) and elsewhere (Lee 2005; Narayan and Singh 2007; Sari and Soytas 2007) identify unidirectional causality from energy consumption to GDP. Further clouding the issue are studies which find bi-directional or differential directions of causality (e.g. Lee and Chang 2007). One stylized empirical fact that seems uncontroversial is that even as aggregate energy consumption continues to increase, energy efficiency tends to improve.[2]

While much, but not all evidence suggests that economic growth eventually results in declining emissions, another benefit of economic growth remains clear, namely that with economic growth and greater per capita incomes, governments and households find it easier to protect against climate risk, through improved infrastructure and savings (UNDP 2007; Goklany

[1] Some studies have utilized methods proposed by Sims (1972), among them Kraft and Kraft (1978) and Yu and Hwang (1984).

[2] A number of time-series studies suggest that, once a peak level of income is attained, country-level output of pollutants may decrease. This "Environmental Kuznets Curve" (EKC) relationship was first identified by Grossman and Krueger (1991, 1995) in the context of air pollutants such as sulfur dioxide (SO_2) and smoke, as well as water contaminants such as dissolved oxygen, nitrates, and arsenic. While other studies have reached similar conclusions (e.g. Seldon and Song 1994; Shafik 1994; Holtz-Eakin and Seldon 1995) the EKC hypothesis is not without critics (e.g., Arrow et al. 1995; Stern et al. 1996; Stern 2004).

2007; Goklany 2008). Goklany (2007) suggests that wealthier societies not only are able to operate and maintain the technologies necessary for improving well-being, but also have greater agricultural productivity due to yield-enhancing technologies and also are able to import necessary food stocks in the event that such technologies are ineffective. Wealthier societies also are better able to provide social insurance or safety nets for the poorer members of their societies. This argument is implicit (or explicit) in the way many developing nations conduct negotiations over climate change policy. Developing countries have repeatedly made it clear that economic development is a greater policy priority than the environment (Beckerman 1992). It could even be argued that the adverse effects of climate change are not even the most pressing environmental danger to human health and well-being in developing countries. For example, in 2000 the World Health Organization (WHO 2002) attributed 1.7 million deaths to unsafe water, sanitation and hygiene; an additional 1.6 million deaths were attributed to indoor smoke from solid fuels; 239,000 deaths were attributed to lead exposure. Most of the deaths were in the poorest and most vulnerable regions in the world, primarily Africa and Southeast Asia. At the same time, the WHO attributed only 154,000 deaths worldwide to climate change, and of these, nearly half were from Southeast Asia, a region particularly susceptible to tropical storms and floods under current climate. Clearly, however, the WHO data suggest the environmental risks in Southeast Asia arising from unsafe water and poor sanitation, urban air pollution, indoor smoke, and lead exposure are greater than the risks attributed to climate change.

By and large, industrialized nations have the ability to cope with climate shocks and other adverse effects of anthropogenic climate change. In other words, developed nations have a low degree of vulnerability and a high degree of adaptive capacity, which itself is a function of technological prowess, supply and distribution of resources, and human, political and social capital (Tol et al. 2004). Heating and cooling capacity in the industrialized world is generally well-established, allowing some semblance of control over interior environments, although the 2003 European heat wave and Hurricane Katrina provide exceptions. Additionally, municipal infrastructure is strong (roads, bridges, water and sewer systems); public health infrastructure is strong (allowing developed nations to more adeptly deal with disease outbreaks, etc.); and communication infrastructure facilitates disaster preparedness and response. There is a stark contrast between this picture of the developed world and examples from the developing world. Whereas the developed world has reinforced structures with, even in the poorest of areas, metal roofs, the vulnerable in developing nations have weak structures with thatch roofs. Developed nations have high levels of sanitation and water filtration, while developing nations have unprotected water supplies and often lack adequate sanitation. Developing nations lack crop insurance and infrastructure to support transportation, communication, and health. So, while heavy rainfall events are unlikely to be disastrous in developed regions, such events could be devastating in developing countries. From 2000-2004, for example, on an average annual basis, one-in-19 people living in the developing world was affected by a climate disaster, compared to one-in-1500 for OECD nations (UNDP 2007). Similarly, while increases in temperature are unlikely to negatively affect (and in some cases, depending on the climate change scenario, may actually benefit) agriculture in higher latitudes, such temperature increases can have a disastrous effect on the agricultural sector in the tropics.

Several attempts have been made to quantify the estimated human costs of climate change on a regional or country-level, either in dollar terms or as a percentage of Gross National Product (GNP). Early studies (e.g., Cline 1992; Fankhauser 1992) focused on aggregating the expected costs of some of the various potential climate change outcomes within a specific country or region, including effects such as sea level rise, decreases in agricultural output and productivity, loss of forestry and other biological diversity, human mortality and morbidity, and damage to infrastructure. Few studies have attempted to move beyond anthropometric concerns to place values on losses to natural systems.

The primary conjecture of this paper is that poverty alleviation may be a better strategy with which to respond to climate-change-induced human risk than is policy aimed at carbon emissions, especially if reductions in vulnerability fall faster with income than emissions-induced risk rises. This hypothesis has been suggested before, by Tobey (1989) and more forcefully by Beckerman (1992), who argued that "the best—and probably the only—way to attain a decent environment in most countries is to become rich" (p.482). That same year, Schelling dedicated his American Economic Association presidential address to the economics of climate change, highlighting the merits of economic development as a means of reducing exposure to adverse climate change risks:

> If per capita income growth in the next 40 years compares with the 40 years just past, vulnerability to climate change should diminish, and the resources available for adaptation should be greater. I say this not to minimize concern about climate change, but to anticipate the question of whether developing countries should make sacrifices in their development to minimize the emission of gases that may change climate to their disadvantage. Their best defense against climate change may be their own continued development.

Goklany (2008) estimates that benefits of focused adaptation greatly outweigh costs of Kyoto-based greenhouse gas reducing policies. Similarly, Kavuncu and Knabb (2005) argue that the net benefits from such policies do not accrue until the late 23rd or early 24th centuries. Our view is that these patterns naturally follow from the inherent and underlying non-linear linkages between carbon emissions and climate risk, on the one hand, and carbon emissions and income growth, on the other hand. Our argument proceeds first in a conceptual way, on the basis of theoretical economic arguments. Having established the key fundamental relationships of interest, we then estimate a series of econometric models to measure the plausible range of values for parameters in the model.

2. Framework

Vulnerability can be defined as "the extent to which a natural or social system is susceptible to sustaining damage from climate change" (Schneider et al. 2001). Within the context of anthropogenic climate change, there are many various climatic hazards and many different factors which contribute to individuals' exposure to such hazards. Within a country, there are varying levels of vulnerability based upon geographic location and socioeconomic status. Additionally, it could very well be argued that an absolute measure of vulnerability to climate change is not possible, but rather one can only assess relative vulnerability. Adger et al. (2004) follow this approach by constructing a vulnerability index. To build their global vulnerability index, they utilize data from the Emergency Events Database (EM-DAT) for various climatic events and varying measures of the social outcomes of such events (i.e., varying combinations of mortality, morbidity, and displacement). They then employ cross-section analysis to identify 11 variables that are highly correlated with at least one of their mortality outcomes at the 10% level. These 11 variables are used to construct a vulnerability index for 204 countries and territories.[3]

We argue that vulnerability can be reduced only slowly, through increased wealth and economic development, with development (in the form of increased per capita income) arising from increased energy consumption. As a simple illustrative example of the argument that development reduces vulnerability, using national accounts data from the World Bank, we have

[3] This index, which we use below, assigns scores ranging from 10 (least vulnerable) to 50 (most vulnerable). For a complete description of how the index is constructed see Adger et al. (2004).

plotted countries' vulnerability against the natural log of per capita income in Figure 1. The data display a well-defined—though imperfect—negative relationship between income and vulnerability. Simply put, countries with higher levels of per capita income have lower degrees of vulnerability.

To proceed, consider vulnerability, V, which we posit to be a function of per capita income and a set of exogenous explanatory variables (X):

$$V = f(GDP, X) \tag{1}$$

where X is a $1 \times k$ vector of explanatory variables comprised of population density, cereal yield (per hectare), degree of industrialization (as a fraction of GDP), the percentage of households with a television (as a proxy for durability of household structures), fertility rate[4] (in average births per woman) and a binary variable equal to unity if the country in question is a net exporter of petroleum.[5] Note that while GDP is not explicitly included in the construction of the vulnerability index (i.e., it was not one of the 11 proxy variables used to calculate countries' vulnerability scores), per capita GDP was substantially correlated with the EM-DAT mortality outcomes (i.e., the correlation coefficient between per capita GDP and the mortality outcome has roughly a 12% probability of being exceeded when the data are subjected to a randomization procedure; for construction of the index, Adger et al. (2004) only included proxy variables with less than a 10% probability of exceedance in their index). It makes sense, therefore, to consider

[4] Schelling (1992; p. 7) suggests that "the most likely adverse impact of climate change on human productivity and welfare could be on food production. In the poorest parts of the world, the adequacy of food depends on the number of mouths and stomachs."

[5] The macroeconomic variables used in this regression come from the World Bank's World Development Indicators. The oil exportation dummy variable was constructed from data obtained from the Energy Information Administration (EIA). The reference year for the vulnerability index is 2000. Accordingly, all reported data come from 2000, with the exception of lagged data for energy consumption and savings which come from 1999.

GDP as an endogenous regressor and to proceed in estimating this model using instrumental variables and two-stage least squares. We define GDP as a function of the exogenous variables X included in the structural equation as well as a $1 \times m$ vector Z comprised of exogenous variables excluded from the structural equation (i.e., our instruments).[6] Thus:

$$GDP = g(X, Z) \tag{2}$$

Based on our discussion of the causal relationship between energy consumption and per capita income, we include lagged per capita energy consumption as an explanatory variable in the reduced-form equation. We also include the square of lagged per capita energy consumption to control for any potential nonlinearity between energy consumption and per capita income. Additionally, lagged household savings and its square are included as instruments, as are openness to trade (exports and imports as a share of GDP) and its square.[7] The variables used in this first stage regression, as well as the variables from the structural equation (1) are summarized in Table 1.[8]

Our structural model is therefore the implicit function:[9]

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[6] In the regression we allow diminishing returns to GDP. Therefore we also instrument the square of GDP in a similar manner, using higher-order terms as instrumental variables.

[7] Data for openness to trade come from the Penn World Tables, version 6.2.

[8] It may seem possible to some readers that these variables used as instruments should be included in the structural equation (1). Davidson & McKinnon (1993) propose a test of the overidentifying restrictions to ensure that the variables included as instruments are indeed valid instruments, that is, that the variables used as instruments are uncorrelated with the residuals from the 2SLS equation, and that the instruments are plausibly excluded from the structural equation. Based on the results of this test, we fail to reject the hypothesis that each component in the vector of instruments is uncorrelated with the 2SLS residuals. We thus conclude that the variables used as instruments are indeed valid instruments and should not have been included in the structural equation.

[9] The results of the standard Wu-Hausman test for endogeneity allow us to reject the exogeneity of GDP, but they do not allow us to fully reject the joint exogeneity of GDP and GDP^2. Nevertheless, because of the high correlation between per capita GDP and the mortality outcomes from the EM-DAT climatic events, we chose to model GDP and GDP^2 as jointly

$$V = f(g(X,Z),X) \tag{3}$$

This specification requires that the only pathway by which past energy consumption influences a country's vulnerability is through its effect on per capita income. In order to estimate the elasticity of vulnerability with respect to energy consumption (ε_{VE}), we work with the total derivative of *V* in equation (3), namely:

$$\varepsilon_{VE} = \frac{\partial V}{\partial E} \cdot \frac{E}{V} = \left(\frac{\partial V}{\partial g} \cdot \frac{GDP}{V} \right) \left(\frac{\partial g}{\partial E} \cdot \frac{E}{GDP} \right). \tag{4}$$

The second term in parentheses can be generated from the estimation of the reduced form equation, namely equation (2). If the reduced form equation is specified as:

$$GDP_i = \alpha_0 + \gamma_1 E_i + \gamma_2 E_i^2 + \sum_{j=1}^{k} \alpha_j x_{j,i} + \sum_{p=3}^{m} \gamma_p z_{p,i} + \omega_i \tag{5}$$

where the index *i* denotes countries, then the empirical estimate of the elasticity of per capita GDP with respect to energy consumption (ε_{GE}) is:

$$\varepsilon_{GE} = \left(\hat{\gamma}_1 + 2 \cdot \hat{\gamma}_2 \cdot E \right) \left(\frac{E}{GDP} \right). \tag{6}$$

The second stage of the estimation uses the predicted values of GDP and its square as instrumental variables in the estimation of the structural equation (1). The econometric model for this stage is specified as:

$$V_i = \beta_0 + \theta_1 G\hat{D}P_i + \theta_2 G\hat{D}P_i^2 + \sum_{j=1}^{k} \beta_j x_{j,i} + \varepsilon_i \tag{7}$$

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endogenous. While we recognize the potential inefficiency of our estimates, we underscore the asymptotic consistency properties of 2SLS.

where, again, the index *i* denotes country and $G\hat{D}P_i$ corresponds to the instrumented values of each country's GDP. Results from this regression are reported in Table 3 and can be used to compute the elasticity of vulnerability with respect to per capita GDP (ε_{VG}). This is:

$$\varepsilon_{VG} = \left(\hat{\theta}_1 + 2 \cdot \hat{\theta}_2 \cdot G\hat{D}P\right)\left(\frac{G\hat{D}P}{\hat{V}}\right). \tag{8}$$

We finally derive the elasticity of vulnerability with respect to energy consumption (ε_{VE}), given in its original form in equation (5). From this equation, ε_{VE} can be written as $\varepsilon_{VE} = \varepsilon_{VG} \times \varepsilon_{GE}$, which, after appropriate substitutions can be written as:

$$\varepsilon_{VE} = \left(\theta_1 + 2 \cdot \theta_2 \cdot GDP\right)\left(\frac{GDP}{V}\right)\left(\gamma_1 + 2 \cdot \gamma_2 \cdot E\right)\left(\frac{E}{GDP}\right) \tag{9}$$

where γ_i, $i = 1,2$, are the coefficients from the estimation of the reduced form equation (5) and θ_i, $i = 1,2$, are the coefficients from the two-stage least squares estimation of the structural equation identified in equation (8). The elasticities defined by equations (6), (8) and (9) are our primary empirical concerns.

3. Results

Regression results from our first-stage regression for equation (6) are reported in Table 2. Because of the inherent nonlinearity of the elasticity measurement, a useful exercise is to examine these elasticities at different levels of income and energy consumption. Figure 2 plots our elasticity estimates by income deciles, where the elasticity of per capita income with respect to energy consumption is evaluated at the mean level of per capita income and energy consumption for each income decile. As Figure 2 illustrates, at low levels of income, a small increase in per capita energy consumption has a large effect on per capita income growth. This elasticity, however, declines rather markedly as income increases, such that additional energy consumption at high levels of income has virtually no effect on per capita income.

As before, it is illustrative to examine these elasticities at varying levels of income. Figure 3 plots the vulnerability elasticities for income deciles, where the elasticity of vulnerability with respect to per capita GDP is evaluated at the mean levels of GDP and vulnerability for each income decile. The change in vulnerability associated with an increase in income is negative across these deciles. At extremely low levels of income, a small increase in income is not substantial enough to generate a dramatic decrease in vulnerability: there are simply too many gaps to fill. However, at higher levels of per capita income, reductions in vulnerability are possible, at a marginally declining rate. At high levels of income it is simply not feasible to generate reductions in vulnerability: rich countries are already fairly impervious to climate shocks, and it is difficult to further insulate themselves from such shocks.

The elasticities of vulnerability with respect to energy consumption (ε_{VE}), based on equation (9) are plotted in Figure 5. As above, we plot these by income decile, evaluating the elasticity at the mean values of energy consumption and vulnerability for each income decile. This final figure displays a U-shape relationship similar to (and derivative from) the relationship between income and vulnerability. At almost all levels of per capita income, an increase in energy consumption reduces vulnerability. However, our data reveal a turning point at approximately $15,000 per capita GDP, after which additional energy consumption yields a marginally decreasing, though positive, effect on reducing vulnerability.

4. Conclusions

Our results are consistent with the hypothesis that, at low- to moderate-income levels, an increase in energy consumption raises standards of living and adaptive capacity, thus reducing vulnerability to climate change. Indeed, even at higher levels of income, energy consumption leads to a reduction in vulnerability, but at a rate that may be insignificant, given these countries' already high degree of insulation and their ability to adapt in the face of climate variability. As such, and because it is simply not possible to reverse the anthropogenic climate change that has already been generated, it may be an appropriate course of action to permit low and medium income countries to continue to consume energy at the same (if not greater) rates, even at the expense of greater emissions. This does not imply that reducing emissions should not be an integral component of a comprehensive global climate policy—indeed rich Western countries that are rather impervious to climate variability should certainly place emissions reductions at or near the top of their environmental priorities. However, for low-income countries, rather than attempting to mitigate the adverse effects of climate change by reducing emissions of greenhouse gases, the global poor may be better served by further economic development and higher standards of living, allowing them to modestly insulate themselves from the potential extreme climate events that are predicted to occur in the future.

These results are not without flaws. Development is a dynamic process and varies greatly from country to country, and certainly a deeper understanding of the processes through which development occurs and vulnerability is reduced would be of great benefit to policy makers. Since the vulnerability data functions much like a snapshot of current conditions (as of 2000), such analysis is not possible. But we contend that imperfections in the data or analysis should not lessen the magnitude of the implications the results suggest. Perhaps future research can consider such time-series elements and more completely inform policies for reducing the vulnerability of global poor to the coming effects of anthropogenic climate change.

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Table 1 Description of data used in the analysis

Variable	Description	Obs	Mean	Std. Dev.	Min	Max
V[1]	Vulnerability score	204	24.5	10.1	10	50
GDP[2]	GDP (real USD per capita)	176	6,118	9,185	86	46,228
CERYLD[2]	Cereal yield (kg/ha)	175	2,627	1,945	130	12,600
POPDEN[2]	Population density (people/km^2)	184	187	656	1.5	6,396
OILEXP[3]	Oil exporter (1=yes, 0 otherwise)	201	0.16	0.37	0	1
INDUSTRY[2]	Industrialization (Value added/GDP)	169	0.30	0.13	0.09	0.86
TELEVIS[2]	Households with television (%)	155	60.8	35.5	1.1	101.4
FERTILITY[2]	Fertility rate (births per woman)	183	3.2	1.7	1.0	7.6
ENERGY99[2]	Energy consumption in 1999 (kg of oil equivalent/capita)	131	2490	2,900	141	20,616
SAVINGS99[2]	Gross savings rate (% of GDP)	159	17.5	9.77	-6.6	49.4
OPENK[4]	Openness to trade (X+M as % of GDP)	185	90.9	51.8	2.0	377.7

Sources:
1 Adger et al. (2004)
2 World Bank, World Development Indicators (2007)
3 EIA (2008)
4 Penn World Tables 6.2 (2006)

Table 2 Regression results for model of GDP, dependent variable is GDP per capita in USD (2000)

Variable	Coefficient	Std. Error
CONSTANT	-957.20	4821.99
ENERGY99	3.12*	1.10
ENERGY992	-8.50×10^{-6}	0.00013
SAVINGS99	-127.30	169.73
SAVINGS992	5.30	4.54
OPENK	-91.43*	33.87
OPENK2	0.38*	0.14
INDUSTRY	-110.48*	48.08
OILEXP	-1985.09	1257.64
CERYLD	2.09*	0.37
POPDEN	-1.37	4.15
TELEVIS	16.14	31.60
FERTILITY	921.51	650.92
n	101	
R^2	0.81	

*indicates significance at $\alpha \leq 5\%$

Table 3 Regression results for vulnerability, dependent variable is vulnerability score in 2000

Variable	Coefficient	Std. Error
CONSTANT	23.66*	3.57
GDP	-0.00063*	0.00024
GDP2	1.07×10^{-8}	6.00×10^{-9}
INDUSTRY	0.16*	0.04
OILEXP	1.09	1.09
CERYLD	-0.00042	0.00043
POPDEN	0.0021	0.0036
TELEVIS	-0.10*	0.028
FERTILITY	1.64*	0.54
n	101	
R^2	0.83	

*indicates significance at $\alpha \leq 5\%$

Figure 1 Vulnerability and GDP per capita, 2000

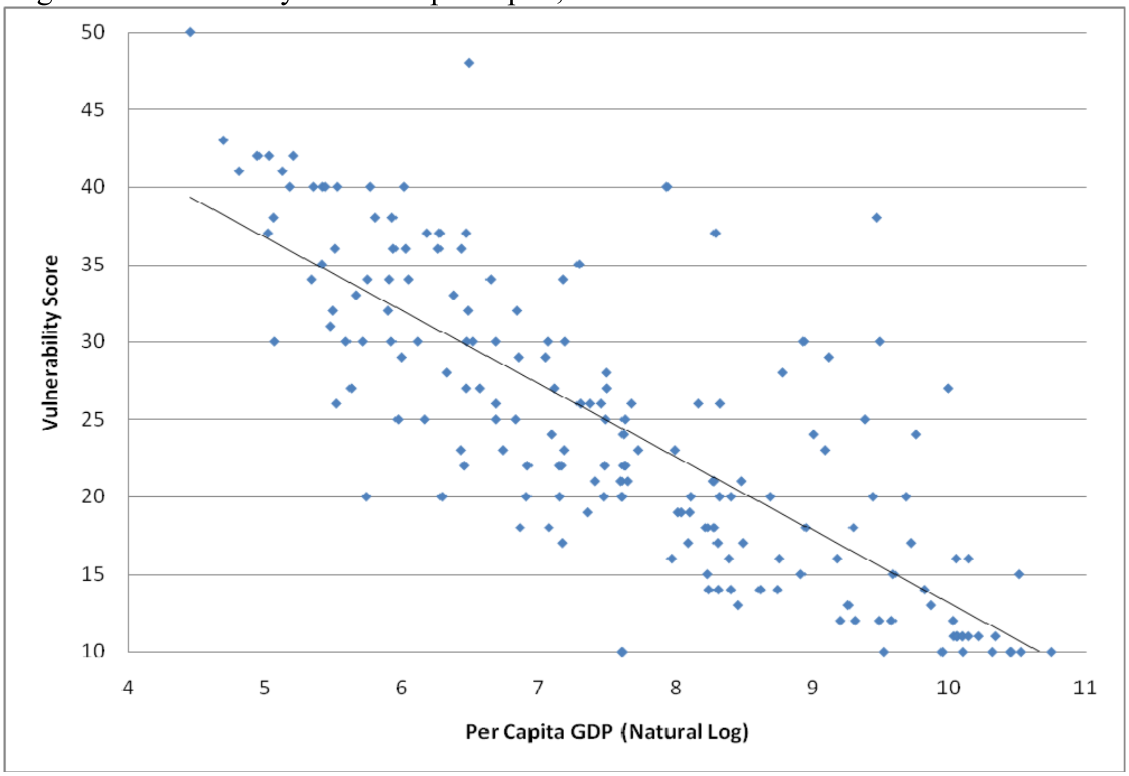

Figure 2 Elasticity of GDP with respect to energy consumption, by decile

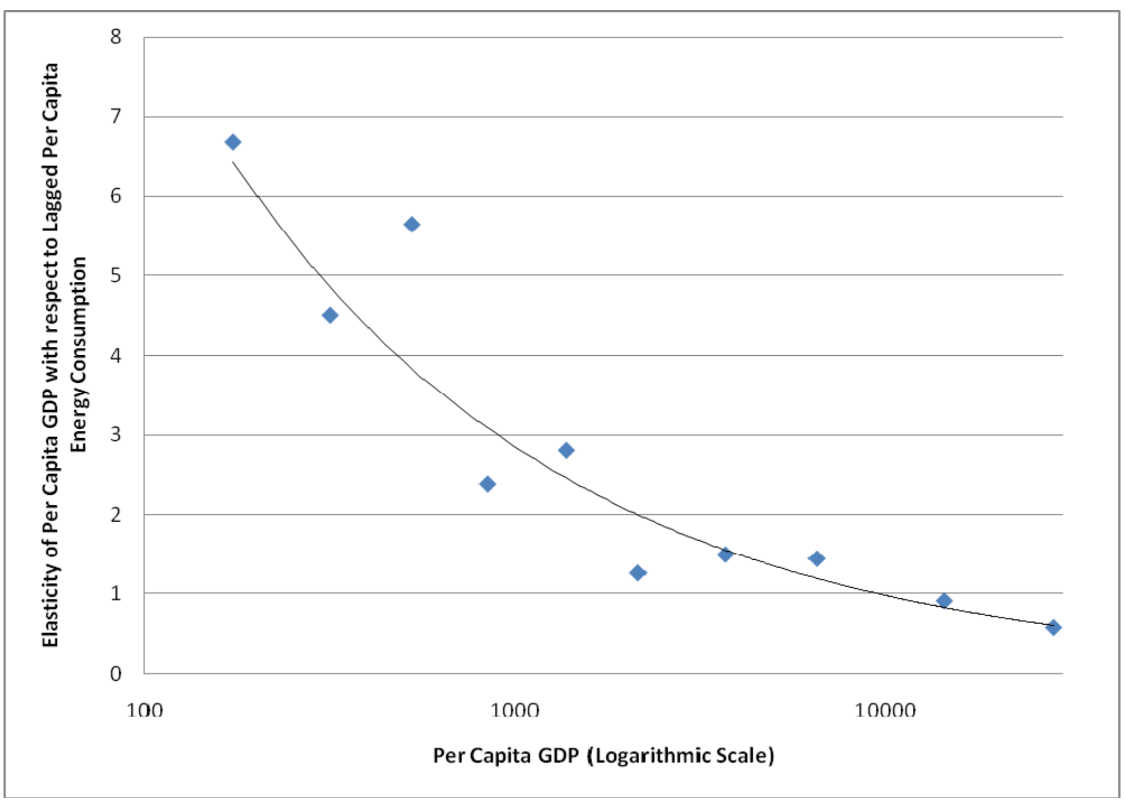

Figure 3 Elasticity of vulnerability respect to GDP per capita, by decile

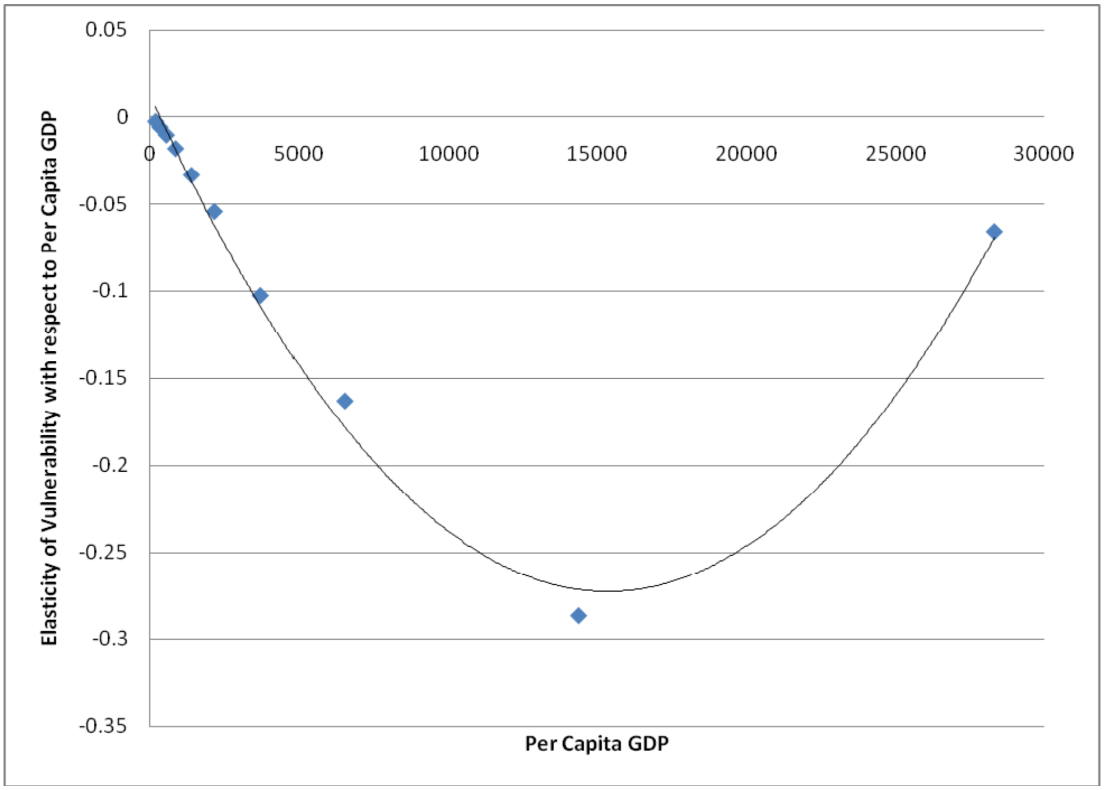

Figure 4 Elasticity of vulnerability with respect to energy consumption, by decile