Diversifying to cope with Environmental Change

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Abstract

This paper aims to find informative proxies of vulnerability and adaptive capacity by using synergies between information theory and vulnerability science. In particular this paper looks at diversification as a key characteristic of adaptive capacity and means of coping with an uncertain environment. It explores proxies of adaptive capacity and vulnerability in two examples. Adaptive capacity is expressed as a function of the varying environmental conditions a system or actor is subjected to and the actions a system or actor can take. By associating maximum long-term growth rates with a system that is optimally adapted to its environment this paper builds a bridge between information theoretical metrics and adaptive capacity. For the explored examples, the adaptive capacity of an actor that diversifies is found to be the relative entropy between the actual distribution of the environment and a distribution for which the actor's diversification level would be optimal.

Keywords: vulnerability, adaptive capacity, climate change, formalisation, diversification, information theory.

1 Introduction

Adaptation is increasingly seen as an inevitable answer to the challenges posed by global environmental change (IPCC, 2001). A challenge for actors is to maintain operation under the increasingly uncertain environmental conditions that they are exposed to. Faced with the limits of predicting future environmental conditions, some academics have moved away from trying to design specific adaptation metrics, and are instead focusing on the vulnerability and adaptive capacity of individual communities. This approach has become more common in the climate change literature, where academics have invested considerable energy into defining resilient communities, social capital and adaptive capacity as a way of identifying regions that may be adversely affected by possible future environmental fluctuations (Adger, 2000 & 2006; Carpenter *et al* 2001; Smit *et al* 2000). In many cases, this approach has generated extensive lists of social, economic, political and environmental variables that must be assessed in order to evaluate social capital or identify resilient communities (Berkes and Folke, 1998; Boggs, 2001; Pretty, 2003). Due to the number of variables and the sheer volume of information this approach can obscure the dynamics of vulnerability and is difficult to translate into action or policy (Fraser *et al*, 2005). In a quest for more integral metrics of adaptive capacity and vulnerability, academics have proposed aggregate indicators, facing all the challenges associated with mapping many dimensions onto a limited number of variables (Smit, 2006; Cutter, 2003).

This paper takes another approach in trying to find suitable proxies for vulnerability and adaptive capacity. It starts from one of the key characteristics of complex systems: diversity. Various scientific disciplines (e.g. ecology, economic theory, agricultural science) support diversity and diversification as a means to cope with shocks and stresses, build adaptive capacity (Holling, 2001; Levin *et al*, 1998) and stimulate innovation and learning (Olsson *et al*, 2006; Ostrom, 2005; Frenken, 2004). How much diversity exists in the system is one of the three key characteristics identified by the resilience alliance—a group of ecologists, economists, mathematicians and social scientists—as appropriate to describe vulnerability and adaptive capacity (the other two are the wealth available in the system and how connected the system is) (Gunderson & Holling, 2002). Holland (1995) identifies diversity as one of four basic properties of complex adaptive systems. Managing for sustainability in socio-economic systems means not pushing the system to its limits but maintaining diversity and variability. It also means maintaining and enhancing adaptive capacity. Diversity provides the source for adaptive response (Berkes et al, 2003).

The authors of this paper were struck by analogies between the fundamental challenges in vulnerability science and information theory. Information theory is at the crossroads of many scientific fields including communication theory, statistics, economics, mathematics, and physics. The fundamental metrics that information theory provides—entropy, relative entropy and mutual information—allow the estimation of the costs associated with uncertainty and making incorrect assumptions about a distribution (Cover and Thomas, 1991). Bergstrom and Lachmann (2004) for example establish a close relationship between maximising long term growth rates in an uncertain environment and the information theoretic metrics entropy and mutual information. Parallels can be seen with key challenges in vulnerability science such as assessing the costs associated with exposure to environmental stress that comes unexpectedly or has not been properly accounted for, and assessing the capacity of an actor to learn about its environment and adapt.

This paper aims to find informative proxies for vulnerability and adaptive capacity by using synergies between information theory and vulnerability science. In particular this paper looks at diversification as a key characteristic of adaptive capacity and means of coping with an uncertain environment. Aiming to approach the issue of adaptive capacity from the concept of diversification, this paper will not provide a comprehensive review of adaptive capacity nor of the merits of diversification. Rather it borrows evidence from different disciplines that, when combined, can help understand adaptive capacity in future case studies. The paper seeks to examine diversification not as a magic bullet that is always required, but as an attribute of the system with consequences for the way the system performs. The paper will show that under some conditions diversification improves system performance; under other conditions it decreases it.

This paper has three main components. First the key concepts and requirements for assessing adaptive capacity are introduced. Secondly, simple examples illustrate the proxies of vulnerability and adaptive capacity. Thirdly, extensions of the paper are discussed that could be pursued in future research.

This paper shows for two simple examples that the most favourable level of diversification—and the resulting adaptive capacity—can be expressed as a function of the environmental conditions a system or actor is subjected to and the actions a system can take. The adaptive capacity is approximated by the value of switching to the strategy with the minimum vulnerability. For the explored examples, the adaptive capacity of an actor that diversifies is found to be the relative entropy between the actual distribution of the environment and a distribution for which the actor's diversification level would be optimal.

This paper was written as part of the Santa Fe Institute's 2006 Complex Systems Summer School. It presents the first results of an investigation into synergies between information theory and vulnerability science. By including a relatively long and speculative list of possible future research directions in Section 4 the paper explicitly calls for discussion and feed back from participants of the summer school, researchers at the Santa Fe Institute and other readers.

2 Key concepts and requirements for assessing adaptive capacity

How can adaptive capacity be measured? Numerous definitions of adaptive capacity are found in the literature. It was originally defined in biology to mean an ability to become adapted (i.e., to be able to live and to reproduce) to a certain range of environmental contingencies. More broadly it can be described as the extent to which a system can modify its circumstances to move to a less vulnerable condition (Smit and Wandel, 2006; Gallopín, 2006). In talking about vulnerability, this paper borrows from the vulnerability framework proposed by Ionescu *et al* (2005): an actor (or system) in a particular state is *vulnerable* to an environment e if the well-being of the actor has decreased after its interaction with the environment. Thus vulnerability is seen as a relative concept and statements about vulnerability require one to specify (i) the actor that is vulnerable and the state it is in, including the actions it has taken or can take to reduce vulnerability, (ii) the environment e to which it is vulnerable and (iii) the well-being criteria to evaluate the outcome of the interaction of the actor and the environment.

Many factors determine a system's ability to modify its vulnerable conditions. The Intergovernmental Panel on Climate Change (IPCC) identified eight determinants of adaptive capacity including available technology, the structure of institutions, human capital such as education, and access to risk spreading processes (IPCC, 2001). The capacity to adapt is distinct from adaptations that a system has made in the past to accommodate disturbing forces (Luers, 2003). Prior adaptations are captured in the current sensitivity of the actor. For example, a farmer may have adapted to drought over the years by shifting management practices, such as using drip irrigation and taking measures to increase soil quality for water retention. This adaptation may lead the farmer to be less sensitive to drought. This same farmer, however, may also have the potential to shift to more drought resistant crops or dig groundwater wells to further decrease its sensitivity to drought over the long run. We refer to this potential as "adaptive capacity". Once the potential to adapt has been fully realized it becomes part of the system's normal functioning and is manifested as a decrease in sensitivity and a corresponding decrease in the vulnerability.

Following Luers (2003) this paper quantifies adaptive capacity AC as the difference in the vulnerability V under existing conditions and under the less vulnerable condition to which the system could potentially shift:

$$AC = V(\text{existing conditions}) - V(\text{modified conditions}) \qquad (1.)$$

It has been recognized that vulnerability studies that include adaptive capacity directly in a vulnerability characterization are actually characterizing what can be referred to as the minimum potential vulnerability, which has to be distinguished from the existing vulnerability (Luers, 2003). This distinction between the minimum potential vulnerability and the existing vulnerability is important both conceptually and practically. For example, consider two farmers who are faced with drought and whose conditions are identical except that one has access to an alternative crop type and the other does not. One farmer may have a greater adaptive capacity and thus a lower potential vulnerability because of its access to the alternative crop. However, if the farmer does not use the other crop then both farmers are equally vulnerable. The alternative crop only provides the potential for lowering the farmer's vulnerability.

Introducing this notion of minimum potential vulnerability (V_{min}) in Equation 1 yields:

$$AC = V - V_{min} \tag{2.}$$

Various criteria have been identified that a metric of vulnerability and adaptive capacity should satisfy (Adger, 2006; Gallopín, 2006; Ionescu, 2005 and Smit, 2006), including:

1. Specify the actor or system that is vulnerable, the environment it is vulnerable to (a combination of sensitivity and adaptive capacity or ability to cope) and a preference criterion to evaluate the interaction of actor and environment
2. Capture relative vulnerability and severity in its distribution
3. Account for temporal dynamics of risk, including whether vulnerability is temporal or chronic and what are the risks of falling into vulnerability
4. Account for the distribution of vulnerability in a system or among actors
5. Include a threshold of risk, danger or harm
6. Allow at least for one of three assessments: i) rating and ranking of vulnerable actors and/or systems ii) identification of process and drivers of vulnerability, iii) support policy and decision making about the conditions that can alter vulnerability or adaptive capacity

Considering these criteria and following Eq. 1 and 2, this paper approximates the adaptive capacity of an actor in interaction with its environment as the difference between (i) the actor's well-being given all the actions it has taken so far to reduce vulnerability, and (ii) the actor's potential well-being if it took all its actions possible to reduce vulnerability. The challenge is to find an appropriate proxy for the well-being function. The next section explores proxies of well-being, adaptive capacity and vulnerability in two examples. It focuses on when and how diversification of activities supports the adaptive capacity of an actor to cope with a varying environment. The authors acknowledge that adaptive capacity has more dimensions than diversification alone. Ways to improve and extend the examples in the next section are discussed in Section 4.

3 Examples

This section illustrates the definition of adaptive capacity in the previous section by elaborating two examples.

3.1 Example 1: an environment fluctuating between two conditions with uniquely matching activities

Consider a simple example of actors living in a variable environment (after Bergstrom and Lachmann, 2006). The state of the environment in each year is an independent random variable e with two states e_1 and e_2 that occur with probability p and $1 - p$ respectively. This corresponds to, for example, collapsing environmental conditions into a 'normal' & 'dry' year. At the beginning of each year each actor has two alternative activities a_1 and a_2 to choose from, suited to environments e_1 and e_2 respectively. For example, the actor can choose between a 'normal' and a 'drought resistant' cropping pattern. An actor selects activities a_1 and a_2 with probability x and (1-x) respectively. All activities and actors are subjected to the same environment in a given year, and an actor is only deemed successful if its activities are suited for that environment. The performance of an activity under each environment is given by the following matrix:

	Activity a_1	Activity a_2
Environment e_1	R_1	0
Environment e_2	0	R_2

How can the effect of the uncertainty of the environment on the actor be measured? Examples from business and biology show that the value of information about the environment can usefully be measured in terms of the consequences on the long-term growth rate of the actor's success. Success can for example be the number of offspring or the return on investment. What these examples have in common is that in both cases the successes combine multiplicatively; the long-term success is measured by the *product* of the successes at individual time steps, rather than their sum. Maximising long-term growth conditions in such cases is the same as maximising the expected value of the logarithm of the success in a single generation (as opposed to the expected value of its success itself) (Lewontin and Cohen, 1969).

This is illustrated for the example introduced above. What can actors decide in the absence of information about the condition of the environment? In the short run, actors maximize expected performance by employing the highest-payoff activity only. This yields an expected single-generation performance of MAX[$p\,r_1$, $(1-p)r_2$]. But in the long run, reinvesting in only one activity will inevitably lead to a year with zero performance and consequent failure (for example bankruptcy). Thus selection between actors will favour not the short run maximization above, but rather a maximization of long-term performance.

The expected long-term success of an actor that reinvests in activity a_1 with probability x over a sequence of N events, in which environment e_1 occurs Np times and environment 2 occurs $N(1-p)$ times, will be: $\left(r_1 x\right)^{Np}\left(r_2(1-x)\right)^{N(1-p)}$. Since log is a monotonically increasing function, this long-term success will be maximized when the expected log growth rate $G(x \mid p) = p\log\left(r_1 x\right) + (1-p)\log\left(r_2(1-x)\right)$ is maximized. This occurs when $x = p$. Thus for almost all sequences of environments, an actor that chooses activity a_1 with probability p will maximize its growth rate.

To find proxies for adaptive capacity and vulnerability to the current climate this paper (i) associates maximum long term growth rates with a system that is optimally[1] adapted to its environment, and (ii) approximates an actor's vulnerability as the difference between its optimal expected log growth rate without environmental stress and the expected log growth rate under its current activities in the current environment. This yields the following proxies:

$$V(x \mid p) = G\left(1|1\right) - G\left(x|p\right) = \begin{cases} \log r_1 - p\log\left(r_1 x\right) - (1-p)\log\left(r_2(1-x)\right) & \text{for } 0 < x < 1 \\ \infty & \text{for } x \in \{0,1\} \end{cases} \tag{3.}$$

$$\begin{aligned} V_{min} &= V(x^* \mid p) = G(1 \mid 1) - G(x^* \mid p) = \log r_1 - p\log\left(r_1 p\right) - (1-p)\log\left(r_2(1-p)\right) \\ &= -p\log p - (1-p)\log(1-p) + (1-p)\log\frac{r_1}{r_2} \end{aligned} \tag{4.}$$

$$AC\left(x|p\right) = V(x \mid p) - V_{min} = \begin{cases} p\log\left(\dfrac{p}{x}\right) + (1-p)\log\left(\dfrac{1-p}{1-x}\right) & \text{for } 0 < x < 1 \\ \infty & \text{for } x \in \{0,1\} \end{cases} \tag{5.}$$

In Equations 3, 4 and 5 a number of typical metrics from information theory can be recognised. When $r_1 = r_2$, V_{min} is the entropy of the environment H(E). The adaptive capacity AC (or the value of switching to the optimal strategy) is the exactly the relative entropy between the distribution of the environment and the current distribution over activities, or D(p| |x). That is, the adaptive capacity can be seen as a measure of the difference between the actor's current distribution of activities, x, and the ideal distribution of activities, $x^* = p$.

Figure 1 illustrates vulnerability and adaptive capacity of an actor that undertakes activity a_1 with a probability of 0.8, where $r_1 = 1$ and $r_2 = 0.7$. Note that the AC is zero when $x = p$. At this combination of possible activities the expected growth rate is maximized and no further reduction of vulnerability can be achieved with the activities available to the actor. Furthermore AC is independent of r_1 and r_2, since the reduction of vulnerability that an actor can achieve by changing its current practise x to $x = p$ depends only on x and p.

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[1] Explicitly addressing uncertainty, this approach goes beyond traditional optimisation techniques. The authors use the word 'optimal' for its simplicity. They are aware of critique on optimisation and the maximum sustainable yield concept (Anderies, 2006).

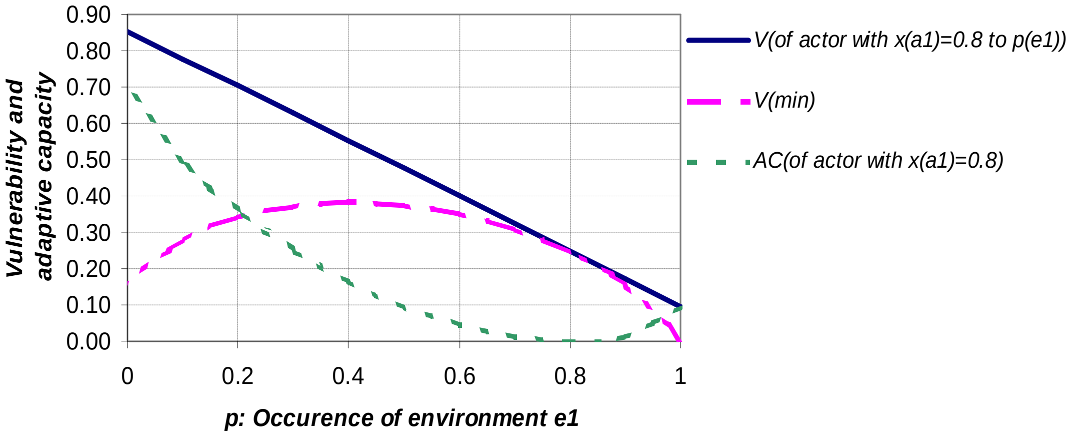

Figure 1: Vulnerability and adaptive capacity of an actor in Example 1

The practical implications of this example are that in the absence of any mechanism to overcome disastrous events, actors are forced to diversify. Unlike the maximum of the expected long-term growth rate, the maximum expected performance in a single generation depends on r_1 and r_2. Thus adaptation to a changing environment can come at the costs of mean performance. This situation is reported in developing countries where rural and urban households engage in a variety of activities, some with low risks but also low mean returns. Risks are spread, with activities skewed to produce more reliability, at the expense of mean returns. A key issue is that diversified or low risk sets of activities, while offering lower overall risks, can come at the expense of lower mean returns, compared to more profitable but more risky activities. This may well mean that households have to choose to be relatively poor to avoid even more serious hardship and destitution induced by shocks. This is one mechanism through which risk may be a cause of poverty (Dercon, 2005a&b).

In this example the performance of an actor is zero when the wrong activity is chosen for the occurring environment. A more common example would allow for a partial loss in performance when the activity is performed under less favourable environmental conditions. This case will be explored in the next example.

3.2 Example 2: an environment fluctuating between two conditions with inversely impacted activities

The second example features a two-environment, two-activity case where the performance of the activities is non-zero. The performance of an activity is given by the following matrix:

	Activity a_1	Activity a_2
Environment e_1	1	R_1
Environment e_2	R_2	1

If an actor invests x in activity a_1 and (1-x) in activity a_2, its expected log growth rate is $G(x\,|\,p) = p\log\left[x + r_1(1-x)\right] + (1-p)\log\left[r_2 x + (1-x)\right]$. In the absence of information about which environmental state occurs, the choice of x that maximizes the expected log growth given the probability p of environment 1 is:

$$x^*(p) = \begin{cases} 0 & \text{for } p \le r_1 c \\ \dfrac{(p/c) - r_1}{1 - r_1} & \text{for } r_1 c < p < c \text{, where } c = \dfrac{1-r_2}{1-r_1 r_2}. \\ 1 & \text{for } p \ge c \end{cases} \qquad (6.)$$

Equation 6 shows that diversification makes sense only in a central region. Beyond that region, the optimal mix of activities a_1 and a_2 would require the actor to do one of the activities with negative probability. This sort of investment may be feasible in a stock market, but in general a negative probability of undertaking an activity lacks meaning. Equation 6 constrains $x^*(p)$ therefore to values between 0 and 1.

Note that using (6.) to determine x requires information about the probability p of environment e_1. In the absence of this information an actor could aim for the most stable growth rate. The log growth rate is independent of p when $x + r_1(1-x) = r_2 x + (1-x)$ and thus for x:

$$x = \frac{1 - r_1}{2 - r_1 - r_2} \qquad (7.)$$

In this situation the actor would always diversify. Though its growth rate would be perfectly stable, it would be below the maximum expected growth rate for $x^*(p)$ in Eq 6.

Since the expected log growth rate $G(1\,|\,1)$ in this example is 0, when there is no uncertainty in the environment the vulnerability of the strategy x under the environmental distribution p is minus the expected log growth rate:

$$V(x\,|\,p) = -G(x\,|\,p) = -p\log\big(x + r_1(1-x)\big) - (1-p)\log\big(r_2 x + (1-x)\big) \qquad (8.)$$

Substituting in the formula for the optimal strategy $x^*(p)$ given in Eq. 6, the minimum vulnerability for this example can be expressed as:

$$V_{\min} = V(x^*\,|\,p) = \begin{cases} -p\log(r_1) & \text{for } p \le r_1 c \\ -p\log p - (1-p)\log(1-p) + (1-p)\log\left(\dfrac{1-r_1}{1-r_2}\right) - \log c & \text{for } r_1 c < p < c \\ -(1-p)\log(r_2) & \text{for } p \ge c \end{cases} \qquad (9.)$$

An understanding of information theory can help to interpret this equation. In the central region, where the actor would do best to diversify, the minimum vulnerability is the sum of the entropy of the environment H(E) and a linear function of the environmental probability p. This means that, like the entropy, the minimum vulnerability is a concave function with an internal maximum. Outside the central region, when the optimal strategy invests in only one of the activities, the vulnerability is simply a linear function of p (see Figure 2 for an example.)

Finally, combining equations 8 and 9, the adaptive capacity over three different regions of p is given by:

$$AC(x\,|\,p) = \begin{cases} -p\log\left(\dfrac{x}{r_1} + (1-x)\right) - (1-p)\log\big(r_2 x + (1-x)\big) & \text{for } p \le r_1 c \\ p\log\left(\dfrac{p}{c\big(x + r_1(1-x)\big)}\right) + (1-p)\log\left(\dfrac{1-p}{1 - c\big(x + r_1(1-x)\big)}\right) & \text{for } r_1 c < p < c \\ -p\log\big(x + r_1(1-x)\big) - (1-p)\log\left(x + \dfrac{1}{r_2}(1-x)\right) & \text{for } p \ge c \end{cases} \qquad (10.)$$

In the central region, where the optimal strategy is to diversify, the adaptive capacity can again be expressed as a relative entropy:

$$AC(x\,|\,p) = D\big(p\|q\big), \text{ where } q = c\big(x + r_1(1-x)\big).$$

Notice that q is a linear function of x ranging from r_1c, when x is 0, to c, when x is 1. This result can be understood by realising that the adaptive capacity can be seen as the value of knowing the distribution p and adjusting x accordingly. The relative entropy is a measure of the costs of choosing x according to an assumed distribution q, when the real distribution of the environment is p.

The practical application of the above example is illustrated by the following case. Farmers in Southern Europe are confronted with increasingly dry summers. During the heat wave in 2003, many southern European countries suffered drops in yield of up to 30 % (EEA, 2004). Farmers consider growing more drought resistant crops. To assess when alternative crop types become viable, we simplify this case by distinguishing between two distinct climatic conditions: e_1, the normal conditions, and e_2, the dry summer conditions. Farmers can decide on two activities: a_1, growing normal crops, and a_2, growing drought resistant crops. The performance of farming is estimated as follows:

	Normal crops	Drought resistant crops
Normal conditions	1	0.7
Dry summer conditions	0.75	1

Table 1 summarises vulnerability and adaptive capacity to the current climate for the above case. Following the above example, the well-being function of the farmer is approximated with the long-term growth rate when the results of last year's crops are fully reinvested. Thus competition between farmers either for space, water or other growth limiting factors is neglected. The fraction of normal to drought resistant crops that produces the maximum long-term growth in crop yield for a known probability of e_1 can be estimated with (Eq. 6). Growing only normal crops remains the best option as long as normal conditions prevail 53 percent of the time or more. When on the other hand 63 percent of the summers are dry, drought resistant crops give a more reliable yield. For drought conditions occurring between 47 and 63 percent of the time, diversification reduces fluctuations in crop performance due to the varying climate.

$x(p)$: fraction of normal crops	For $p(e_1)$	$p(e_1)$	$x(p)$ using Eq.6	Vulnerability of growing normal crops	V_{min}, taking full advantage of knowing p	Adaptive capacity
0	$p(e_1) \leq 0.37$	1	1	0	0	0
		0.6	1	0.050	0.050	0
$6.33p - 2.33$	$0.37 \leq p(e_1) \leq 0.53$	0.5	0.83	0.063	0.062	0.001
		0.4.	0.2	0.075	0.061	0.014
1	$p(e_1) \geq 0.53$	0	0	0.125	0	0.125

Table 1: Vulnerability and adaptive capacity of a farmer that chooses between two crop types

Figure 2 illustrates vulnerability and adaptive capacity of an actor that is growing *normal crops* at present for different values of p, the probability of occurrence of *normal years*.

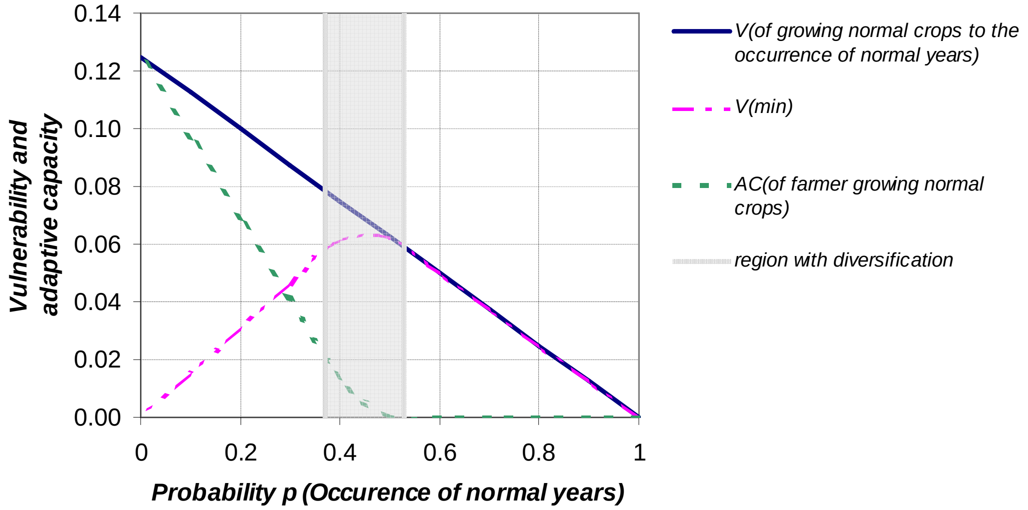

Figure 2: Vulnerability and adaptive capacity of an actor in Example 2

It is recalled that the above case considers the highly simplified situation of an actor with access to only two possible activities, which are is subjected to environmental conditions that fluctuate between two distinct states. Actors in general have more activities to choose between and a more detailed representation of the environmental conditions may be desired. Extension of the example above to n environments and activities will be attempted in future work. In general, however, an analytic solution cannot be found except for simple performance matrices, like the one used in the first example.

4 Discussion & potential extensions

This section first discusses the strength and limitations of the concepts and proxies arrived in the examples presented above. Next it lists possible extensions of the paper to be pursued in future research.

The main strength of the proxies presented is that they explicitly look at the interaction of socio economic activities and the environment. This interaction is often identified as determining vulnerability (Adger, 2006). The proxies support the assessment of the preferred level of diversification of activities under varying environmental conditions. Looking at the criteria in Section 2, the proxies at least partly satisfy five out of the six criteria. The proxies are specific for an actor, its actions and the environment. The preference criterion used is the long-term growth rate (criterion 1). The proxies can be used to compare vulnerability and adaptive capacity between actors, though the long-term growth rate does not cover all aspects of well-being and will therefore not cover all vulnerability aspects (criterion 2 and 4). The proxies account for the temporal dynamics of risk, but are less suitable for distinguishing between temporal and chronic vulnerability (criterion 3). In the interpretation of vulnerability given by Equations 8 and 9, V and V_{min} are defined relative to the situation where there is no environmental stress and the actor is appropriately adapted. Thus any stress (through a loss of log growth rate) adds to the vulnerability. This interpretation could be changed to include a threshold beyond which an actor is considered vulnerable (criterion 5). The proxies allow for the rating and ranking of vulnerable actors and/or systems. They are particularly suitable to study diversification as one of the process underlying vulnerability. The examples show they can inform decision-making about the appropriate level of diversification to alter vulnerability and adaptive capacity (criterion 6).

Limitation of the proxies discussed include:

- Activities need to have similar timescales
- Assumes that the performance of activities under different environments is independent and memory free
- There is no competition between actors over resources and the performance of each activity is linearly dependent on the investment in it
- Contributions to vulnerability and adaptive capacity other than diversification (e.g. network structure, wealth and social learning) are neglected in the examples
- Though explicitly addressing uncertainty and robustness in a varying environment, the approach may face some of the difficulties associated with optimisation techniques and the maximum sustainable yield concept (Anderies, 2006)

The authors recall that the paper in its current state reports on first results following the Santa Fe Institute's Summer School. It explicitly aims to stimulate discussion. Possible extensions of the paper to be pursued in future research are:

- Diversity can be achieved and maintained by two fundamentally different strategies: stochastic switching and learning, or responsive switching. The costs associated with the latter are higher than with the former. The optimal strategy and switching rates depend on the statistics of environmental change. The greater the uncertainty of the environment, and the faster the responsive actor responds, the more beneficial is learning. The longer environments remain constant, however, the less it pays to learn about the environment. Stochastic switching is therefore favoured when environments change infrequently (Kussell and Leibler, 2006). This notion relates to the *value of information* that decision theorists and behavioural biologists use to measure the costs of uncertainty about the environment. Bergstrom and Lachmann (2006, 2004) have shown that under conditions where diversification is advantageous and with observations that convey little information about the environment, the value of information associated with the observation is exactly the mutual information between the observation and the environment. These results allow biological fitness and information theoretical metrics as entropy and mutual information to be related to the concept of adaptive capacity. It would help understand how and when adaptive capacity can be increased by learning about the environment and when by random diversification. Well-established in information theory, these considerations would be a natural extension of the examples presented in this paper.
- Use an agent based model to explore under what rules agents learn about the environment and employ their full adaptive capacity to deal with a changing environment, given a set of possible activities. That is: which individual-based rules would allow the agents to take full advantage of the theoretical benefits of diversification and bet hedging in a changing environment. Possibly rules could be defined and tested following the work of Holland (1995).
- The proxies suggest means of achieving the ultimate limits of vulnerability and adaptive capacity. However the theoretically optimal limits—beautiful as they are—may turn out to be computationally and/or experimentally impractical. Nevertheless it is because of the computational feasibility of simple cases that we use them (after Cover and Thomas, 1991). The proxies may be expanded by new insights from network information theory, focussing on networks of many communicating agents and multiple environmental stresses.
- Management consideration: treat the environment as a portfolio of resources and services rather than commodities that can be sequentially exploited or conditions that has to be brought under control (Berkes et al, 2003). Compare to proxies in this paper to proxies derived from using portfolio theory (Aerts and Werners (in prep), Aerts *et al* (in review)).

- Distinguish between functional diversification—the existence of different functional groups of actors (e.g. farmers and tourist operators)—and response diversification—variability in the response of actors within one functional group (e.g. farmers growing different crops)—in assessing adaptive capacity. This would be particularly interesting in relation to the social and institutional structure of actor networks. For example are benefit sharing mechanisms in place that allow actors to specialise in one activity and take advantage of the potential benefits of diversification without having to diversify individually (link to work Ostrom, 2005).
- Diversity could also be seen as memory about the current variation in the environment. To innovate, renew and adapt to new environmental conditions there has to be a balance between change and memory, and between disturbance and diversity. A parallel may be sought to the strategy of exploitation vs. exploration, typically found in human and animal problem solving (feed-back summer school participant Tamás Makany, literature computational neuroscience).
- Application in case studies in water management in particular. Rationale: The relationship between diversity and the ability to cope with uncertain stresses has been a neglected research area in river basin management. For a long time river basin management has focussed on selecting the most cost effective measure to cope with a specific quantified stress. The underlying structure of how diverse water system services and their users interact with the full range of the natural disturbances regime has been addressed only rarely. The relationship of diversification and adaptive capacity remains largely unexplored. This may require the extension of the examples above to the interaction of *n* environments and activities.

5 Conclusions

This paper shows for two simple examples that the most favourable level of diversification—and the resulting adaptive capacity—can be expressed as an information theoretic function of the environmental conditions a system or actor is subjected to, and the values of the actions an actor can take. The adaptive capacity is defined as the value of switching to the strategy with the minimum vulnerability, where the value (inspired by examples from economics and biology) is measured in terms of the long-term growth rate. The adaptive capacity of an actor that should diversify to cope with its environmental conditions is found, in the cases examined, to be the relative entropy between the actual distribution of environments, and the distribution of environments for which the current level of activities would be optimal. In a continuation of this work, the authors hope to generalize this result and apply it to case study data.

6 Acknowledgement

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