A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico

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Abstract

We propose measuring vulnerability of selected outcome variables of concern (e.g. agricultural yield) to identified stressors (e.g. climate change) as a function of the state of the variables of concern relative to a threshold of damage, the sensitivity of the variables to the stressors, and the magnitude and frequency of the stressors to which the system is exposed. In addition, we provide a framework for assessing the extent adaptive capacity can reduce vulnerable conditions. We illustrate the utility of this approach by evaluating the vulnerability of wheat yields to climate change and market fluctuations in the Yaqui Valley, Mexico.
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1. Introduction

Vulnerability, defined here as the degree to which human and environmental systems are likely to experience harm due to a perturbation or stress (e.g. Kasperson et al., 2003; Turner et al., 2003a), has in recent years become a central focus of the global change and sustainability science research communities (Clark et al., 2000; IHDP, 2001; IPCC, 2001; Kates et al., 2001; Kasperson, 2001). This new emphasis on vulnerability marks a shift away from traditional scientific assessments, which limit analysis to the stressors (e.g. climate change, hurricanes) and the corresponding impacts, towards an examination of the system being stressed and its ability to respond (Ribot, 1995; Clark et al., 2000). By focusing on the mechanisms that facilitate or constrain a system's ability to cope, adapt or recover from various disturbing forces, vulnerability assessments aim to not only identify which systems are most at risk but also to

understand why. This information is critical for decision makers who often must prioritize limited resources in the design of vulnerability-reducing interventions.

Although vulnerability research has produced an insightful and extensive literature in the social and global-change sciences, the application of the concept in policy-driven assessments has been limited by a lack of robust metrics to model and measure vulnerability within and across systems. Developing measures of vulnerability is complicated by the lack of consensus on the exact meaning of the term, the complexity of the systems analyzed, and the fact that vulnerability is not a directly observable phenomenon. Yet without some ability to measure vulnerability, at least in a relative sense, it will be difficult to operationalize the concept in environmental assessments.

In this paper we provide an introduction to the vulnerability concept and briefly review existing approaches to quantifying vulnerability. We then propose a new approach to quantifying vulnerability that integrates four essential concepts: the state of the system relative to a threshold of damage, sensitivity, exposure and adaptive capacity. We illustrate the utility of this approach in an assessment of the vulnerability of wheat yields in the Yaqui Valley, Mexico, to climate variability

and change, and market fluctuations. Finally, we conclude with a discussion of the implications of our analysis for future research and practice.

2. Vulnerability concept

2.1. Defining vulnerability

Vulnerability research has its roots in the social sciences. It has a particularly long history in the risk-hazards and geography literature (Kasperson et al., 2003), where vulnerability has been defined as the potential for loss (Mitchell et al., 1989) and is often understood to have two sides: an external side of shocks and perturbations to which a system is exposed; and an internal side which represents the ability or lack of ability to adequately respond to and recover from external stresses (Chambers, 1989). Over the last decade, social scientists have focused on the socio-economic and political structures and processes that makes people vulnerable (Blaikie et al., 1994; Bohle et al., 1994; Cutter, 1996; Ribot, 1996; Kelly and Adger, 2000), and have identified critical components of vulnerability such as the exposure to stressors, the capacity to anticipate, cope with, resist and recover from natural hazards, and the consequences of stresses (Watts and Bohle, 1993; Blaikie et al., 1994). Vulnerability is also implicit in much of the economics literature that focuses on poverty issues (e.g. Alwang et al., 2001; Murdoch, 1994). Within this context vulnerability to poverty has been conceptualized as the likelihood of falling below a consumption threshold, such as a poverty line (Pritchett et al., 2000), and as the variability of income or consumption (Glewwe and Hall, 1998).

In ecology, although the term vulnerability is rarely used, an opposite concept—stability—has preoccupied theoretical ecology discussions for over three decades. Many ecological concepts associated with stability, such as resistance, resilience, and persistence (e.g. Grimm and Wissel, 1997), appear implicitly and explicitly throughout the vulnerability literature. Ecological resilience, the ability of a set of mutually reinforcing structures and processes to persist in the presence of disturbance and stresses (Holling, 1973; Gunderson, 2000), is particularly prominent within the discourse of the global change vulnerability community (Carpenter et al., 2001; Folke et al., 2002; Kasperson et al., 2003).

In recent years, interdisciplinary research teams have begun to explore the vulnerability of linked human–environmental systems (e.g. Turner et al., 2003a; Folke et al., 2002). For example, the Research and Assessment Systems for Sustainability Program proposed a multi-dimensional framework for vulnerability analysis that finds vulnerability, which is defined as a function of exposure, sensitivity, adaptive capacity, manifested within the interactions of social and ecological systems (Turner et al., 2003a, b).

2.2. Quantifying vulnerability

To apply the concept of vulnerability in policy-driven assessments researchers need to be able to measure it. It is difficult if not impossible to systematically identify which systems are most vulnerable and why without some criteria by which one system is said to be more or less vulnerable than another. However, defining criteria for quantifying vulnerability has proven difficult, in part because of the fact that vulnerability is often not a directly observable phenomenon (Downing et al., 2001). In certain case studies, depending on the type of stressor and outcome variables of concern, the relative impacts of stressors in a region could be used as objective ex-post measures of vulnerability. For example, an ex post assessment of a hurricane might use the number of storm-related deaths within a given region that experienced equal-forced hurricane winds as one measure of which areas were most vulnerable to the hurricane. This simple approach, although useful, is not easily applied to a greater variety of stressors and outcome variables. For example, if the measure of well-being is not limited to just life and death (as in the above example) but also considers such variables as ecosystem function, average income, or human health then defining which region is the most vulnerable would be more subjective. Is a population most vulnerable if the decrease in average income is the highest immediately after the hurricane? However, what if one year after the hurricane the community with the least overall drop in income has still not recovered but the community whose income initially dropped the most had recovered completely—which was most vulnerable to the hurricane? The situation is even more complicated when assessments are extended from discrete stressors such as a hurricane to gradual and continual stresses such as climate change.

Despite the many challenges that exist in quantifying vulnerability several quantitative and semi-quantitative metrics have been proposed and applied (e.g. Stephen and Downing, 2001; Schellnhuber et al., 1997; Petschel-Held et al., 1999; Pritchett et al., 2000). Perhaps the most common method of quantifying vulnerability in the global change community is by using a set or composite of proxy indicators (e.g. Moss et al., 2002; Kaly et al., 2002). For example, USAID Food Emergency Warning System (FEWS) program has used indices, calculated as averages or weighted averages of selected variables, to measure vulnerability to food insecurity in different regions throughout Africa (http://www.fews.org/fewspub.html). These studies focus on compiling data in different areas, such as crop risk (e.g. length and variability of growing season), income risk (e.g. income variability, average cash crop production)

and coping strategies (e.g. staple food production, access to infrastructure). The Pacific Northwest Laboratory (PNL) Vulnerability Assessment Program also uses a composite approach to develop an index of vulnerability to climate change for 38 countries (Moss et al., 2000, 2002). The PNL vulnerability index represents a composite of 16 variables selected from five sectors of sensitivity (settlement, food security, human health, ecosystem, and water) and three sectors for coping capacity (economic, human resources and environmental). Examples of the variables include life expectancy, percent of unmanaged land, and GDP per capita. Additional examples of the composite indicator approach include the South Pacific Applied Geosciences Commission (SOPAC) environmental vulnerability index (EVI), which is a composite of 54 independent variables categorized under the headings—degradation, resilience, exposure (Briguglio, 1995; Kaly et al., 2002) and the Index of Human Security, which is a composite of 16 indicators drawn from four major thematic areas (environment, economy, society, and institutions) (Lonergan et al., 2000).

While the indicator approach is valuable for monitoring trends and exploring conceptual frameworks, indices are limited in their application by considerable subjectivity in the selection of variables and their relative weights, by the availability of data at various scales, and by the difficulty of testing or validating the different metrics. Perhaps most importantly, the indicator approach often leads to a lack of correspondence between the conceptual definition of vulnerability and the metrics. For example, researchers with the PNL Vulnerability Assessment program define vulnerability as "the extent to which climate may change or harm a system" and measure it, as described above, as a composite of 16 variables that represent a system's sensitivity to climate and ability to adapt to change (Moss et al., 2002). Although these 16 variables may represent critical factors in a wide range of regions, they are not likely to capture the "change or harm" that may result from climate change equally well in different regions with distinct cultural systems, values and biophysical systems. By focusing on developing metrics that represent the vulnerability of a place, the indicator approach is forced to link the variables of concern for a region to the measure of vulnerability and as a result the measure becomes difficult to apply in diverse settings.

Vulnerability measures can only accurately relate to specific variables, rather than the generality of a place, because even the simplest system is so complex that it is difficult to fully account for all of the variables, processes and disturbances that characterize it. Therefore, we argue that vulnerability assessments should shift away from attempting to quantify the vulnerability of a place and focus instead on assessing the vulnerability of selected variables of concern and to specific

sets of stressors. This approach requires a set of generic metrics that can assess the relationships between a wide range of stressors and outcome variables of concern. To the extent that the selected variables of concern and the stressors characterize a given place, the vulnerability of these variables may provide important characterization of the vulnerability of that place. The selected variables and stressors are likely to change over time and space, resulting in changes in the relative vulnerability; however, the functional form of the generic vulnerability metric remains the same.

A few generic vulnerability metrics have been proposed. For example, the variability of selected variables of concern has been applied as a metric of vulnerability especially in economic and agricultural studies (Pritchett et al., 2000; Heitzmann et al., 2002). Another generic metric is the probability that a variable of concern will cross a threshold (Schimmelpfennig and Yohe, 1999; Mansuri and Healy, 2002; Peterson, 2002). While both of these measures are useful, neither is sufficient to fully capture vulnerability. For example, contrast an elite business woman who might have an extremely variable income but a mean income of well above a regional average with a poor laborer who may have a low base income but with much less variability. In this case, it is apparent that variability in income alone might not fully capture the relative vulnerabilities accurately.

3. A new approach for quantifying vulnerability

In this section we derive a generic vulnerability metric by translating a general definition of vulnerability, the susceptibility to damage, into a mathematical expression. To do this we first define a threshold of damage and then measure susceptibility in terms of the system's sensitivity to and exposure to stressors. We then propose a framework for estimating a system's ability to modify its vulnerable conditions by adapting and responding to changing circumstances. To illustrate the form of the proposed vulnerability metric we introduce a simple idealized human–environment system where some measure of human well-being (W) is a parabolic function of an independent variable (X) (Fig. 1a). For simplicity, we present a one-dimensional example, however, this approach could be applied to a system of multiple stressors and multiple outcomes variables of concern.

3.1. Vulnerability

3.1.1. Sensitivity and threshold
Defining the vulnerability of a system first requires understanding the sensitivity of the system to different stressors and identifying a threshold of human well-being at which the system is said to be "damaged." The
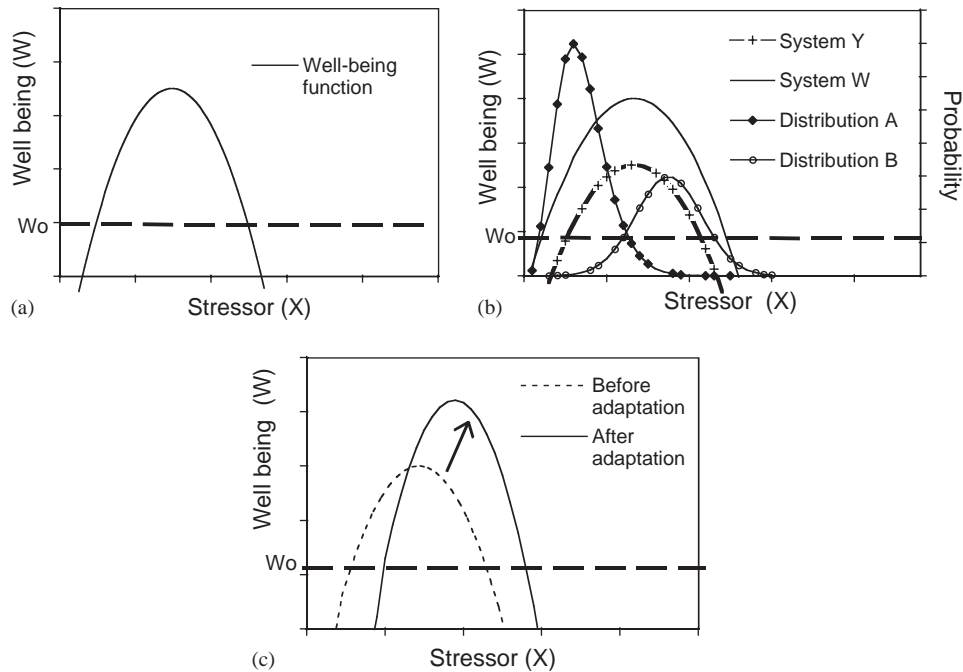
Fig. 1. (a) A hypothetical well-being function for an idealized system. (b) Different exposures can lead to different vulnerabilities. (c) Adaptive capacity is represented by the ability of a system to shift its well-being function.

vulnerability of a system to small changes in forcings is a function of the system's sensitivity to a given perturbation and the relative proximity of the system to its damage threshold (Fig. 1a):

$$V = f\{\text{sensitivity/state relative to a threshold}\},$$
$$= f\left(\frac{|\partial W/\partial X|}{W/W_0}\right), \tag{1}$$

where W_0 represents a threshold value of well-being below which the system is said to be damaged. In this example, the sensitivity is represented as the absolute value of the derivative of well-being with respect to the stressor, however, other measures of sensitivity could be used, for example the coefficient of variations.

3.1.2. Exposure

Different communities and ecosystems are exposed to varying magnitudes and frequencies of disturbing forces, often resulting in differential vulnerabilities (IPCC, 2001; Turner et al., 2003a, b). We capture these differences in exposure by calculating 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:

$$V = \text{Expected Value}$$
$$\quad (\text{sensitivity/state relative to a threshold}),$$
$$V = \int\left(\frac{|\partial W/\partial X|}{W/W_0}\right)P_X\,\mathrm{d}X, \tag{2}$$

where P_X refers to the probability of the occurrence of stressor X.

Although it is impossible to determine the precise functional relationships that include all of the stressors and variables of concern, analysis based on simple theoretical models and multivariate regressions from empirical data can provide valuable information about critical relationships that can be applied in this measure.

This metric of vulnerability provides a means for distinguishing between systems with different average states of being, sensitivities and exposures (Fig. 1b). For example, suppose there are two farming communities where total crop production per capita is a measure of well-being. The two communities may each have similar well-being functions. However, one community (System W) may have more crop land per capita than another community (System Y) resulting in a higher average well-being (Fig. 1b). Based on the proposed vulnerability measure, if these two systems were exposed to the same distribution of stressors (say distribution A), then System Y would be more vulnerable, even though they both had the same exposure and sensitivity. On the other hand, if there were two separate systems with identical well-being functions (both represented by System Y) but dramatically different distributions of stressors (distributions A and B) the vulnerabilities of these two systems would be distinct from each other (Fig. 1b). For example, consider two farmers who have identical wheat production functions (with crop production as a measure of well-being) but live in two drastically different climates. The first farmer might live

in a region that experiences a very steady moderate temperature range while the second lives in an area that is characterized by high climatic variability with frequent extreme events. In this case, the second farmer would have the higher vulnerability despite the fact that they had identical well-being functions.

3.1.3. Adaptive capacity

We define adaptive capacity as the extent to which a system can modify its circumstances to move to a less vulnerable condition (Fig. 1c). We quantify adaptive capacity (A) as the difference in the vulnerability under existing conditions and under the less vulnerable condition to which the system could potentially shift:

$$A = V(\text{existing conditions}) - V(\text{modified conditions}). \tag{3}$$

A system could decrease its vulnerability by modifications that would lead to one or more of the following: (1) a shift in the well-being function that decreases the sensitivity to critical stressors; (2) a change in the position relative to a threshold of damage and (3) a modification in the system's exposure to stressors of concern.

The capacity to adapt is distinct from adaptations that a system has made in the past to accommodate disturbing forces. Prior adaptations are captured in the characterization of the well-being function, specifically in the sensitivity and the position relative to the threshold of damage. 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 her 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 or an increase in the state relative to the threshold of damage and a corresponding decrease in the vulnerability.

Many factors may determine a system's ability to modify its vulnerable conditions, including the rate of change of the disturbing forces, and the social and natural capital of the system. For example, if the average temperature increases gradually, farmers may be able to adapt by changing crops or management practices that result in a shift in the well-being function, which would result in lower vulnerability. However, if the temperature change was rapid the same farmers might be limited in their abilities to adapt the changing 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). These are all examples of factors that could contribute to a system's ability to decrease its vulnerability.

3.1.4. Units

The units of the above metrics for vulnerability and adaptive capacity are the units of well-being divided by the units of the stressor (W/X). For example, in the case study below our measure of well-being is agricultural yield (measured as tons/ha) and the stressor we consider is temperature (°C) and the resulting units of our vulnerability measure is ((tons/ha)/°C). However, for practical purposes, in our analysis we represent both vulnerability and adaptive capacity as relative unitless measures by normalizing each by a reference state. In general, the reference state that is used will depend on the focus of the particular study. In the case study below, the reference state we use is the vulnerability of the average farm in the study region.

3.1.5. Combining vulnerability and adaptive capacity

We argue that vulnerability studies that include adaptive capacity directly in a vulnerability characterization are actually characterizing what we refer to as the minimum potential vulnerability, which we distinguish from the existing vulnerability. We measure the existing vulnerability under current and future conditions and the minimum potential vulnerability (V_{min}) as the existing vulnerability minus adaptive capacity:

$$V_{min} = V - A. \tag{4}$$

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 insurance and the other does not. One farmer may have a greater adaptive capacity and thus a lower potential vulnerability because of his access to insurance. However, if the insurance program does not respond as promised in a crisis then both farmers are just as vulnerable. The insurance program only provides the potential for lowering the farmer's vulnerability. On the other hand, consider two farmers who are identical except they have different soil types and are both faced with drought. It may be that a farmer with one soil type that has a greater water holding capacity—and therefore require less water—is less vulnerable to drought conditions than the other farmer with a different soil type. In these examples, the soil influences both farmer's existing vulnerability, while the insurance program as part of a farmer's adaptive capacity only influences the potential of lowering the farmer's vulnerable conditions.

4. An example: assessing vulnerabilty in the Yaqui Valley

4.1. Yaqui Valley

The Yaqui Valley, an intensively managed wheat-based agricultural region, is located in Sonora, Mexico, between the Sierra Madre Mountains and the Gulf of California (Fig. 2). The Valley consists of approximately 225,000 ha of irrigated agricultural fields. Referred to as the birthplace of the Green Revolution for wheat, it is one of the country's most productive breadbaskets (Naylor et al., 2001). 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, in a world of globalized markets, reduced subsidies and price supports, drought, and other forces, many Valley farmers and managers are concerned about sustaining yields and maintaining household incomes.

The climate in the Yaqui Valley is semi-arid, with variable precipitation rates averaging $317 \, \text{mm yr}^{-1}$ and an average daily temperature of $24°C$. The natural ecosystems of the Valley have co-evolved with, and are thus likely to be resilient to, the natural climatic variability of the region. However, the agricultural system, which was developed by attempting to control the local environmental factors, such as water supply by building reservoirs, is likely to be vulnerable to climatic extremes. Prolonged droughts, such as the one that has persisted in the region since 1994, have lead to dramatic declines in total reservoir volume, increases in well pumping, and reduced water allocations to farmers. Meanwhile, recent studies have pointed to the concerns

that increasing temperatures resulting from global warming may lead to decreased wheat yields (e.g. Lobell et al., 2002). These concerns arose during a period when a series of policy reforms were promulgated to increase the efficiency of the agricultural sector by opening it to the international market and by decreasing government intervention in production and marketing decisions (Naylor et al., 2001). The effects of these various changes are not felt uniformly across the Valley but depend in part on relative access to natural and social capital (Turner et al., 2003b; Lobell et al., 2002; Naylor et al., 2001). Here we apply the process-based approach described above to begin to evaluate the relative vulnerability among Valley farmers faced with multiple stresses. This case study is presented only as an example application of the proposed methodology, and is not intended to be a complete vulnerability analysis of the region.

4.2. Methods

4.2.1. Defining the system

Our unit (or system) of analysis is the "farm unit"— that is an agricultural field and the farmer or farmers responsible for the field. For practical purposes, we define our agricultural field as a $30 \, \text{m} \times 30 \, \text{m}$ pixel as described below. Of the many outcomes of concern to the Valley farmer, we focus on wheat yield as our measure of well-being. Wheat yield alone obviously does not fully capture the well-being of Valley farmers, however, we use it here to illustrate the proposed methodology. Wheat yield in any given farm unit is affected by factors both internal and external to the
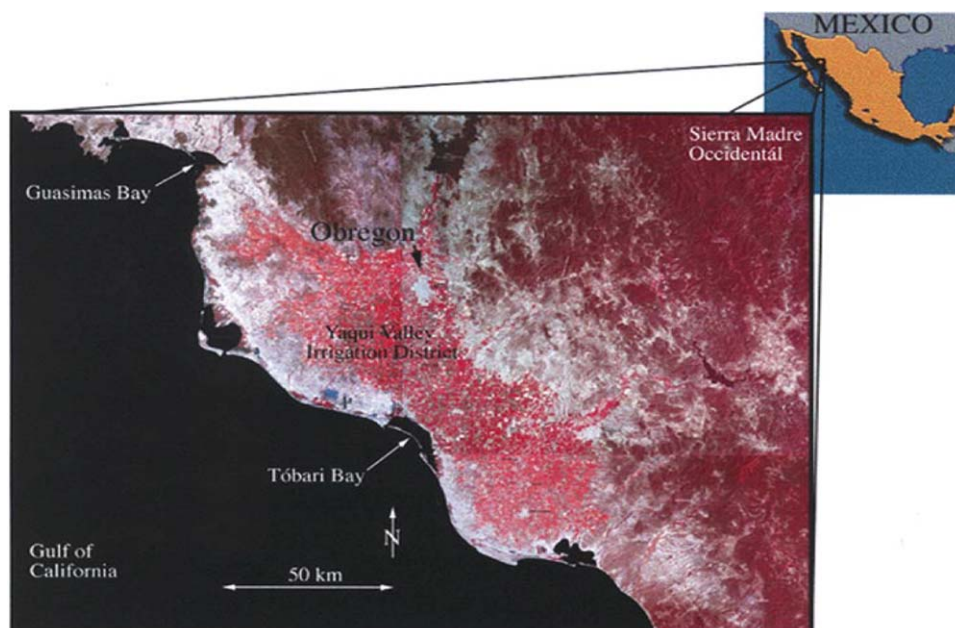

Fig. 2. Yaqui Valley, Sonora, Mexico.

system. For example, regional temperature changes may affect plant growth, changes in national agricultural policies may influence farmer cropping decisions, and variation in farm unit technological resources may influence planting and harvesting methods. We base our analysis on a previous study that suggests that over recent history wheat yields in the Valley are a function predominantly of temperature, soil type and management (Lobell et al., 2002). We use the term management loosely to refer to all factors other than temperature and soil that influence yield (Lobell et al., 2002). Lobell et al. (2002) showed that most of the variability in yield that was not explained by soils or temperature was between-field variability rather than within-field variability and was therefore attributed primarily to management, where management included such factors as amount and timing of fertilizer application, number and timing of irrigations, tillage and cultivation practices and pest control.

We focus our assessment on two external stressors—climate (variability and change) and market fluctuations—to calculate relative vulnerability of yields and to begin to explore how biophysical and socio-economic conditions contribute to the variability of vulnerability within the Valley. Specifically, we address the following three questions:

1. On which farm units are wheat yields most vulnerable?
2. To which stressors are wheat yields most vulnerable?
3. What factors explain differences in vulnerability of wheat yield between farm units in the Valley?

4.2.2. Measuring vulnerability

To illustrate an application of the proposed metric, we utilize remotely sensed estimates of yields in the Yaqui Valley for four years: 1994, 2000, 2001, and 2002. Yield estimates are derived from Landsat TM and ETM + data, as described in detail by Lobell et al. (2003). The four years span a range of climatic conditions useful for assessing sensitivity of yields to climate. Yields in the Yaqui Valley are strongly determined by average night-time minimum temperatures during the growing season, which govern rates of plant respiration and development, where lower temperatures correlate with higher yields. Previous work has shown that the sensitivity to temperature is greater for fields with lower yields, suggesting a significant interaction between climate and management (Lobell et al., 2002). In addition, the Lobell et al. (2002) analysis suggests that while soil type and temperature variation all represented significant sources of yield variability, farm management, as estimated by yield variation within soil type, was most important for determining wheat yields. Based on these results, we pursue a two-tiered approach to our vulnerability analysis. First, we

hold management level constant and measure relative vulnerability. We, then hold soil type constant and explore the relative effects of soil type in determining the vulnerability within management levels. Each of these methods is described in detail below.

For each of the four years, we compute the distribution of yield within the entire Valley, and then rank yields by percentile for each year. We then use a linear least-squares regression of yield with average night-time temperature for January–April to define the average yield and sensitivity for each percentile. To define the vulnerability corresponding to each percentile, we run a Monte Carlo simulation where temperature varies according to a normal distribution with mean equal to $9.61°C$ and standard deviation equal to $0.99°C$, as determined from 20 years of historical climate records. We then calculate the vulnerability according to Eq. (2) using a threshold value of $4 t/ha$, which is the approximate minimum yield required for farmer's to "break-even" (i.e. zero net profit) based on the average management practices (Matson et al. 1998). We normalize these vulnerability values by the average vulnerability calculated for the entire Valley. We generate a map of vulnerability by matching the average yield percentile for each pixel to the associated vulnerability (Fig. 3).

4.2.3. Measuring adaptive capacity

As described above, the critical factors that may influence a farm unit's yield function include soil type and management level. Management is the only one of these factors that farmers can potentially manipulate to move to a less vulnerable condition. Therefore, in our analysis we estimate adaptive capacity from our time series of yields as the extent to which a farm unit has exceeded its average management percentile over the study period. We assumed that the highest relative yield, as represented by the yield percentile, could be achieved every year with the appropriate management. We estimate the adaptive capacity as the difference between the vulnerability calculated as above and the vulnerability calculated for a yield temperature function where we assume the expected yield is equal to the maximum yield percentiles observed over the four years. To create a unitless measure we normalize this difference by the average value of the difference calculated for all pixels over the Valley:

$$A = \frac{(V_{R\,mean} - V_{R\,max})_{pixel-i}}{(V_{R\,mean} - V_{R\,max})_{valley\,ave}}, \tag{5}$$

where R refers to the relative yield percentile.

4.2.4. Explaining vulnerability and adaptive capacity

To explore the factors contributing to the different vulnerabilities among farm units we compare our vulnerability map with other spatially explicit data,
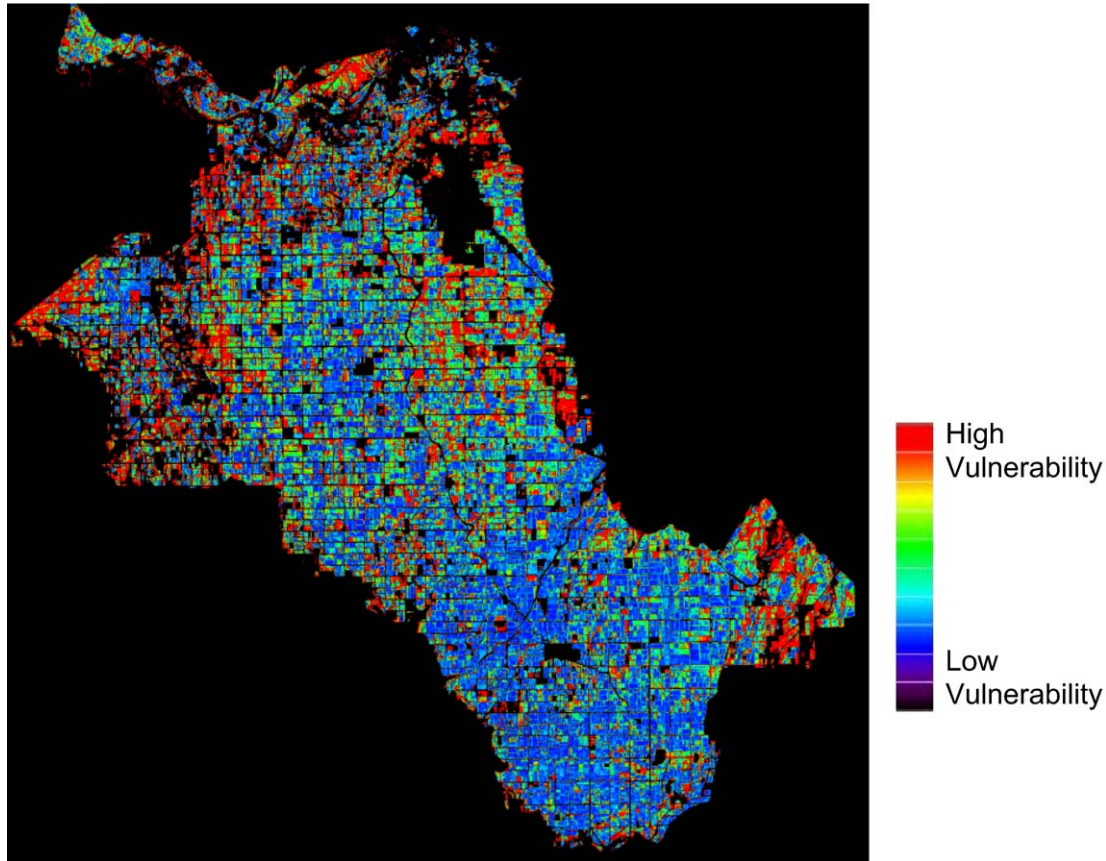
Fig. 3. Vulnerability, Yaqui Valley irrigation district. The most vulnerable are shown in red and the least vulnerable in dark blue.

including soils type and management. To assess the relative effect of soils we calculate the vulnerability for what we refer to as different "management categories" within each soil type. We define three management categories within each soil type as the top, middle and bottom thirds of the distribution of average yields over the four years of data. We calculate the distribution of vulnerability and adaptive capacity for the farm units within each of these three management categories.

4.3. Results and discussion

4.3.1. Vulnerability

Fig. 3 shows the spatial variability and patterns of vulnerability throughout the Valley. Overlaying these relative vulnerability estimates with spatially explicit biophysical and institutional factors allows us to explore links between these factors and the spatial patterns of vulnerability. Our analysis indicates that both soil type and management practices appear to contribute to the spatial variation in vulnerability. Not surprisingly, the "best managed" soils are the least vulnerable, irrespective of the soil type (Fig. 4). However, the calculated vulnerabilities suggest that soil type becomes more important in the poorly managed lands. The most

vulnerable yields are those on poorly managed farm units with stony-clay and compacted-clay soil.

The frequency distribution of vulnerability for the Valley as a whole is skewed towards vulnerabilities lower than the average (Fig. 5), indicating that while the majority of farm units are relatively resilient in the face of variable climate a few farm units remain highly vulnerable. However, estimates of relative vulnerability are not fixed. As changes occur inside and outside of the system, so will the vulnerability. For example, if the average minimum temperature increases by 1°C the vulnerability of the average farmer would increase by roughly 10%, resulting in an effective shift to the right in the whole Valley distribution (Fig. 5). Meanwhile, a 10% decrease in the effective price of wheat (either as a result of shifts in market prices or shift in subsidy policies) would result in a rise in the identified threshold of damage in this model and result in approximately a 30% increase in the vulnerability of the average farmer.

These results illustrate how the proposed methodology can provide a framework for assessing the relative importance of market fluctuations compared to temperature changes in determining vulnerability. The differential effects of fluctuations in international markets is particularly relevant to the region, which has begun a transition to an open economy after the
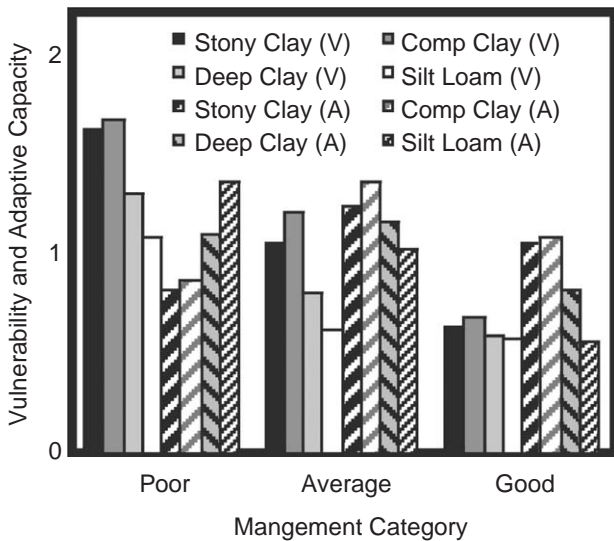
Fig. 4. Vulnerability (*V*) and adaptive capacity (*A*) by soil type and management type. The values shown are means of the distributions for each category (soil type and management category). $P < 0.0001$ from Two-way ANOVAs with soil type and management category as fixed effects and *V* and *A* as response variables.
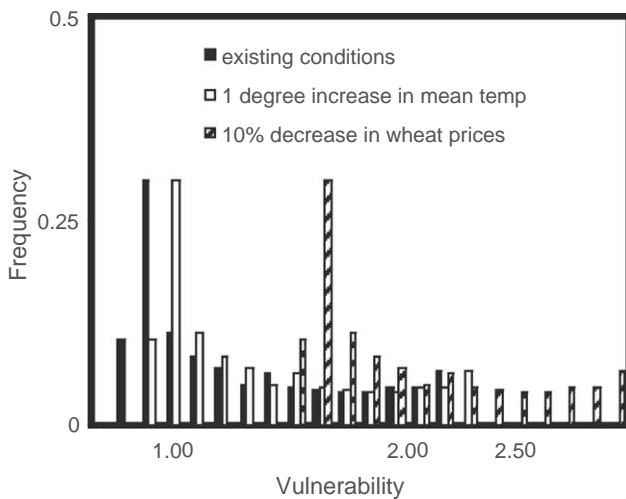

Fig. 5. Frequency distribution of vulnerability of wheat yields of farm units throughout the Valley. All vulnerability calculations are normalized by the Valley average under existing conditions.

promulgation in the 1990s of a series of neo-liberal reforms, which included the signing of the North American Free Trade Agreement (NAFTA) and resulted in a reduction of many subsidies and price supports for Valley farmers (Naylor et al., 2001). In 2002, the Mexican government reintroduced price supports for wheat in response to fears that Mexico's farm sector was being threatened by unequal competition in the international market (Malkin, 2002).

4.3.2. Adaptive capacity

The implications of changes in temperature and prices for Valley farmers will depend on farmer's abilities to respond to and adapt to the changing conditions. For example, farmers may respond to a drop in wheat price by shifting to higher value crops, or to a change in temperature by shifting the timing and amount of irrigation. The extent to which farmers are able to respond to changing environmental and economic conditions will depend on a range of social, political and biophysical factors. Our analysis here does not set out to explain these factors for the Yaqui Valley but rather presents an example of a framework in which these affects can be explored.

Our analysis indicates that average estimated adaptive capacity varies only slightly between the three management categories, yet distinct patterns appear between soil types in the poor and best managed fields (Fig. 4). In poor management areas, those farm units on the best soil types (silt loam and deep clay) with the lowest vulnerabilities exhibit above average-adaptive capacities while the farm units on the worst soil types (compacted clay and stony clay) with highest vulnerabilities exhibit below-average adaptive capacities. These results suggest that soil type may limit the ability of some poorly managed farm units to adapt to stressors such as increases in temperature. However, the best managed farm units on the best soils (e.g. silt loam) exhibit the lowest adaptive capacities and those on the poorer soils exhibit slightly above-average adaptive capacities. These results suggest that the best managed farm units with silt-loam soils have reached a maximum yield for the existing conditions, which contributes to their relatively low vulnerability but also results to their having a low adaptive capacity.

Fig. 6 illustrates the relative vulnerability implications of a 1°C shift in the mean minimum temperature for two groups of farm units in the Valley, those with the poor management on stony-clay soil (referred to here after as stony-clay farm units) and those with the best management on silt-loam soil (referred to here after as silt-loam farm units). The yield and temperature values shown in Fig. 6 were generated using Monte Carlo simulations of the minimum growing season temperatures and the corresponding predicted yields under existing climate conditions, and a possible future scenario with and without adaptations. This simulated times series illustrates that under existing conditions the stony-clay farm units, with a mean vulnerability 1.6 times that of the average farm unit in the Valley, maintain yields at or in close proximity to the threshold of damage (i.e. the point at which a farmer nets no profit). Meanwhile, the silt-loam farm units, with an average vulnerability 0.56 times that of the average farm unit in the Valley, remains well above the threshold. A 1°C shift in the average minimum temperature results in an increase in vulnerability to 1.9 and a corresponding increase in the frequency of the stony-clay farm units dropping below the threshold, with a relatively minor shift in the
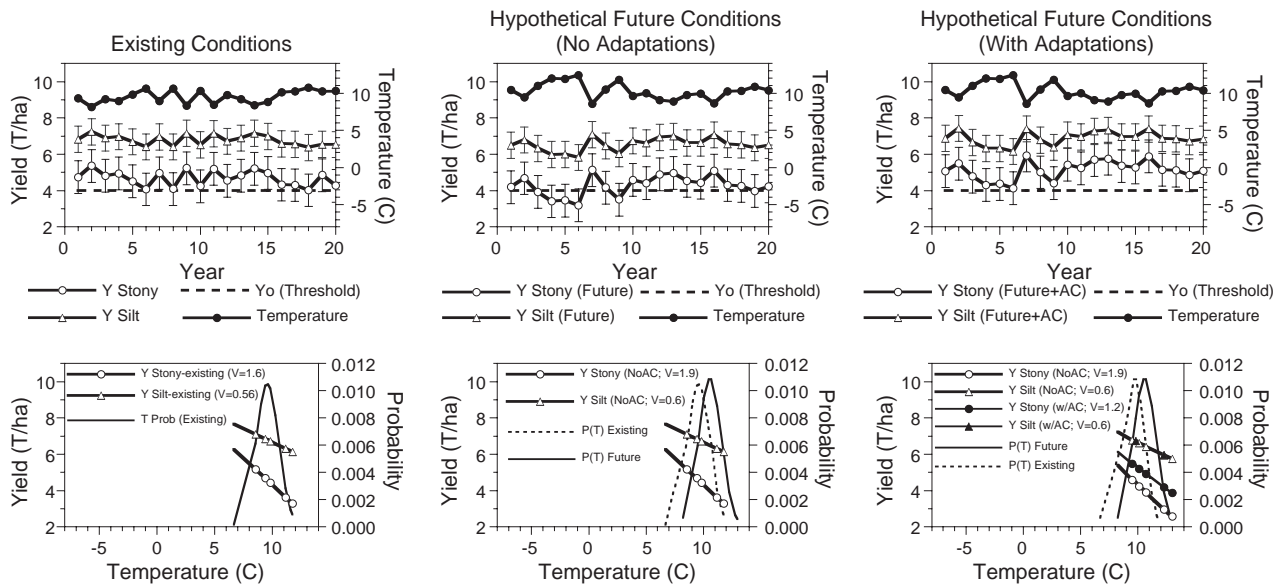
Fig. 6. Comparison of vulnerability implications for two groups of farm units under existing climatic conditions and a hypothetical future climate scenario. The times points on each graph were randomly selected from Monte Carlo simulations ($N = 500$) based on randomly generated temperature values from the distribution of temperatures derived previously from 20 years of data and the yield temperature function (Lobell et al., 2002) with random perturbations for the error in the slope and constant estimates generated from distributions representing their variability.

vulnerability and yield pattern in the silt-loam units. When potential adaptations are included in the analysis, however, the vulnerability of the stony-clay units decreases to 1.2 times that of the average farm unit under existing conditions, and the variability of yields shifts to primarily above the threshold. However, the relative vulnerability of the silt-loam farm units remains relatively unchanged in the future conditions even when the adaptive capacity has been realized.

Overall, this study suggests that farm units with the lowest minimum potential vulnerability (V_{min}) are those that are well managed on silt-loam soils and the farm unit with the highest minimum potential vulnerability are those that are poorly managed on stony-clay and compacted-clay soils. However, this analysis suggests that management can overcome soil type constraints. As a result, the factors that determine management level are likely to have the most effect on vulnerabilities in this region in the future. Our management variable incorporates many different factors that need to be examined to identify the causes of vulnerability and constraints on adaptive capacity. For example, can different management practices be attributed to differential access to credit, information or other institutional factors? We are currently conducting a survey that will address some of these questions.

4.3.3. Defining the system

Accurately defining the system, including identifying the appropriate outcome variables of concern and setting the relevant spatial and temporal scale, is critical for vulnerability analysis. In this case study, we selected wheat yield as our outcome variable of concern. Our analysis suggests, however, that yield alone might not be sufficient to capture the vulnerability of Valley farmers. For example, important coping strategies for farmers, such as shifting production patterns in response to price shifts, are not easily captured with wheat yield. An alternative outcome variable to consider would be household income. Focusing on the vulnerability of household incomes to a set of multiple stressors including temperature variability and change and market fluctuations would allow us to capture the differential abilities of households to diversify, not only within the agricultural sector but also across industries. We will explore these issues in future work.

Examining the management and coping strategies of farmers in the Yaqui Valley highlights the importance of spatial scale in vulnerability assessments. In this case study, we chose the farm unit as our system of analysis for simplicity. The farm unit however is not isolated, it affects and is affected by its surroundings. For example, high fertilizer application rates for wheat production, which have increased from 80 to 250 kg N ha^{-1} between 1968 and 1995 and contributed to more than a doubling of wheat yields during the same period, have led to large nitrogen losses in the ground and surface waters (Matson et al., 1998; Panek et al., 2000; Harrison, 2003). Although the ecological consequences of the transfers of these and other wastes to downstream estuaries have not been evaluated, they may pose a threat to important ecosystems on which coastal

communities depend for their livelihoods (Valdez et al., 1994). These sorts of externalities must be considered when defining the system of analysis, because, as suggested in this example, factors that may contribute to a farmer's resilience, such as fertilizer application, may lead to a fisherman's increased vulnerability.

The dynamic nature of vulnerability illustrated in this case study highlights the importance of the temporal scale of analysis. Ultimately, for policy makers, the vulnerability implications of annual fluctuations in the world wheat prices may not be as important as other factors such as resource scarcity. For example, in the semi-arid region of the Yaqui Valley, after 7 years of drought, water scarcity has become a serious threat to the region (Osuna, 2003). Over the short-term, water limitation does not appear to be a major factor in the vulnerability of yields, in part because farmers have adapted to drought by extracting groundwater. Over the long-term, however, if groundwater is extracted at a rate above the regional recharge rate, this may lead to increased vulnerabilities as pumping costs increase. Pumping groundwater may be increasing farmer's resilience to drought today while contributing to the vulnerability of farmers in the future. Evaluating these sorts of resilience and vulnerability tradeoffs between different temporal and spatial scales must be a focus of vulnerability assessments in the future.

5. Conclusions

This paper presents a methodology for quantifying vulnerability as the expected value of the sensitivity of selected variables of concern to identified stressors divided by the state of the variables of concern relative to a threshold of damage. In addition, we present a method for estimating the minimum potential vulnerability by accounting for a system's ability to adapt and respond to changing circumstances.

The application of the proposed metric in a vulnerability assessment requires: (1) the identification of outcome variables of concern (e.g. income, yield, health, ecosystem function); (2) the identification of stressors of concerns (e.g. climate change, drought, market fluctuations); (3) a model of the relationship of the outcome variables of concern to the stressors; and (4) base-line data from which the stressors-outcome model can be calibrated. The final assessment will depend on the strength of the data and model on which they are based. However, the proposed approach does not require detailed multi-variable predictive models of human–environmental systems, and can be applied using simple regression models that incorporate the critical factors.

We illustrate the proposed methodology in a vulnerability assessment of the Yaqui Valley, Mexico. Using a combination of remote sensing and GIS techniques we model the differential vulnerability of wheat yields to climate variability and change, and to market fluctuations. Our analysis suggests a skewed distribution of vulnerability exists within the study region, with most farmers exhibiting low vulnerabilities and a few farmers with high vulnerability. In addition, our method reveals that Valley farmers, without adaptations, are on average more vulnerable to a 10% decrease in wheat prices than a 1°C increase in average minimum temperature. Soils and management both contribute to relative vulnerabilities in the region, however, it appears that the constraints imposed by poor soil types can be overcome by improved management practices.

No single measure will be able to capture completely the multiple dimensions of vulnerability. Ultimately, vulnerability research will require a set of metrics that can help analyze and explain vulnerability characteristics within and between systems. The most effective metrics will be those that are generic enough that they can be applied to a wide range of settings. There are several reasons why we believe the proposed metric is an example of the type of measures that are needed. Firstly, the form is sufficiently general to apply to simple one-dimensional systems or complex multi-dimensional systems modeled in matrix form. Second, because the measure is unitless it is easily comparable between and within systems. Third, the metric can be used in a modeling framework where the vulnerability implications of future environmental or political scenarios can be evaluated and the uncertainties can be incorporated. Fourth, the proposed measure allows researchers to analyze four essential aspects of vulnerability independently—the state relative to a threshold of damage, sensitivity, exposure and adaptive capacity. Finally, the proposed metric is not confined to a particular conceptual framework but rather could be applied to test and compare the appropriateness of multiple frameworks in different systems.

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