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The weakest link hypothesis for adaptive capacity: An empirical test

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Abstract

Yohe and Tol (2002. Global Environmental Change 12, 25–40) built an indexing method for vulnerability based on the hypothesis that the adaptive capacity for any system facing a vector of external stresses could be explained by the weakest of its underlying determinants—the so-called ''weakest link'' hypothesis. Their structure noted eight determinants, but the approach could handle any number. They quoted analogies in support of the hypothesis, but loose inference is hardly sufficient to confirm such a claim. We respond to this omission by offering an empirical investigation of its validity. We estimate a structural form designed to accommodate the full range of possible interactions across sets of underlying determinants. The perfect complement case of the pure ''weakest-link'' formulation lies on one extreme, and the perfect substitute case where each determinant can compensate for all others at constant rates is the other limiting case. For vulnerability to natural disasters, infant mortality and drinking water treatment, we find qualified support for a modified weakest link hypothesis: the weakest indicator plays an important role because other factors can compensate (with increasing difficulty). For life expectancy, sanitation and nutrition, we find a relationship that is close to linear—the perfect substitute case where the various determinants of adaptive capacity can compensate for each other with relative and persistent ease. Moreover, since the factors from which systems derive their adaptive capacities are different for different risks, we have identified another source of diversity in the assessment of vulnerability.

JEL classification: Q0; O2

Keywords: Adaptive capacity; Vulnerability; Perfect complementarity; Substitution

1. Introduction

Some of the factors that define the vulnerability of any human system are defined by the physical properties of its environment, but other factors are framed by social-economic context and social preferences. Smit et al. (2001, Chapter 18) noted this distinction, but they ultimately argued that it was irrelevant. Regardless of whether physical or social factors were in play, they saw that any system's vulnerability to any vector of external stresses is determined fundamentally by its exposure to the manifestations of those stresses and its baseline sensitivity to those manifestations. Moreover, any system's ability to cope with exposure and/or sensitivity depends, in turn, on the degree to which it can exploit its innate (or developed) adaptive capacity—a capacity that is, itself, supported by underlying determinants such as the availability of economic resources, technology, information and skills, infrastructure, institutions, and equity (Smit et al., 2001, pp. 895–897). In the IPCC view of adaptation, then, all three of these factors work together to define social-economic thresholds of tolerance to external stresses (of which climate change and climate variability may be two of

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many) in ways that are clearly path dependent and site specific.

To sort through the implications of how this insight might be applied across a diverse globe in the climate arena, Yohe and Tol (2002) suggested organizing one's thoughts about adaptive capacity at any one place at any point in time around their own derivative list of underlying determinants:

1. the range of available technological options for adaptation,
2. the availability of resources and their distribution across the population,
3. the structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed,
4. the stock of human capital including education and personal security,
5. the stock of social capital including the definition of property rights,
6. the system's access to risk spreading processes,
7. the ability of decision-makers to manage information, the processes by which these decision-makers determine which information is credible, and the credibility of the decision-makers, themselves, and
8. the public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.

Yohe and Tol (2002) drew their list from the Smit et al. (2001) assessment of the adaptation literature reported above, but they went farther in their application of this organization structure. Indeed, they conjectured that the adaptive capacity of any system would, for all intents and purposes, be limited by the weakest of these underlying determinants (or the weakest determinant from any other list of alternative determinants that might be more appropriate for a different context). Formalized in their Eq. (5), this is the so-called "weakest link" hypothesis upon which they constructed an indexing scheme that could be employed to judge the relative vulnerabilities of profoundly different systems to climate change.

The IPCC authors, as well as Yohe and Tol (2002), recognized that the determinants identified on any such list would not be independent of one another. Nor would they be mutually exclusive. At the very least, they would frequently be highly collinear. Nonetheless, the idea behind their the "weakest link" conjecture and their vulnerability index is that a significant weakness of any single critical component of a system's capacity to cope with the manifestation of an external stress, whether it worked to undermine the strength of a single element on a list of determinants or undercut the strengths of multiple determinants on such a list, would be the limiting factor of that system's ability to adapt. Ambiguity across the elements on the list creates problems when it comes to empirical estimation of vulnerability, as will be seen shortly, but it does not undermine the possibility that such a weakest link might describe much of reality.

Before we turn to a discussion of our approach to the complexities of estimating the sensitivity of vulnerability to changes in underlying determinants, Section 2 offers a little more motivation for the "weakest link" conjecture. Intuitive support, based mostly on tracking functional analogs from one context to another, is offered; but so, too, is the alternative hypothesis found elsewhere in the literature that strength in one determinant can compensate for weakness in another. The need for empirical work thereby established, we develop our modelling approach in Section 3, we describe our data in Section 4, we report our results in Section 5, and we offer concluding thoughts about context, applicability and next steps in Section 6.

2. Motivation for and critique of the "weakest link" hypothesis

The conjecture that a system's capacity to function well depends on the weakest of a list of underlying factors makes perfect sense to economists who have long understood that the efficiency (and perhaps even the existence) of economic markets can be undermined if *even one* of a long list of primary conditions were *not* satisfied. Intuitive support for the hypothesis from the economics literature is not, however, confined to theoretical discussions of hypothetical efficiency or ruminations that focus exclusively on climate change. Some of the more applied economics literature suggests that (1) the determinants listed above and by Smit et al. (2001) and reframed in Yohe and Tol (2002) are germane to the success or failure of development programs and (2) the likelihood of success or failure of a specific plan can be influenced by the weakest of those factors.

Lucas (1988), for example, argued that human capital externalities *alone* are large enough to explain differences between the long-run growth rates of poor and rich countries. Guiso et al. (2004) expanded the scope of analysis when they explored the role of social capital in supporting successful application of financial structures; they found that social capital matters most when education levels are low *or* when law enforcement is weak. Meanwhile, Rozelle and Swinnen (2004) looked across transition countries across central Europe and the former Soviet Union and observed that countries which grew steadily if their reforms had managed to create macroeconomic stability, reform property rights, harden budget constraints, and create institutions that facilitate exchange and develop an environment within which contracts can be enforced and new firms can enter. Order and timing did not matter, but success depended upon on meeting *all* of these underlying objectives. Winters et al. (2004) reviewed a long literature to conclude that the ability of trade liberalization to reduce poverty depends on the existence and stability of markets, on the ability of actors to handle changes in risk, on access to technology and resources, on competent and honest government, *and* on policies that promote conflict resolution and promote human capital accumulation; shortfalls in any of these underpinnings makes it extremely difficult for the gains to trade to reach the most disadvantaged citizens. Sala-i-Martin et al. (2004) applied new Bayesian estimation techniques to popular data to find robust power in explaining economic growth residing in a nation's level of participation in primary school education, other measures of human capital, the relative prices of investment goods *and* the initial level of per capita income. Finally, in their analysis of increased flood risks in the Netherlands, Tol et al. (2003) find that, for all the economic and technological might of the country, adaptation may fail only on the basis of a lack of rapid and decisive decision making.

Yohe and Ebi (2005) meanwhile observed that the public health sector works under the presumption that the ability to influence a public health problem (i.e., to adapt to a perceived level of vulnerability) depends on a number of factors that are as path dependent and site specific as the determinants of success or failure of economic initiatives. They also recognized the applicability of a weakest link approach to analyzing health initiatives because the practitioners in the health sector generally expect that their efforts will be futile if any *one* of the following "prerequisites for prevention" are missing:

1. an awareness that a problem exists,
2. a sense that the problem matters,
3. some understanding of what causes the problem,
4. a demonstrated capability to intervene, and
5. the political will to influence the problem.

Yohe and Ebi argued that this list of prerequisites maps well into the determinants of adaptive capacity listed earlier. The match is not exact, of course, because the scales at which risks can be spread vary by health outcome and by disease determinant. Nonetheless, experience in the public health context offers evidence the list of determinants recorded above is workable, especially with its emphasis on public infrastructure (governance, social capital), human capital (education and behavior) and the ability to manage information.

Working within the modelling structure set forth in Yohe and Tol (2002), Alberini et al. (2006) used a sample of expert opinion from the public health and climate fields to support an empirical investigation of the determinants of adaptive capacity. Their work suggests that per capita income, income inequality, access to universal health care, and high access to information were the critical determinants of adaptive capacity. Expert opinion, summarized through statistical methods, saw a universal health care system and high levels of access to quality information to be equivalent to \$12,000 to \$14,000 in per capita income. Their results, when applied to real countries, produced indices of adaptive capacity that worked well as predictors of mortality to weather disasters. Their results also provide a logical bridge to an alternative hypothesis—one where strength in one determinant can be expected to compensate for weakness in another. The idea behind the alternative hypothesis is that, although a specific configuration of variables may be necessary to produce a desired effect, many such configurations may suffice. There may be a core set of determinants across a multitude of settings for which a "weakest link" hypothesis might apply, but it can be hard in practice to identify all of the relevant factors much less what might be the limiting factor.

The economics literature again provides a perfect illustration—this time of the notion of compensation. Williamson (2005) reflected on a lifetime of work in which he tried to explain diversity in the structure of firms across developed economies. In his work, the primary driver of how firms would organize themselves was their desire to maximize their ability to adapt to external stress. He ultimately saw three possibilities for which governance patterns could be described in terms of differential incentive intensity, differential administrative control, and differential reliance on background regime that set the rules for contract law. At one extreme, firms would find it in their best interest to rely on autonomous adaptations in circumstances if they operated within strong market structures (see above) that could sustain strong reliance on "high-powered" incentives (in lieu of elaborate administrative mechanisms); these markets would, of course, have to be supported by a well-understood legal-rules contract-law regimes. While these firms would find themselves well suited to respond individually to external stress, they would find it difficult to sustain cooperative adaptations difficult. No matter, though; such arrangements would be unnecessary given the underlying legal structure.

Williamson sees hierarchies (organizational structures built around significant administrative control perhaps through vertical integration) at the other extreme. These firms would discover the largest adaptive capacity under conditions where the legal system was "deferential" so that incentive contracts could not be efficiently administered. They would, therefore, find it necessary to create and maintain cooperative adaptive options even if that meant doing it all themselves. In between, hybrid structures would evolve. They would assume selected and advantageous characteristics of both extremes depending on the "efficacy of credible commitments" (i.e., penalties for premature termination, information disclosure, verification mechanisms, specialized dispute settlement, etc. components of the list of determinants provided above). Put another way and regardless of which structure emerges from which context, Williamson argues that firms organize themselves in ways that maximize their adaptive capacities by *compensating* for deficiencies in the underlying determinants provided by their economic environments.

Brenkert and Malone (2005) formalized the notion of compensation in their analysis of vulnerability and resilience to climate change in India. Following the lead of Moss et al. (2001), they created indices from a set of underlying determinants for coping capacity and sensitivity. More specifically, their index for coping capacity was supported as the geometric mean of two components of economic capacity (GDP per capita and income distribution equity), two components of human and civic resources (percent of the population in the workforce and an illiteracy rate) and three components of environmental capacity (percent of non-managed land, sulfur dioxide emissions, and population density); and their overall index was the arithmetic mean of this index and a corresponding index of sensitivity drawn from settlement infrastructure, food security, human health, ecosystem management, and the availability of water resources. As such, they recognized the potential of some degree of compensation within their measures coping capacity and sensitivity, they asserted perfect compensating potential across those aggregates, and so their weights are really ad hoc—but no more ad hoc, to be sure, than asserting the perfect complementarity of the weakest link. The need for an empirical investigation that can test a wide range of possibilities is thus clear.

3. The modelling structure

In pursuit of a structure that could accommodate the extremes of complementarity and/or substitutability across any set of underlying determinants of adaptive capacity in coping with any external stress, we let the vulnerability V of any country C to an external stress can be measured as

$$\{1/V_{\mathrm{C}}\} \equiv \left\{\sum \alpha_i A_i^{(1-\gamma)}\right\}^{1/(1-\gamma)}, \tag{1}$$

where the A_i are indicators of n distinct determinants of adaptive capacity. The α_i and γ are parameters in the relationship that is motivated by the usual structure of constant elasticity of substitution production functions. In this regard, $(1/\gamma)$ is the "elasticity of substitution" between any two determinants in supporting the exercise of adaptive capacity in reducing vulnerability to the chosen stress. It therefore reflects the sensitivity of the ratio of the "marginal products" of two determinants to changes in the ratio of their observed levels. Put another way, $(1/\gamma)$ reflect the sensitivity of the "marginal rate of substitution" between any two determinants to changes in their relative strengths.

The parameter γ is of primary interest in examining the degree to which determinants can compensate for one another. To see why, notice that

1. $\gamma = 0$ would mean that $\{1/V_{\mathrm{C}}\} \equiv \{\Sigma\alpha_i A_i\}$. In this case, the determinants of adaptive capacity would be perfect substitutes regardless of their individual levels. In words, the determinants can substitute for one another at constant rates to maintain the same level of vulnerability.
2. $\gamma \to \infty$ would mean that $\{1/V_{\mathrm{C}}\} \equiv \min\{\alpha_i A_i\}$. In this other extreme case, the determinants of adaptive capacity would be perfect complements and overall vulnerability would be entirely determined by the "weakest link" in the sense that strengthening any but the weakest determinant would do nothing to reduce vulnerability. Put another way, increasing the strength of anything but the weakest determinant would do nothing to change vulnerability. This is the Yohe and Tol (2002) structure in its purest form.
3. $\gamma = 1$ would mean that $\{1/V_{\mathrm{C}}\} \equiv \{\Pi A_i^{\alpha_i}\}$. This is a threshold case because, as γ converges to unity from above, the "iso-vulnerability" loci do not intersect any of the $A_i = 0$ axis. It follows that vulnerability would be infinite if any single determinant were not present. In all other cases, the determinants can substitute for one another to maintain the same level of vulnerability, but compensation would become increasingly expensive as strength in one or more determinants became weaker. This is nearly the functional form of the geometric mean employed by Brenkert and Malone (2005), although the geometric mean imposes the condition that all of the α_i coefficients are identical.
4. $\gamma < 1$ would mean that the determinants can substitute for one another to maintain the same level of vulnerability and that compensation would become less expensive as strength in one or more determinants became weaker.

Estimated values of γ between 0 and unity would therefore imply varying degrees of substitution between determinants as γ grows toward unity. In other words, strength in one determinant could compensate, in terms of reducing vulnerability, for weakness in another regardless of the levels of underlying support distributed across the A_i (even if one or more, but not all, of the underlying determinants were zero). Finite values above 1 would also show some but increasingly limited (again, as γ grows past unity) potential for substitution. In any of these cases, though, substitution could never overcome a total shortcoming in one or more of the A_i.

Fig. 1 provides some insight into this structure by portraying "iso-vulnerability" loci for three values of γ ($\gamma = 0.5$, 0.9 and 1.1) for a simple case of two determinants with $\alpha_1 = \alpha_2 = 1$. These three cases straddle the boundary case where $\gamma = 1$ so that the elasticity of substitution ranges from 2 on the high side to 0.91 on the low side. Notice that the first case shows a locus that intersects both axes around $A_i = 1$; this is a case where a complete deficiency in one determinant can be overcome by relatively modest investment in the other (bringing the other up to around 4). The intermediate case drawn there also allows for complete compensation, but the remaining determinant must be orders of magnitude higher than 4. The locus for the other extreme case, where the elasticity of substitution is below unity, never comes close to either axis, so complete compensation is impossible.

Table 1 defines some illustrative hypothetical cases across which this structure can be explored in a more complicated case. Notice that five underlying determinants are considered and that the 11 cases span a range beginning with perfect equality across the A_i and ending with the possibility that one value is nearly zero. All of the cases are symmetric in their distribution of relative strength, and the overall sum of the five A_i is always the same. Table 2 reports the corresponding vulnerability values for each case across a range of values for γ that straddle the unity threshold under the assumption that the α_i are all equal to 0.2 (so they sum to unity). Fig. 2 portrays the results graphically. The structure has the pleasing characteristic that all values of γ produce the same vulnerability value for the perfect equality of Case 1. They all show increasing vulnerability as the distribution of the underlying determinants becomes more uneven, with higher values of γ showing the largest changes. Indeed, were Case 11 to allow A_1 to fall to zero, then the vulnerability values for cases in which $\gamma \geqslant 1$ would be undefined.

The possibility that the strength of a determinant must exceed a specific threshold A_i^{T} can also be accommodated in this structure by defining

$$B_i \equiv \begin{cases} \{A_i - A_i^{\mathrm{T}}\}, & \text{for } A_i > A_i^{\mathrm{T}}, \\ 0, & \text{otherwise.} \end{cases} \tag{2a}$$

Then,

$$\{1/V_{\mathrm{C}}\} \equiv \left\{\sum \alpha_i B_i^{(1-\gamma)}\right\}^{1/(1-\gamma)} \tag{2b}$$

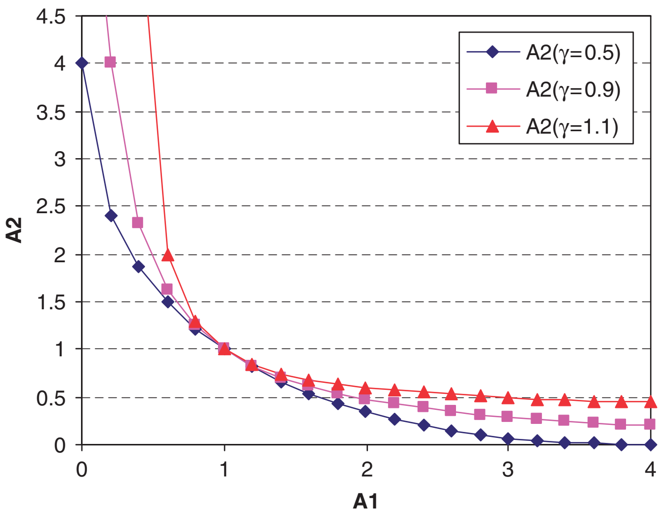

Fig. 1. Iso-vulnerability loci for various values of γ.

Table 1
Illustrative cases for underlying strengths of five determinants of adaptive capacity

	A1	A2	A3	A4	A5
Case 1	1	1	1	1	1
Case 2	0.9	0.95	1	1.05	1.1
Case 3	0.8	0.9	1	1.1	1.2
Case 4	0.7	0.85	1	1.15	1.3
Case 5	0.6	0.8	1	1.2	1.4
Case 6	0.5	0.75	1	1.25	1.5
Case 7	0.4	0.7	1	1.3	1.6
Case 8	0.3	0.65	1	1.35	1.7
Case 9	0.2	0.6	1	1.4	1.8
Case 10	0.1	0.55	1	1.45	1.9
Case 11	0.02	0.51	1	1.49	1.98

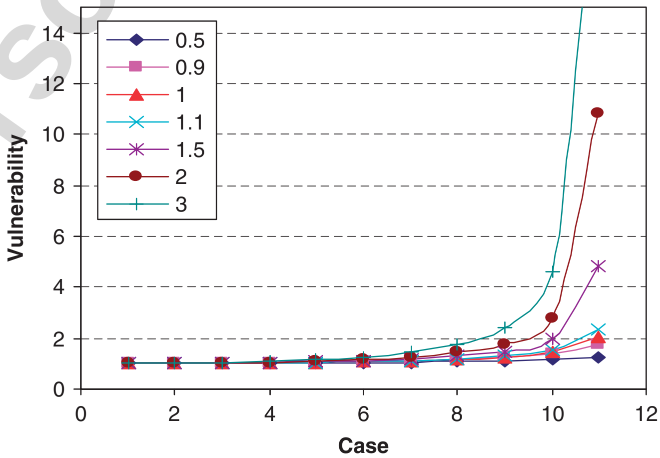

Fig. 2. Corresponding estimates of vulnerability for various values of γ.

Table 2
Corresponding estimates of vulnerability for various values of γ

	Gamma						
	0.5	0.9	1	1.1	1.5	2	3
Case 1	1	1	1	1	1	1	1
Case 2	1.0012545	1.0022616	1.0025138	1.0027662	1.003777	1.0050429	1.007579
Case 3	1.0050734	1.0091902	1.0102264	1.0112652	1.0154432	1.0207071	1.0313058
Case 4	1.0116323	1.0212477	1.0236898	1.0261459	1.0360975	1.0487676	1.0745007
Case 5	1.0212591	1.0393237	1.0439745	1.0486755	1.0679377	1.0928571	1.1441089
Case 6	1.0345035	1.0649828	1.0729846	1.0811318	1.1150675	1.16	1.2539715
Case 7	1.052284	1.1010236	1.1141809	1.1277192	1.1854832	1.2645604	1.4333986
Case 8	1.0762246	1.1528946	1.1744554	1.196995	1.2967366	1.4401542	1.7534362
Case 9	1.1095899	1.2331604	1.2702337	1.3100096	1.4969878	1.7873016	2.4329662
Case 10	1.1609859	1.3830885	1.4584889	1.5437474	1.9974782	2.8068306	4.5838503
Case 11	1.2437577	1.7700063	2.0151606	2.3383737	4.8410991	10.827395	22.385487

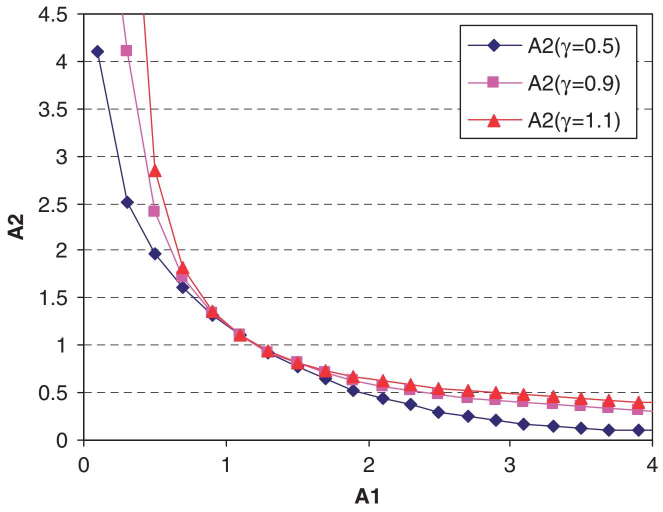

Fig. 3. Iso-vulnerability loci for various values of γ with $A_1^{\mathrm{T}} = A_2^{\mathrm{T}} = 0.1$.

would represent the relationship between "threshold constrained" determinants and vulnerability. Notice that the discussion of ability of substitution to support the reduction of vulnerability would continue to hold, but the thresholds A_i^{T} would serve as boundaries for the "iso-vulnerability" loci for cases in which $\gamma \geqslant 1$. This possibility is displayed in Fig. 3—a replication of the simple illustration of Fig. 1 with $A_1^{\mathrm{T}} = A_2^{\mathrm{T}} = 0.1$. Notice, to clearly differentiate this case from the one displayed in Fig. 1, that the $\gamma = 0.5$ locus converges to vertical and horizontal asymptotes defined by $A_1^{\mathrm{T}} = A_2^{\mathrm{T}} = 0.1$. Note that we do not further investigate this specification.

Note that we measure adaptive capacity and vulnerability with the characteristics of the system under stress, rather than with the characteristics of the stress, let alone its source. Our data do not allow us to test this hypothesis. The source of stress should not matter, at least not for adaptation. For instance, a health care system can either cope with a surge in infectious disease, or it cannot, regardless of whether the increase is due to climate change and migration. Of course, outside help may be different; as would the implications for mitigation. The characteristics of the stress obviously matter for the precise impact, but given the variability of and uncertainty about multi-faceted stress, an invulnerable system would respond well to almost any challenge, while a vulnerable system would not be able to cope with any but minor challenges.

4. Data

We used six alternative indicators for vulnerability, four of which are in fact indicators for the absence of vulnerability. The fraction of people affected by natural disasters was the first indicator that we explored. The data are from EMDAT (2005). We normalized their "number affected" with the size of the population. We averaged over 1991–2000 to smooth interannual variations. We aggregated all types of hazards, again to smooth variability, and we assumed that the data represent the hazard situation in 1995.

The second indicator was infant mortality, taken from WRI (2005). Infant mortality integrates a range of problems of poverty and health. Although disease-specific (infant) mortality would be more informative, data coverage is insufficient, particularly in poorer countries. The third indicator was life expectancy at birth, taken from WRI (2005); it is an indicator of invulnerability. Life expectancy is related to infant mortality, but also includes health risks in later life. We used data for 1995 where available and the average of 1992 and 1997 otherwise.

Nutrition reflected by the average calorie supply per person per day taken from WRI (2005) served as the fourth indicator. Risk of hunger would have been a better indicator, but there are no such data available and the coverage of famines by EMDAT (2005) is sparse. The fifth indicator, the percentage of people with access to improved sanitation (pit latrines and better) from WRI (2005), has similar drawbacks. We would have preferred to use an indicator of the problems caused by faulty sanitation, but this is not available. We used the average of 1990 and 2002, the only years for which data are available. The percentage of people with access to an improved source of drinking water (rainfall collectors and better), again from WRI (2005), completed the list of indicators that we explored. We used the average of 1990 and 2002, the only years for which data are available. Note that the last three are indicators of invulnerability.

We grouped the indicators of adaptive capacity into five categories. Table 3 lists them all. Political indicators include the nature of government (democracy, etc.), and the nature of government intervention in society (rule of law, etc.). Cultural indicators include average attitudes (e.g., to risk). Related to that, we included a list of dummies giving the dominant religion in a country;[2] note that a country may be labelled "Christian" even though most of its inhabitants are secular. Per capita income, income distribution, and poverty rates were employed as economic indicators. Finally, enrolment and literacy reflected education.

5. Results

5.1. Natural disasters

We began by trying to explain the number of people affected by natural disasters, per thousand people, per year, averaged over 1991–2000. Two problems with estimating (1) quickly became apparent. The first was model selection. There were many potential indicators of

[2]As befits a scientist, a referee questioned the inclusion of religion. However, religion often correlates with other variables, such as income (Sala-i-Martin et al., 2004). This is because culture and religion are closely related, and together shape institutions and behaviour. Note that the religion dummies only play a minor role in the empirical analysis below.

Table 3

Indicator	Description	Source
Institutions		
Accountability	Political, civil and human rights	Kaufmann et al. (1999)
Autocracy	Institutionalized autocracy	Marshall and Jaggers (2003)
Civil liberties	Freedom of expression, assembly, association, education and religion	Freedom House (2003)
Executive competition	Extent to which executives are chosen through competitive elections	Marshall and Jaggers (2003)
Corruption	Petty and grand corruption, and state capture	Kaufmann et al. (1999)
Democracy	Institutionalized democracy	Marshall and Jaggers (2003)
Economic freedom	Corruption, barriers to trade, fiscal burden, regulatory burden (health, safety, environment, banking, labor)	Heritage Foundation (2003)
Government effectiveness	Competence of bureaucracy and quality of public service	Kaufmann et al. (1999)
Government quality	Quality of public institutions	Gallup and Sachs (1999)
Rule of law	Contract enforcement, quality of policy and judiciary, and crime	Kaufmann et al. (1999)
Political rights	Free and fair elections, competitive politics, opposition power, minority protection	Freedom House (2003)
Executive recruitment	Institutionalized procedure for the transfer of executive power	Marshall and Jaggers (2003)
Extent of regulation	Incidence of market-unfriendly policies	Kaufmann et al. (1999)
Political stability	Violent threats or changes in government	Kaufmann et al. (1999)
Religion		
Buddhism	Predominantly Buddhist	Adherents.com (2003)
Christianity	Predominantly Christian	Adherents.com (2003)
Hinduism	Predominantly Hindu	Adherents.com (2003)
Islam	Predominantly Moslem	Adherents.com (2003)
Yorubaism	Predominantly Yoruba	Adherents.com (2003)
Animalism and spiritism	Predominantly Animist	Adherents.com (2003)
Culture		
Individualism	Reinforcement of individual achievement and interpersonal relationships	Hofstede (2001)
Masculinity	Degree of gender differentiation and male dominance	Hofstede (2001)
Uncertainty avoidance	Tolerance of uncertainty and ambiguity	Hofstede (2001)
Power distance	Degree of inequality in power and wealth	Hofstede (2001)
Long-term orientation	Degree of orientation on the future	Hofstede (2001)
Trust	Degree of trust of others	WVS (2003)
Economics		
Gini coefficient	Degree of income inequality	WRI (2005)
Absolute poverty	Percentage of population living on less than $1/day	WRI (2005)
Relative poverty	Percentage of population below national poverty line	WRI (2005)
Per capita income	Per capita GDP, purchasing power parity exchange rate	WRI (2005)
Education		
Primary	Total enrolment relative to school-age population, primary education	WRI (2005)
Secondary	Total enrolment relative to school-age population, primary education	WRI (2005)
Tertiary	Total enrolment relative to school-age population, primary education	WRI (2005)
Literacy	Percentage of the population over 15 able to read and write	WRI (2005)

adaptive capacity, each with missing observations for different countries. Furthermore, regressions are plagued by multicollinearity. One would preferably start with the model that includes all possible explanatory variables. Estimates could then be refined by eliminating variables that are neither individually nor jointly significant in a step-wise process. This procedure was not possible, however, because all of the variables are actually available for only a small number of countries. Indeed, this number is smaller than the number of potential explanatory variables. We were therefore forced to group the explanatory variables; Table 3 provides the details. For each group, therefore, we first included all variables in a linear model and then systematically reduced the model to include significant variables only. Of the institutional variables, only economic freedom mattered; it increases vulnerability. Of the religious variables, only Christianity and Islam had a significant effect on vulnerability; both reduce vulnerability. Of the economic variables, absolute poverty and per capita income were individually significant, but not jointly; poverty increases vulnerability. Of the cultural variables, only uncertainty avoidance mattered: it reduces vulnerability. Of the education variables, only enrolment in tertiary education was significant; it reduces vulnerability. Significant explanatory variables per group were then combined in a new model, and the number of significant variables was further reduced. In the end, only per capita income, uncertainty avoidance, and tertiary education were included.

Non-linearity was the second problem in estimating Eq. (1). Although non-linear estimators are now generally available, CES functions are complicated. We therefore linearly estimated Eq. (1) for specific γ's, and then conducted a grid search to produce both a maximum likelihood estimate for γ and the maximum likelihood function as well. The estimated function is:

$$V_c^{ND} = (1-\gamma)^{1-\gamma}\left(\underset{(6.2)}{36.4} - \underset{(2.5)}{11.2}\,Y^{1-\gamma} - \underset{(4.0)}{8.0}\,U^{1-\gamma} + \underset{(3.9)}{10.0}\,T^{1-\gamma}\right)^{1/1-\gamma},$$
$$\gamma = \underset{(0.05)}{0.90}, \quad R^2 = 0.41, \quad N = 68, \tag{3}$$

where V^{ND} is the fraction of people affected by natural disasters, Y is per capita income, U is uncertainty avoidance, and T is tertiary enrolment.

Eq. (1) suggests strongly that richer countries are less vulnerable, as are cultures that avoid uncertainty. All else being equal, a greater number of people with tertiary education *increases* vulnerability. The correlation between per capita income and tertiary education is strongly positive, or course.[3] This acts to temper, but not reverse, the positive income effect. At the average income ($6848) and the average tertiary enrolment (19%), the positive effect of income is 80% lower than suggested by the income parameter alone.

The estimated value of γ is 0.90, with a standard deviation of 0.05.[4] That is, substitution is difficult but not impossible. The weakest link hypothesis holds, but only in a weak sense that approximates a variant of the "Cobb-Douglas" structure employed by Brenkert and Malone (2005). Unlike the geometric mean that they employed, however, the proximate Cobb–Douglas form for Eq. (3) would not all be equal. Some degree of substitution across determinants is not surprising, since the indicators chosen are proxies rather than "actual inputs into the production of safety from natural disasters".

5.2. Infant mortality

The same procedure was followed for infant mortality. A number of institutional variables had a significant effect on infant mortality: civil liberty (positive),[5] democracy (positive), economic freedom (negative), and political stability (positive). From the religion variables, only Christianity had a significant, positive influence. Individualism and long-term orientation were the only significant cultural variables, both with a positive effect. Secondary education and literacy had significant, positive effects on infant mortality. Absolute poverty, average per capita income, and the Gini coefficient had significant, positive effects on infant mortality.

When all significant (by group) variables were combined, only absolute poverty, per capita income and literacy remain. The estimated equation is

$$V_c^{IM} = (1-\gamma)^{1-\gamma}\left(\underset{(2.1)}{20.6} - \underset{(0.04)}{0.15}\,Y^{1-\gamma} - \underset{(0.37)}{1.52}\,L^{1-\gamma} + \underset{(0.19)}{0.91}\,P^{1-\gamma}\right)^{1/1-\gamma},$$
$$\gamma = \underset{(0.11)}{0.60}, \quad R^2 = 0.84, \quad N = 49, \tag{4}$$

where Y is per capita income, L is literacy, and P is absolute poverty. A modest version of the weakest link hypothesis is again somewhat supported, but none of the indicators is essential.

5.3. Life expectancy

We followed the same procedure for life expectancy. Democracy and the rule of law positively affected life expectancy, as did Christianity. High incomes and low fractions of people in absolute poverty had positive effects on longevity, but so did an *unequal* income distribution. A greater degree of trust, more individualism, and a larger aversion to uncertainty positively affected life expectancy, as did a higher literacy and a greater enrolment in secondary and tertiary education.

Combining all significant variables, democracy, the Gini coefficient, absolute poverty, and literacy remained. The estimated equation is

$$1/V_c^{LE} = (1-\gamma)^{1-\gamma}\left(\underset{(10.2)}{122.6} + \underset{(0.06)}{0.13}\,G^{1-\gamma} + \underset{(0.31)}{1.11}(D+1)^{1-\gamma} + \underset{(0.03)}{0.08}\,L^{1-\gamma} - \underset{(0.04)}{0.23}\,P^{1-\gamma}\right)^{1/1-\gamma},$$
$$\gamma = \underset{(0.30)}{-0.27}, \quad R^2 = 0.76, \quad N = 53, \tag{5}$$

where G is the Gini coefficient, D is democracy (shifted to lie between 1 and 11), L is literacy, and P is absolute poverty. The estimated γ is negative, but it is not statistically significantly different from zero. Recall, though, that life expectancy is not an indicator of vulnerability; it is, instead, an indicator of the inverse of vulnerability.

5.4. Nutrition

Following the same procedure in investigating vulnerability through nutritional levels, democracy and the rule of law were the only significant institutional indicators; both had a positive effect. Christianity and Islam affected nutrition positively, whereas the Yoruba religion had a negative effect. Both the average per capita income and the level of absolute poverty had a significant effect on nutrition with the expected signs. Cultures that are

[3] The estimated relationship is $T_c = \underset{(1.41)}{5.20} + \underset{(0.00014)}{0.00227}\,Y_c$, $R^2 = 0.67$, $N = 122$.

[4] The boundaries of the 95% confidence interval are taken as the parameter values for which the log-likelihood is two points below its maximum value. The standard deviation is one-quarter of the length of the 95% confidence interval.

[5] Note that we use "positive" and "negative" in the intuitive sense: civil liberty reduces infant mortality.

individualistic and avoid uncertainty had higher nutrition, as did countries with higher enrolments in secondary and tertiary education.

Grouping all of these variables, only individualism, uncertainty avoidance, and absolute poverty remain. The estimated relationship is:

$$1/V_c^{\mathrm{N}} = (1-\gamma)^{1-\gamma}\left(\underset{(131)}{1919} - \underset{(1.50)}{8.83}\, I^{1-\gamma} + \underset{(1.58)}{3.45}\, U^{1-\gamma} - \underset{(1.71)}{8.64}\, P^{1-\gamma}\right)^{1/1-\gamma},$$
$$\gamma = \underset{(0.26)}{0.03}, \quad R^2 = 0.74, \quad N = 50, \tag{6}$$

where I is individualism, U is uncertainty avoidance, and P is absolute poverty. The equation is almost linear, but the estimate is not statistically significantly different from zero.

5.5. Sanitation

Again, the same procedure was followed. The rule of law had a positive, significant effect on sanitation. Sanitation was higher in Christian and Moslem countries. A higher average income and less absolute poverty increased sanitation, but a higher income inequality had the same effect. Sanitation was higher in cultures that are individualistic and avoid uncertainty. Literacy and enrolment in secondary and tertiary education all increased sanitation.

Combined, literacy, uncertainty avoidance, and Islam remain. The estimated relationship is:

$$1/V_c^{\mathrm{S}} = (1-\gamma)^{1-\gamma}\left(-\underset{(6.6)}{35.3} + \underset{(2.9)}{17.9}(I+1)^{1-\gamma} + \underset{(0.13)}{0.37}\, U^{1-\gamma} + \underset{(0.11)}{1.04}\, L^{1-\gamma}\right)^{1/1-\gamma},$$
$$\gamma = \underset{(0.20)}{0.15}, \quad R^2 = 0.69, \quad N = 66, \tag{7}$$

where I is Islam, U is uncertainty avoidance, and L is literacy. The functional form is not significantly different from linear. Especially given that the estimate for γ is statistically insignificant, the data do not support the weakest link hypothesis.

5.6. Drinking water treatment

Still following the same procedure, we found that democracy and the rule of law had a positive effect on the spread of drinking water treatment. It was also greater in Christian countries, countries with higher average incomes, more equal income distribution, and less absolute poverty also improved water treatment. Uncertainty avoidance and individualism had a positive effect, as did literacy and enrolment in secondary education.

Combined, secondary education, income distribution, and absolute poverty remained. The estimated relationship is:

$$1/V_c^{\mathrm{W}} = (1-\gamma)^{1-\gamma}\left(\underset{(60.8)}{293.9} - \underset{(0.11)}{0.42}(P+1)^{1-\gamma} + \underset{(0.16)}{0.42}\, G^{1-\gamma} + \underset{(0.05)}{0.22}\, S^{1-\gamma}\right)^{1/1-\gamma},$$
$$\gamma = -\underset{(0.51)}{0.48}; \; R^2 = 0.70; \; N = 45 \tag{8}$$

where P is absolute poverty, G is the Gini coefficient, and S is secondary education. Once again, linearity cannot be rejected given the insignificant estimate for γ, but the data rather give weak support to the weakest link hypothesis.

6. Discussion and conclusion

We estimated a functional form that allowed a wide range of possibilities about the way in the relative strengths of some underlying determinants of adaptive capacity may or may not be able to compensate for weakness in others. Indeed, all of the possibilities, including perfect complements consistent with a strict interpretation of the "weakest link" hypothesis, perfect substitutes consistent with maximal and perfect compensation, and the "strongest link" in which one underlying indicators determines adaptive capacity largely by itself, could be accommodated.

We investigate six cases. For vulnerability to natural disasters, infant mortality and drinking water treatment, we find that the weakest indicator plays an important role but it is not essential. For life expectancy, sanitation and nutrition, we find a relationship that is close to linear so that the various determinants of adaptive capacity potentially compensate each other (within the range of experience). Although some of best estimates of γ are negative, none is negative and significantly different from zero. We therefore find no empirical support for the strongest link hypothesis, in which one single determinant dominates.

We must emphasize, of course, that we have worked with national data where the very process of aggregation produces some degree of perhaps spurious substitutability across underlying determinants. Adaptive capacity is, of course, really a characteristic of specific systems, and it is possible that we would have noticed stronger evidence about the limits of compensation if we had been able to use more micro data. Still, the list of potentially significant determinants of adaptive capacity included a wide range of economic, social, political and cultural traits: the fraction of people in absolute poverty, the average per capita income, income distribution, literacy rates, enrolment in secondary and tertiary education, democracy, religion, individualism, and uncertainty avoidance. Just as telling, 24 of our initial list of 34 potential determinants did not have a significant effect on our alternative measures of vulnerability.

We find, therefore, that the statistically significant determinants of adaptive capacity are different for the different measures of vulnerability, which suggests strongly that there is no such thing as a general adaptive capacity for all stresses. Rather, the factors from which systems draw to create adaptive capacity is different for different risks. In this conclusion, we add support to Adger and Vincent (2004) who confronted the likely diversity of context by arguing that adaptive capacity essentially describes the adaptation space within which decision-makers in any system (regardless of location or state of development) might find feasible adaptation options. They argued that recognizing diversity makes it easier to anticipate changes in generic adaptive capacity than it is to foresee changes in adaptation, per se. As a result, we and they show how linking the determinants of adaptive capacity to available response (i.e., policy) levers can help to explain why certain responses to fundamentally identical stressors work sometimes in some places, but not at other times in other places.

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