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The surface of vulnerability: An analytical framework for examining environmental change

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Abstract

This paper introduces an analytical framework for evaluating the vulnerability of people and places to environmental and social forces. The framework represents the relative vulnerability of a variable of concern (e.g. such as agricultural yield) to a set of disturbing forces (e.g. climate change, market fluctuations) by a position on a three-dimensional analytical surface, where vulnerability is defined as a function of sensitivity, exposure, and the state relative to a threshold of damage. The surface is presented as a tool to help identify relative vulnerability in order to prioritize actions and assess the vulnerability implications of management and policy decisions.

Keywords: Vulnerability; Resilience; Environmental assessment; Indicators

1. Introduction

Numerous conceptual frameworks have been proposed for examining the causal structure of the vulnerability of people and places to environmental and social forces (e.g. Watts and Bohle, 1993; Bohle, 2001; Kasperson et al., 2003; Turner et al., 2003a; Adger et al., 2001). These various frameworks help to characterize the multiple dimensions of vulnerability, however, they are often difficult to apply to policy analysis and decision making because they provide limited assistance for identifying relative vulnerability in specific locations to prioritize actions.

In this paper, I propose an analytical framework for evaluating relative vulnerability that is not intended to replace the richness of the existing conceptual frameworks or explain vulnerability, but rather to help link existing conceptual frameworks to vulnerability assessments in practice. The framework is proposed as a tool to help organize information and sort through complexity in a manner that specifically seeks to address two challenges in vulnerability management: (1) identifying relative vulnerability in order to prioritize actions and (2) assessing the vulnerability implications of management and policy decisions.

The proposed approach builds on a method presented in a previous study (Luers et al., 2003). In this previous analysis, we estimated vulnerability as the expected value of the ratio of sensitivity to the state relative to a threshold based on the frequency distribution of the stressors of concern. While this approach provides a systematic method of identifying vulnerability in certain systems, it is limited in its application to those systems in which the critical social and ecological processes can be described mathematically in some detail. Unfortunately, there are many systems of concern that cannot be easily described by simple mathematical equations. The framework I propose in this paper seeks to expand the general form of this previous approach to guide vulnerability assessments in a greater diversity of settings.

This paper is organized into four sections. In Section 1, I briefly discuss the opportunities and constraints of

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different approaches to vulnerability assessment. In Section 2, I define a vulnerability surface as a function of sensitivity, exposure, and the state of the system relative to a threshold of damage. In Section 3, drawing on Luers et al. (2003) analysis of the agricultural zone in the Yaqui Valley, I illustrate how the surface can provide an organizing framework for analyzing the multiple dimensions of vulnerability. Finally, I conclude with a summary and a brief discussion of the implications of this analysis for future research and practice.

2. Vulnerability assessments

The primary objective of vulnerability assessments is to identify people or places that are most susceptible to harm and to identify vulnerability-reducing actions (Stephen and Downing, 2001; Downing et al., 2001; Clark et al., 2000; Polsky et al., 2003). In this section, I briefly examine different conceptual frameworks and discuss some of the challenges of translating these concepts into analytical tools to help reduce vulnerable conditions.

2.1. Conceptualizing vulnerability

Although there is considerable diversity in existing theories, vulnerability is generally defined as the susceptibility to damage, and is often characterized in terms of one or more of the following: the sensitivity to or exposure of a system (people or place) to shocks, stresses or disturbances, the state of the system relative to a threshold of damage, and the system's ability to adapt to changing conditions (e.g. Luers et al., 2003; IPCC, 2001; Turner et al., 2003a, b; Smit and Pilifosova, 2002; Dowing, 2001; Mitchell et al., 1989; Chambers, 1989). The terms "shocks," "disturbances," "stresses" and "perturbations" are often used to refer to exogenous forces that have the potential of creating an adverse impact (e.g. Kelly and Adger, 2000; Turner et al., 2003a, b; Chambers, 1989; Bohle et al., 1994). A force is seen to be "exogenous" if its occurrence is beyond the power of the unit of analysis such as the individual or household (Kelly and Adger, 2000). These forces include phenomena such as climate variability and change, floods, hurricanes and market fluctuations.

Typically, these exogenous forces are the only "stresses" explicitly considered in vulnerability studies, however, social and ecological systems are subjected to a wide range of endogenous forces that can also stress a system and make it more vulnerable to collapse. For example, poor land-management practices can stress a system and increase its sensitivity to exogenous forces such as hurricanes (e.g. Scheffer et al., 2001; Holt-Gimenez, 2000). Endogenous stresses are generally incorporated implicitly in vulnerability analysis as sensitivity. In this paper, I take a similar approach, however, I emphasize the dynamic nature of the sensitivity term as the manifestation in large part of the endogenous forces.

These concepts or vulnerability characteristics (i.e. sensitivity, exposure, adaptive capacity) are not new. They have emerged from the risk-hazards and food security literature, and over the last decade have been expanded and integrated into the discourse of the global environmental change research community (Kasperson et al., in press).

Several conceptual frameworks have been proposed that incorporate these concepts to describe the general processes that lead to vulnerable people and places (e.g. Blaikie et al., 1994; Bohle et al., 1994; Turner et al., 2003b). For example, in the pressure-and-release framework (PAR) (Blaikie et al., 1994) vulnerability is defined as a system's ability to respond and recover from stresses, a system's sensitivity and adaptive capacity. Another common framework for characterizing vulnerability is what is known as the "social space" of vulnerability (Bohle et al., 1994), which highlights the processes of human ecology, entitlements and political economy as those that govern the conditions that determine the risk exposure, coping capacity and recovery potentiality. More recently, Turner et al. (2003a) proposed the SUST framework as a guide to the broad processes and feedbacks within the human–environmental system that defines the sensitivity, exposure and resilience, and lead to the vulnerability of a system.

2.2. Analyzing vulnerability

The basic concepts presented in the frameworks described above have been explored in a variety of case studies that seek to characterize the vulnerability of specific populations or places (e.g. Smit and Pilifosova, 2002; Downing et al., 2001; Adger, 2000; Turner et al., 2003b; O'Brien and Liechenko, 2000; Moss et al., 2000). While such case studies have contributed valuable insight into a range of processes that may lead to vulnerable conditions, they often present only general conceptual findings that can be difficult to translate into policy or management decisions in specific locations.

The complexity of social and ecological systems often makes it difficult to identify relative vulnerability of specific people and places in practice in a manner that provides relevant information to decision makers. This issue becomes particularly challenging in regional and national assessments (e.g. Moss et al., 2002; Kaly, 2002; Briguglio, 1995; Cutter et al., 2000) that focus on evaluating the vulnerability of people or places to a single stress or a set of multiple stresses, without explicitly stating which characteristics of the people and places may be vulnerable. For example, the South

Pacific Applied Geosciences Commission (SOPAC) developed an environmental vulnerability index (EVI), which is a composite of 54 independent variables selected to represent three characteristics of vulnerability–degradation, resilience, exposure (Kaly, 2002; Briguglio, 1995). Examples of variables included for each of these characteristics are greatest average deviation in sea surface temperature in the last 5 years (exposure), undeveloped land area (resilience) and number of endangered species per land area (degradation). While all of these are likely to be important characteristics to consider, the ambiguity in what exactly is being assessed as "vulnerable" make the results difficult to analyze and to act upon.

Other studies are narrower in focus and highlight the need for vulnerability assessments to be "outcome-based." For example, much of the food security literature on vulnerability argues that assessments should be approached as vulnerability to hunger rather than vulnerability to drought (e.g. Downing, 1991; Ribot, 1995). This outcome-based approach focuses on examining the multiple causes of a single outcome. In this paper, I argue that vulnerability assessments should take the outcome-based approach a step further by focusing on assessing the susceptibility of specific variables (e.g. food supply, income) of concern, which are believed to characterize the well being of a specific people or place, to a specific damage (e.g. hunger). This more focused approach, which has been illustrated in various studies (e.g. Luers et al., 2003; Peterson, 2002; Schimmelpfennig and Yohe, 1999), in many cases may provide more policy-relevant results.

3. A surface of vulnerability

I conceptualize vulnerability as a vector, where relative vulnerability is represented by a position on a three-dimensional surface. I define the surface based on a generic vulnerability function, which I derive by translating a general definition of vulnerability, the susceptibility to damage, into a mathematical expression (Luers et al., 2003). To do this I first define a threshold of damage and then represent susceptibility in terms of its sensitivity and exposure to exogenous disturbing forces and its state relative to a threshold of damage:

$$\text{Vulnerability} = f\left[\frac{(\text{Sensitivity, Exposure})}{\text{State/Threshold}}\right]. \quad (1)$$

Vulnerability expressed in this form is proportional to sensitivity and exposure and inversely proportional to the state of the system relative to a threshold of damage. While the specific functional form will vary by context and location, the general relationship between the components of the equation is likely to characterize vulnerability broadly. The goal here is not to simply define a quantifiable measure, but rather to represent a relationship in a standard form that can be used as a tool to help sort through the complexity of vulnerability analysis.

3.1. Surface dimensions

Fig. 1a illustrates a three-dimensional surface where vulnerability is determined simply as a measure of sensitivity and exposure divided by a measure of the state relative to a threshold of damage. This is the simplest representation of the functional form presented in Eq. (1). Fig. 1b is the two-dimensional representation of the surface. It is interpreted similar to a topographic map of a landscape. The contour lines of the surface are lines of equal vulnerability and are defined by the variables on each of the other coordinate axis. Below I discuss each of the dimensions of the surface.

3.1.1. Dimension one: sensitivity and exposure

I refer here to sensitivity and exposure to exogenous forces and incorporate endogenous stresses as those

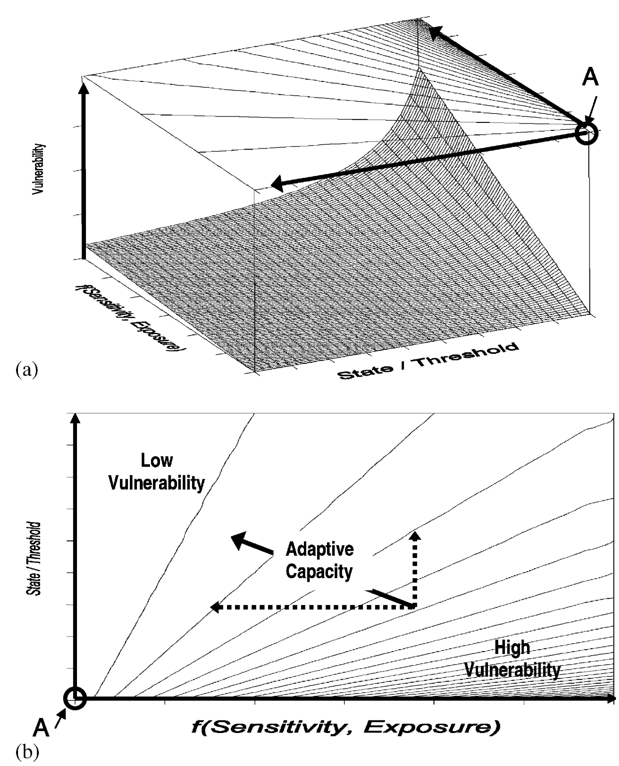

Fig. 1. Vulnerability surface: (A) A perspective view of the three-dimensional surface of vulnerability. The top plane is the two dimensional representation of the same topographic surface represented by contour lines of equal vulnerability. (B) The two-dimensional representation of the vulnerability surface shown above rotated so that point A shown on each figure represents the origin. Adaptive capacity is shown as the potential to shift a system's position on the surface to a lower vulnerability either by decreasing sensitivity or exposure or increasing the state relative to threshold.

internal processes that contribute to changes in one or more of the vulnerability characteristics and in particular to sensitivity. I define sensitivity as the degree to which a system will respond to an external disturbing force. It includes the ability to resist change and the ability to return to a previous condition after a stress has been removed. Exposure refers here to the characteristics of forces that could stress the system (e.g. temperature) such as magnitude and frequency.

In this framework I represent sensitivity and exposure as inherently linked. Characterizing exposure without characterizing sensitivity (and vice versa) provides little insight into the relative vulnerabilities of two systems because the relative effect of exposure on a system is dependent on the relative sensitivities. For example, if we compared two agricultural districts that grew the same crops and had similar climates, the exposure of each district to climate variability might be similar; yet, differences in sensitivity between the districts might be large. If one system relied on irrigation it would have low sensitivity to short-term precipitation variability where a rain-fed system would have greater sensitivity to the same exposure.

Characterizing the sensitivity term for a specific population or place will depend on the characteristic of the disturbing force and the time frame of analysis. Over the short term (relative to the responsiveness of the system being studied), the sensitivity of the system under current conditions or to gradual disturbing forces and to discrete disturbances might be represented simply by the system's ability (or lack of ability) to resist change. Over the longer term in the case of the discrete disturbance, where an exogenous stress is applied and then removed (e.g. a flood), the sensitivity will be a function not only of its resistance to change but also of its ability to "bounce back." This bouncing back is not relevant in the continuous stress situation because the stress is never removed. However, in the case of the continuous disturbing force the sensitivity of the system might change as a result of adjusts made to adapt to the changing conditions. In reality, decision makers are not confronted simply with these two extremes but with a continuum from discrete to continuous stresses.

There are a variety of measures of sensitivity and exposure that might be used to characterize a system. For example, a linked measure of sensitivity and exposure for agricultural yield might combine exposure to climate, represented as the frequency distribution of temperature and sensitivity, represented as the change in yield per unit change in temperature. These could be combined as an integral of the change in yield multiplied by the temperature and weighted by the frequency of a given temperature (e.g. Luers et al., 2003). In the example below, I represent the linked sensitivity and exposure of white field as the coefficient of variation (CV) of yield.

3.1.2. Dimension two: state relative to a threshold

Defining the vulnerability of a system requires identifying a threshold (or reference point) above or below which the system is said to be "damaged." The state of the system relative to the defined threshold of damage provides a relative representation of the condition of the system, such as the level of degradation of an ecosystem or the average income level relative to a poverty line. The threshold is a subjective measure that is likely to vary with different systems and the variable of concerns. It is also likely to be time-scale dependent. For example, we might be less concerned if a household drops below a poverty line in any given year then if a household drops below a poverty line multiple times over a given time period.

3.1.3. Dimension three: vulnerability

As illustrated in Fig. 1a, vulnerability as represented here is a non-linear function. At a high state relative to the threshold and a low sensitivity the surface remains relatively flat, indicating small changes in vulnerability result from small changes in either of the other two dimensions. However, at low levels of the state relative to the threshold and high sensitivity, small changes in either of these dimensions will result in large changes in vulnerability. As discussed in more detail below, this general pattern seems to be consistent with patterns that have been documented in nature where a system, such as a lake or coral reef, is stressed leading to gradual increases in vulnerability until a point when the system collapses as a result of relatively low magnitude disturbing forces (Scheffer et al., 2001; Carpenter et al., 1999).

3.2. Dynamic vulnerability

The position on the vulnerability surface is not fixed. Vulnerability is a dynamic quality that can be altered suddenly or gradually by changes in the social and biophysical conditions (Adger and Kelly, 1999; Leichenko and O'Brien, 2002). As a result, effectively managing vulnerability requires conducting assessments not only as periodic snap shots in time, but as an ongoing process that includes the monitoring of underlying conditions and evaluations of decisions that may lead to incremental changes in vulnerability over different spatial and temporal scales.

One of the biggest challenges in analyzing dynamic vulnerability is capturing the evolution of a system's sensitivity, the effects of which are often not immediately apparent. Ecologists have highlighted this challenge through studies that suggest gradual changes in critical variables, which determine the sensitivity and resilience of a range of ecosystem types, can lead to increased vulnerability to stochastic events such as hurricanes that result in sudden shifts to alternative and potentially less desirable states (e.g. Scheffer et al., 2001; Folke et al., 2002). These studies point to the need for decision makers to expand their focus to include not only the ‘‘fast-changing’’ variables but also the ‘‘slow-changing’’ variables that often control sensitivity over the long run. For example, in many lakes water clarity (a fast-changing variable) often only changes slightly with nutrient loading until a critical threshold is passed at which point it shifts abruptly from clear to turbid water (Carpenter et al., 1999). Evidence suggests that a cause of this shift is the accumulation of phosphorus in lake sediments and watershed soils (a slow-changing variable), which over time results in the erosion of the lakes resistance and resilience, or ‘‘buffering capacity’’, to discrete events (Carpenter et al., 2001). This sort of understanding of human–environmental systems that links stresses to variables of concern are the foundation of vulnerability assessments. Consider an assessment of the vulnerability of a community within a lake region (or a population that is dependent on lakes for its livelihood or quality of life) to natural hazards such as hurricanes. In such a region, water clarity might arise in stakeholder discussions as an outcome variable of concern. However, given the existing model of fresh water lake processes, the assessor might want to select a slow-changing variable such as soil phosphorous levels, as an outcome variable of concern, rather than water clarity, especially if the assessment is concerned with long-term issues.

The vulnerability of a system could also shift as a result of a change in its state relative to a threshold of damage. Such a change could be closely linked to shifts in a system’s sensitivity or buffering capacity. For example, in evaluating the relative vulnerability of income among agricultural households in a peasant village, over a given time period, one might find that some agricultural households have assets that allow them to maintain consumption over multiple droughts. However, after an extended drought period their buffering capacity might decrease making them more sensitive to weather extremes and decreasing their mean consumption level; thereby, bringing them closer to the threshold of damage and increasing their vulnerability.

The threshold of damage might also change as a result of a shift in the threshold itself. This could happen because society redefines ‘‘damage’’ for a given system to adjust to changing social or biophysical conditions or because of new information that suggests the need to modify a given threshold. For example, society might redefine what is considered the minimum food intake to be healthy or the minimum income to maintain a household (‘‘poverty line’’).

Other external factors could lead to a shift in the threshold of damage. For example, an assessment of the vulnerability of wheat yields to climate variability and change might be based on a threshold of damage defined as the minimum economically viable yield, which would be directly influenced by international wheat prices. In this case, changes in the world wheat market could lead to changes in the threshold of damage.

Adaptations to changing social and biophysical conditions can also lead to a change in the vulnerability of a system and thus a shift in the position on the surface. Here I refer to adaptations as actions that lead to a decrease in the vulnerability of the system (e.g. a shift to the upper left of the vulnerability surface (see Fig. 3). Such actions would lead to one or more of the following: (1) an increase in the state relative to a threshold of damage; (2) a decrease in the sensitivity of the system to the set of stresses of concern; or (3) a decrease in the level of exposure to the stresses of concern.

3.3. Adaptive capacity

Adaptive capacity refers to the potential to adapt and reduce a system’s vulnerability. I represent this potential on the surface by an arrow pointing toward lower vulnerability (Fig. 1). I do this so as to distinguish adaptive capacity from adaptations. Adaptive capacity is the set of potential actions that contribute to the potential minimum vulnerability but not to the existing vulnerability (Luers et al., 2003). Consider for example a rain-fed agricultural region where some farmers have the resources to potentially drill wells and access groundwater supplies. These farmers with the potential to access groundwater have a greater adaptive capacity to lower their sensitivity to drought. However, in the event of an extended drought some farmers might find that their ability to access the groundwater is limited by some unforeseen socio-economic, institutional or technological constraints. This potential to adapt would then not be realized and these farmers would remain just as vulnerable as those who never had even the potential to access well water.

4. An example: vulnerability in the Yaqui Valley, Mexico

4.1. Yaqui Valley

The Yaqui Valley is an intensively managed irrigated wheat-based agricultural system located in northwest Mexico (Fig. 2). The Valley consists of approximately 225,000 ha of irrigated agricultural fields. Using a combination of irrigation, high fertilizer rates and modern cultivars (Matson et al., 1998), Valley farmers produce some of the highest wheat yields in the world (FAO, 1997). However the changing political and economic environment, combined with extended drought and the threat of changing climatic conditions, are leading many farmers and mangers to become concerned about sustaining yields and household incomes.

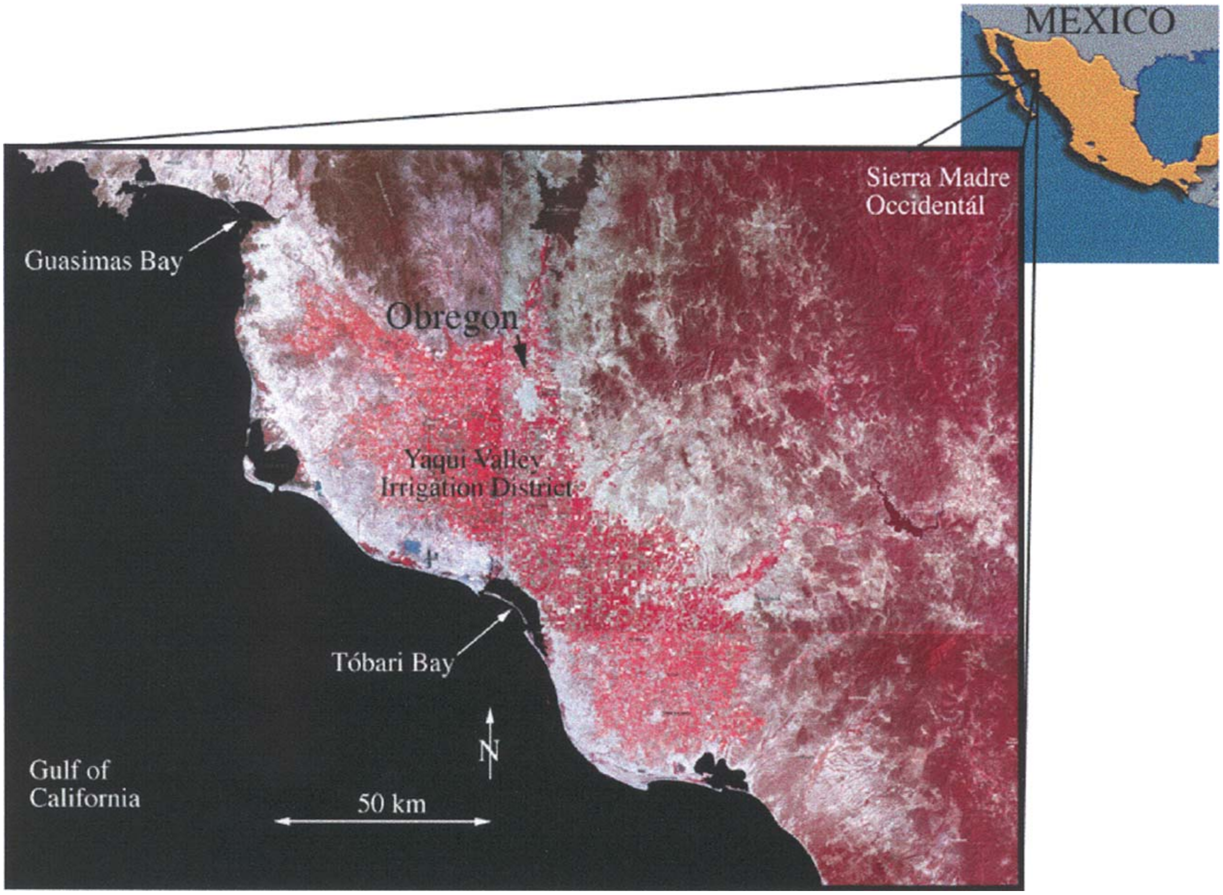

Fig. 2. Yaqui Valley, Sonora, Mexico.

Here I apply the vulnerability surface to begin to systematically evaluate the relative vulnerability of agricultural yield to climate variability and change, and market fluctuations among farmers in the Yaqui Valley. The focus of this example is to illustrate an application of the vulnerability surface and is not intended to be a complete vulnerability assessment of the region.

4.2. Methods

The unit of analysis (the "system") is the agricultural field and the people responsible for the management of that field, the farm-unit. For practical purposes, I define the agricultural field as a 30 m × 30 m pixel as described below. Of the many variables of concern to the Valley farmers I focus on wheat yields as our measure of well being. I focus on wheat as it is the dominant crop in this region (Naylor et al., 2001). Specifically, the study addresses the following questions:

1. On which farm units are wheat yields most vulnerable to climate variability and change, and market fluctuations?
2. What factors contribute to the differential vulnerability of wheat yields among farm units?

To address these questions I use the data and models presented in a previous study (Luers et al., 2003) of the same region. What is distinct in the study presented here is the analytical approach. In the previous study of the region vulnerability of wheat yield was estimated as

$$V = \int \left(\frac{|\partial Y / \partial T|}{Y / Y_0} \right) P_T \, \mathrm{d}T, \qquad (2)$$

where V represents vulnerability, Y represents wheat yield, T represents average minimum temperature and P_T represents the probability of T.

While this metric can be useful in a variety of settings, especially in well-understood systems, it is limited to systems where the relationships between the stressors and variables of concern can be described by mathematical equations. Many human and biophysical systems are difficult to describe explicitly using differential equations. Yet often scientists have estimates of sensitivity, exposure and the state relative to a threshold of specific system characteristics based on empirical data and integrated models. For example, in the analysis presented below, I use coefficient of variation of yields as a linked measure of sensitivity and exposure rather than the weighted derivative presented above (Eq. (2)). The application of the vulnerability surface below seeks to illustrate how key characteristics of the metric presented in Eq. (2) could be generalized to a diversity of systems.

4.2.1. Data sources

The analysis of wheat yields for the Valley is based on yield estimates derived from Landsat TM and ETM+ data for four years, 1994, 2000, 2001 and 2002, as described in detail by Lobell et al. (2003). Luers et al. (2003), building on the analysis of Lobell et al. (2003), developed a linear least-squares regression model of yield with average night-time temperature for January–April. Here I use this same regression model to generate a time series of yields for the Valley, using Monte Carlo simulations ($N = 500$) where temperature varies according to a normal distribution with a mean equal to 9.61 °C and a standard deviation of 0.99 °C, as determined from 20 years of historical climate records.

I use the Monte Carlo-generated time series of yields to systematically explore the relative effect of soil and management on the vulnerability of yields to climate variability and change, and market fluctuations. My analysis is based on Lobell et al.'s (2002) study that suggests that over recent history wheat yields in the Valley have been a function predominantly of average night-time minimum temperature, soil type and management. The term management is used loosely here to refer to all factors other than temperature and soil that influence yield. Lobell et al. (2002) showed that most of the variability in yield that was not explained by soils and temperature was between-field variability rather than within-field variability and was therefore attributable to management. Management was assumed to include such factors as amount and timing of fertilizer application, number and timing of irrigations, tillage and cultivation practices and pest control.

Similar to our previous analysis of the region (Luers et al., 2003), I define here two management levels ("good" and "poor") for each soil type as the top and bottom thirds of the distribution of average yield percentiles for the four years of data. The "yield percentile" refers to the relative yield (represented as a percentile) of a given farm unit within the distribution of yields for a given year. I then group the farm units by management level and soil type, defining six groups–well-managed farm units on silt loam soils (WMSL), well-managed farm units on compacted-clay soils (WMCC), well-managed farm units on stony-clay soils (WMSC), poorly managed farm units on silt-loam soils (PMSC) poorly managed farm units on compacted-clay soils (PMCC) and poorly managed farm units on stony-clay soils (PMSC).

4.3. Vulnerability surface

I characterize the relative vulnerability among farm units in the Valley by locating the position on the surface based on the average crop yield of each farm-unit class divided by a threshold of 4 t/ha, the average minimum yield that results in no-net profit under average management and economic conditions (Luers et al., 2003). I represent sensitivity and exposure as the coefficient of variation of yields for each farm unit group. The diagonal lines are contours of equal vulnerability normalized by the average vulnerability in the Valley. A vulnerability of one ($V = 1$) represents the average farm unit.

Fig. 3 illustrates the relative position of each farm-unit group on the vulnerability surface. The least vulnerable groups include the well-managed farms on the silt-loam soils while the most vulnerable groups are the poorly managed farms on the stony-clay and compact-clay soils.

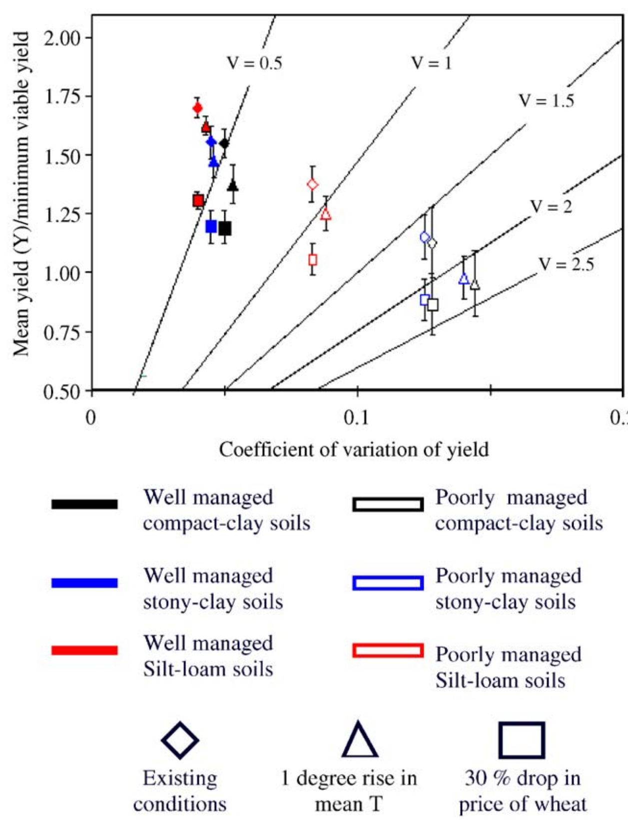

Fig. 3. Relative vulnerability of wheat yields to climate variability in the Yaqui Valley agricultural region. The lines are contours of equal relative vulnerability, where the values are normalized by the average farm unit (i.e. vulnerability of the average farm unit is one). Where color indicates soils type (*red* = silt loam, *blue* = stony clay, *black*-compact clay), solid shapes indicate good management and open shapes indicate poor management, the shape indicates differences among conditions (*diamond* = existing conditions, *triangle* = 1 degree rise in mean temperature, *square* = 30% drop in wheat price).

4.3.1. Dynamic vulnerability

Changes in institutional, socio-economic and biophysical conditions will lead to shifts in the position on the surface over time. For example, an increase in the mean or variability of temperature would result in an increase in exposure. Meanwhile, adaptations to changing conditions, such as modifications in management or crop types, could decrease sensitivity to increased exposure pushing the system back toward the upper left of the diagram (i.e. lower vulnerability). In Yaqui Valley, our analysis suggests that an increase in mean temperature would result in a shift toward the lower right (higher vulnerability) for all farm units (Fig. 3). However, the shift is greater for the poorly managed farms on the stony-clay soils because the yields on these soils are more sensitive to climate (Fig. 3).

Changes in vulnerability of this system over time will result from changes in slow- and fast-changing variables, affecting the sensitivity that could arise from endogenous stresses on the system. Here I represent the sensitivity of wheat yield to temperature change as a function of soils and management. In this example, over the short term, soil quality is treated as a constant (slow-changing) while the management term is treated as a variable (fast-changing variable). However, over the longer term the constants become variables and lead to a change in sensitivity. In this case changes in soil quality, as well as any institutional and political-economic factors (such as accessibility to credit or water management policies) that limit management options, may result in a change in vulnerabilities.

Salinity is an example of a slow-changing soil characteristic that appears to be contributing to changes in the vulnerability of wheat yields. Studies show that at salinity levels of approximately six decisiemens per meter (dS/m) yields of wheat tend to decrease and at 13 dS/m yields may reach only 50% of the non-saline soil yield potential (Ortiz-Monestario, pers. comm.). Today, approximately 8% of the agricultural region has salinity levels high enough to reduce productivity (Matson et al., in press) and increase the vulnerability to climate variability and change.

4.3.2. Managing vulnerability

Managing vulnerability requires consideration of both observable and non-observable characteristics of a system. Vulnerability has often been characterized as "non-observable" (Downing et al., 2001). Yet, managers and policy makers often rely on information and observations to make decisions. Local and regional manifestations of broad social and ecological processes produce proximate causes of vulnerability that can help identify immediate action priorities and provide a guide for further research into the complexities of underlying causes. The vulnerability surface provides an approach to help analyze proximate factors and link them to broader processes.

In the Yaqui case study, the vulnerability surface highlights the relative effects of soil, management and average temperature, and prices as proximate factors contributing to the vulnerability of farm units in the region (Fig. 3). While the vulnerability of each group increases with increases in average temperature and decreases in average prices, the surface illustrates that the effects of these stresses on the spread of vulnerability among the groups are not as important as the differences in management. Furthermore, the surface suggests that while soil is contributing to relative vulnerability, management can reduce many of the biophysical constraints set by soil type, at least in the short term. These findings point to the need for managers interested in addressing vulnerability of wheat yields in the valley to determine the differences in farm management practices and understand the reasons for the differences. The analysis presented here does not explore the potential relative implications of changes in variability of temperature and prices, which would likely add complexities to these findings.

Some of the critical underlying causes of vulnerability may be found in the explanation of differences in management practices and soil type and quality. Currently, researchers in the Yaqui Valley are exploring these differences. Possible sources of the variation in management practices may include differential access to technology, credit or water, differences in the incentive structure for Valley farmers, or variability in knowledge about effective farming practices. Meanwhile, the differences in soil characteristics among farmers may be the result of the history of land distribution or the legacy of management practices on a particular field. Identifying the proximate causes of vulnerability and understanding the links to underlying processes may help decision makers identify priorities in the near-term while planning longer-term management strategies. Managing vulnerability over the long term requires addressing the underlying process while monitoring changes in the system's slow-changing characteristics that support the current conditions.

5. Conclusion

This paper proposes a three-dimensional surface of vulnerability as a tool for analyzing vulnerability. I illustrate the approach through an analysis of the agricultural district in the Yaqui Valley, Mexico. The surface provides a structure for distinguishing on which farm units wheat yields are most vulnerable and highlights the relative importance of soil and management factors contributing to the vulnerability of farm units exposed to changes in average temperatures and prices. While these findings are similar to those found by (Luers et al., 2003) the vulnerability surface presented in this study may be a more generalizable analytical framework than the vulnerability metric used in the earlier analysis of the region.

Neither the vulnerability surface presented here nor the metric presented in previous work (Luers et al., 2003) provide an explanation of vulnerability, but are merely tools to systematically examine a system's susceptibility to damage. The methods help identify relative vulnerability under a given set of conditions and identify proximate factors that are contributing to the vulnerability. It is likely that in many cases these proximate factors such as soil or management can provide a guide for analysis of the broader social and ecological processes that define the causal structure of vulnerability.

The vulnerability of people and places is a complex phenomenon that is defined by a long history of human and environmental interactions. Managing vulnerability effectively in a dynamic and unpredictable world will require more than simple analytical tools; it will require a fundamental shift in the way in which local, regional and national decision makers approach resource and development problems. Such a shift is only likely to occur through major institutional and legal reforms that set up rewards for flexibility in management approaches that are forward-looking and focus on vulnerability issues such as sensitivity and adaptive capacity. However, analytical methods for systematically assessing vulnerability, such as the one proposed here, may be critical for defining current and future management needs and policy decisions.

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