DPSIR-ESA VULNERABILITY ASSESSMENT (DEVA) FRAMEWORK: SYNTHESIS, FOUNDATIONAL OVERVIEW, AND EXPERT CASE STUDIES

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HIGHLIGHTS

- A new DPSIR-ESA Vulnerability Assessment (DEVA) framework for land-resource assessment is presented.
- We broadly define a land-resource target system to include ecological resources and socioeconomic systems.
- DEVA operationalizes the process of assessing the vulnerability of a target system to external stressors.
- Six case studies provide examples of the key DEVA concepts and the seven DEVA steps.

ABSTRACT. *Land resources are central to understanding the relationship between humans and their environment. We broadly define land resources to include all the ecological resources of climate, water, soil, landforms, flora, and fauna and all the socioeconomic systems that interact with agriculture, forestry, and other land uses within some system boundary. Understanding the vulnerability of land resources to changes in land management or climate forcing is critical to developing sustainable land management strategies. Vulnerability assessments are complex, given the multiple uses of the assessments, the multidisciplinary nature of the problem, limited understanding, the dynamic structure of vulnerability, scale issues, and problems with identifying effective vulnerability indicators. Here, we propose a novel conceptual framework for vulnerability assessments of land resources that combines the driver-pressure-state-impact-response (DPSIR) framework adopted by the European Environment Agency to describe interactions between society and the environment, and the exposure-sensitivity-adaptive capacity (ESA) framework used by the Intergovernmental Panel on Climate Change to assess impacts of climate change. The DPSIR-ESA Vulnerability Assessment (DEVA) framework operationalizes the process of assessing the vulnerability of a target system to external stressors. The DEVA framework includes seven steps: (1) definition of the target system (land resource), (2) description of internal characteristics of the target system (state), (3) description of target system vulnerability indicators (adaptive capacity, sensitivity), (4) description of stressor characteristics (drivers, pressures), (5) description of stressor vulnerability indicators (exposure), (6) description of target system response to stressors (impacts), and (7) description of modifications to target system or stressors (responses). In stating that they have applied the DEVA framework, analysts acknowledge that they (1) have considered the full breadth of each DEVA element, (2) have made conscious decisions to limit the scope and complexity of certain elements, and (3) can communicate both the rationale for these decisions and the impact of these decisions on the vulnerability assessment results and recommendations. The DEVA framework was refined during invited presentations and follow-up discussions at a series of special sessions with leading experts at two successive ASABE Annual International Meetings. Six case studies drawn from the sessions elaborate on the DEVA framework and provide examples of the key concepts. The DEVA framework gives engineers, planners, and analysts a flexible new approach to apply a broad array of useful tools for vulnerability assessment of land resource systems.*

Keywords. *Driver-pressure-state-impact-response (DPSIR) framework, Exposure-sensitivity-adaptive capacity (ESA) framework, DPSIR-ESA Vulnerability Assessment (DEVA) framework, Land resource, Systems thinking.*

Increased demand for commodities produced from the land, climate change, land degradation, land conversion, and urbanization (Lambin et al., 2013) have increased the demand for land resources (Lal, 2019) and

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increased the interactions between socioeconomic and ecological processes (Estes et al., 2018). Land resources are central to understanding the relationship between humans and their environment (Rounsevell et al., 2012). However, few studies fully describe or define land resources, stressors, and their relationships. For example, a Google Scholar search on "land resources definition" (18 November 2019) provided only three studies that used the term. In its broadest definition, a land resource includes the environmental resources of climate, water, soil, landforms, forests, pastures, and wildlife on which agriculture, forestry, and other kinds of land use depend within some system boundary (Young, 2000). In this definition, a land resource includes abiotic aspects (such as climate, topography, and soil mineralogy) and biotic aspects (such as soil biota, vegetation, and fauna) that together define the state of the system. All biotic and abiotic components of the land resource have an ecological dependency and operate as a system. This definition notably leaves out the critical and integral influence of socioeconomic processes on the land resource. This definition also does not provide for a narrow definition of land resources that includes fewer components within the scope of the broad definition. The complex nature of land resources demands that research into sustainable land-resource management use a systems approach, i.e., interdisciplinary research that combines multiple dimensions to understand the dependencies among system components (Tripathi and Bhattarya, 2004). The sustainable provision of goods and services depends critically on managing land resources without damaging or depleting the natural resource base (Reenberg, 2006). To support the transition toward sustainable development, science needs to inform how changes in the use of land resources affect the environment and how this, in turn, feeds back into human livelihood strategies or influences the vulnerability of people and places (Rounsevell et al., 2012). Therefore, understanding the vulnerability of land resources to changes in land management or climate forcing is critical to developing sustainable land management strategies.

In general, vulnerability assessments are complex, given the multiple uses of the assessments, the multi-disciplinary nature of the problem, limited understanding, the dynamic structure of vulnerability, scale issues, and problems with identifying effective vulnerability indicators (Adger et al., 2004). Additionally, vulnerability is a theoretical concept and difficult to measure directly (Tonmoy et al., 2014). Making a theoretical concept operational requires providing methods or procedures (an operation) for mapping the operations to observable concepts (Kim, 2015). The methods or procedures are then called the operational definition, while in the case of vulnerability, the operational definition is called the methodology of a vulnerability assessment (Hinkel, 2011). The scientific information and knowledge in the methodology later become part of a process in a much broader decision-making system (Weaver et al., 2013). Due to the complexity of both vulnerability assessment and land resources (dual complexity), estimating the vulnerabilities of land resources to changes in land management or climate forcing is challenging but very important.

Modeling frameworks can be useful tools. However, a single operational framework for vulnerability assessments likely will not be applicable both in general as well as for specific applications (e.g., agriculture, water resources, poverty, coastal regions). The European framework of driver-pressure-state-impact-response (DPSIR) and the IPCC framework of exposure-sensitivity-adaptive capacity (ESA) are common tools. Many studies have used the DPSIR and ESA frameworks either partly, fully, or in combination with other frameworks for vulnerability assessment, often with smaller boundaries of target system and stressors. For example, the DPSIR and ESA frameworks were combined in several studies addressing vulnerability of agriculture to climate change in Black Sea catchments (Bär et al., 2015) and vulnerability of water resources to changes in climate and population in Kansas (Anandhi and Kannan, 2018). Previous studies have also used econometric methods (using survey information from questionnaires) or index-based methods (using indicators) for vulnerability assessments (Deressa et al., 2008). The index-based method is the most commonly used approach in vulnerability assessment (Bär et al., 2015). A good review of the frameworks used in vulnerability studies for agriculture and water resources can be obtained from Anandhi et al. (2016) and Anandhi and Kannan (2018).

The common challenges in using the ESA and DPSIR frameworks for vulnerability assessments of land resources are:

- The scope (boundary) of the land resource system is not clearly defined.
- Components of the vulnerability framework (e.g., exposure, sensitivity, adaptive capacity, driver, response) are not clearly defined.
- The scope of the study does not capture the complex nature of sustainable land-resource management (i.e., lack of a systems approach).
- The vulnerability assessment is either too broad (general frameworks applied universally for broad vulnerability assessments) or too focused (specific case studies, such as water resource vulnerability in a river basin or vulnerability of sea turtles in south Florida to changing climate) to provide useful guidance for assessments applied to other regions, scales, or objectives.
- The frameworks are constantly evolving. There are more than 25 derivative DPSIR-type conceptual frameworks, and they are constantly evolving. A good review can be obtained from Patrício et al. (2016).

To address some of these challenges, an invited technical session titled "Vulnerability Assessment of Land Resources for Sustainable Agricultural Development" was organized at the 2016 and 2017 Annual International Meetings of the American Society of Agricultural and Biological Engineers (ASABE) and synthesized at the 2018 Annual International Meeting. The invited presentations were given by a group of multi-disciplinary professionals (engineers, agronomists, soil scientists, and climate scientists) who shared case studies, lessons learned, overviews of cutting-edge technologies and design strategies, and best practices aimed at improving land-resource sustainability through vulnerability assessments. This multi-disciplinary approach through a series of

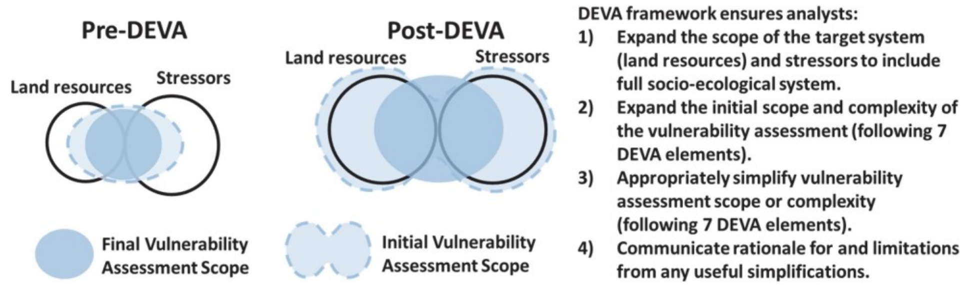

Figure 1. Enhanced vulnerability assessment with the DPSIR-ESA Vulnerability Assessment (DEVA) framework, showing traditional (pre-DEVA) and enhanced (post-DEVA) vulnerability assessment scope and complexity.

talks opened avenues to explore climate and land-use stressors important for vulnerability assessments. This article reviews and synthesizes the talks and the multiple discussions that followed, and develops a new integrated DPSIR-ESA Vulnerability Assessment (DEVA) framework for land resources assessment.

The DEVA framework is an important innovation for vulnerability assessments that represents a major re-evaluation of the known concepts: land resources and stressors (fig. 1). Consideration and description of the seven DEVA elements allows analysts to fully and systematically define the scope of the assessment. Limitations of scope within an element or exclusion of one or more elements are important to recognize, as they will limit the predictive power of the assessment and the robustness of the recommendations. In stating that they have applied the DEVA framework, analysts acknowledge that they (1) have considered the full breadth of each DEVA element, (2) have made conscious decisions to limit the scope and complexity of certain elements, and (3) can communicate both the rationale for these decisions and the impact of these decisions on the vulnerability assessment results and recommendations.

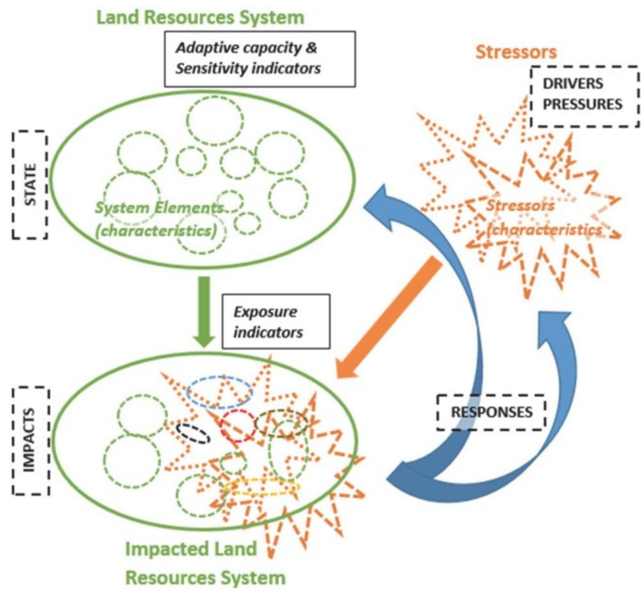

Figure 2. Proposed conceptual model of the DPSIR-ESA Vulnerability Assessment (DEVA) framework as applied to land resources.

THE DEVA FRAMEWORK

The proposed conceptual model of the DEVA framework (fig. 2) uses a novel systems approach to operationalize the theoretical concept using indicators. The enhanced model is evolved from Anandhi et al. (2016) and Anandhi and Kannan (2018) to take a broader view of the target system, stressors, and overall scope of the assessment. The hypothesis in the conceptual modeling of the DEVA framework is that there is a target system, and it is vulnerable to external stressors. In this article, the target system (ovals in fig. 2) is identified as a land resource, and the external stressors (dotted stars in fig. 2) can be changes in land use, climate forcings, or other external changes. Additional descriptions of the target system and external stressors are discussed in the various steps:

1. Definition of the target system: land resource.
2. Description of internal characteristics of the target system (state).
3. Description of target system vulnerability indicators (adaptive capacity, sensitivity).
4. Description of stressor characteristics (drivers, pressures).
5. Description of stressor vulnerability indicators (exposure).
6. Description of the target system response to stressors (impacts).
7. Description of modifications to the target system or stressors (responses).

In this article, the target system is comprised of internal elements, and those elements are defined by characteristics (dotted circles within the ovals in fig. 2). Stressors are external to the target system and are also defined by characteristics (dotted stars in fig. 2). Representation of the land resource can include multiple elements, including biophysical (BP), economic (E), social (S), and their combination (BPES). When the target system is exposed to stressors, the impacts are represented as changes in the characteristics (shape and color) of the target system elements (disfigured circles in fig. 2), representing changes to BP, E, S, and BPES. Each element responds differently (or not at all) to a stressor. The arrows represent the overall direction of processes in the conceptual framework as well as the direction of movement or time.

DEFINITIONS AND PERSPECTIVES

The target system, stressors, and intended uses of the vulnerability assessment define the complexity required in the conceptual framework. It must include essential components while excluding extraneous components. The conceptual framework simplifies the target system, stressors, and their interactions but still allows the effects of important scenarios to be represented in the target system response. We describe a seven-step process to develop a conceptual framework for a land-resource vulnerability assessment. Included in the description are the important factors to consider, how choices in each step affect the quality of the overall vulnerability assessment, and how decisions made in early steps impact later steps. The following sections describe considerations for each step of the framework in a way that can be adapted to different settings, situations, and scales, and recognizes that specific decisions must be made on a case-by-case basis.

Land Resource Target System

Defining the Target System

Definition of a target system for the purposes of a specific vulnerability assessment is a critical step. It is important to define the spatial, temporal, and functional boundaries that will be considered internal to the target system. Spatial boundaries define the areal extent of the system under consideration. The boundary may be defined by land ownership, political or other social units, agricultural or ecological region, or some other area of interest. Temporal boundaries define the time periods representing native, baseline, current, and future periods for the assessment. Depending on the analysis, it may be important to define a period of time that represents pre-settlement or native conditions, which may differ depending on the stakeholder viewpoint. Some other baseline-condition time period might be relevant for comparison to other scenario time periods. Current conditions may represent a snapshot based on conditions today or some near-past period, depending on the availability of data to define the period or the need to span a natural system cycle. The future period often depends on the planning time horizon but may also be determined by the availability of realistic forecasts for stressors or system states. Functional boundaries define the important elements, processes, and states within the system under consideration. The nature of interactions within the system or with stressors may make some elements more important than others to include when defining the system. Similarly, some processes or states may be more important than others to include or define for understanding how or to what degree elements are interrelated within the system or with stressors.

Definition of the target system impacts how the analysis is structured, how the results are presented, and perhaps how the land is valued. For example, placing value in the land rather than in products from the land may affect the structure of the system or what is considered internal to the system. The definition of land resources varies depending on the specific target land resource system being described and the goals of the vulnerability assessment. A narrow definition of the land resource (fig. 3) may include only the physical geography or soil elements but exclude biological components of the carbon cycle or climatic elements, despite their close relationship to the physical geography and soil elements of the land. This approach simplifies the description of the

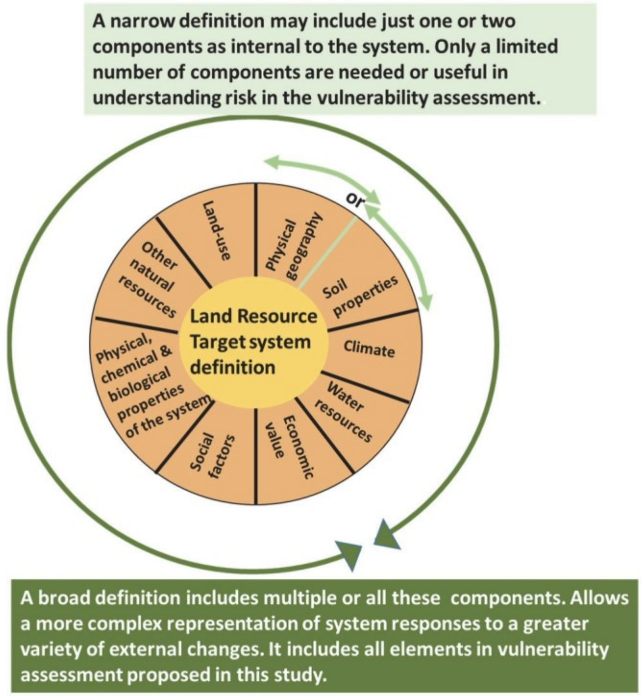

Figure 3. Definition of the target system for DEVA land resource vulnerability assessment.

state, adaptive capacity, and sensitivity of the system and focuses on a limited number of elements in the vulnerability assessment. This narrow definition might be appropriate to help understand the risk of various land-use changes to the sustainability of a soil-resource base of a region; in this case, crop type, land-use practices, climate, and other components would all be considered external to the system.

The definition of the land resource is broadened when it considers biotic elements produced by the land as internal to the system. Relationships between biotic elements and abiotic elements can be represented explicitly, which increases the flexibility of the assessment to consider a broader range of stressors. This also allows biotic elements to be considered as part of the land resource, and thus part of the economic value of the land.

A broad definition of a land resource system at a particular location and time may include physical, chemical, biological, climatic, economic, and social functional elements (fig. 3). This explicit representation allows a more complex representation of system responses to a greater variety of external changes. Expanding on the definition of Young (2000), we propose that, broadly defined, a land resource includes all the ecological resources of climate, water, soil, landforms, flora, and fauna, and all the socioeconomic systems that interact with agriculture, forestry, and other land uses within some system boundary.

Perspectives on the Target System

Definition of the land resource system can have major ramifications on an assessment. For example, in a land resource system described by one expert, it was well known that both the irrigation water source (surface water or groundwater) and the irrigation method (flood, sprinkler, drip) had large impacts on the simulated effects of irrigation on soil moisture, field runoff, and groundwater table depth (Leng et al., 2017), each of which were important system responses in this vulnerability assessment. If the target system was defined as the soil root zone, then flood irrigation would have the lowest crop water use efficiency, as it increases recharge to groundwater and increases runoff, which are both considered losses to the target system, resulting in reduced root zone soil moisture for the crops per unit of water applied. However, if the target system was defined more regionally to include the alluvial aquifer and diversion canals used for irrigation, then water use efficiency would be defined by the broader system definition, and crop evapotranspiration would be the only system loss for all irrigation sources. Thus, the target system definition would have a major influence in defining water use efficiency and interpreting differences among flood, sprinkler, and drip systems in this vulnerability assessment.

Land Resource System State

Defining the System State

Once the target land-resource system is defined, the state of the system must be defined for a given place and time. From a systems perspective, the state represents the characteristics of various internal biophysiochemical elements necessary to describe land resources, the relationships among internal elements, and how the target system interacts with external stressors and external land-resource systems. It is important to consider that (1) the characteristics of many elements vary continuously and anisotropically (i.e., they exhibit an uneven distribution) in three-dimensional space and time, (2) the elements interact with stressors or other external land-resource systems (e.g., geology, aquifers, cultural resources, other elements associated with the land resource that are not internal to the system definition, or other adjacent land-resource systems external to the land-resource system being considered), and (3) the characteristics can be measured non-exhaustively at specific locations and time periods (Grunwald and Barak, 2003). The state may also define the characteristics of important elements (e.g., weather, soil, plant, and animal characteristics) that determine the biophysical production potential of the land-resource system (Bindraban et al., 2000).

In the narrow definition of land resource focusing on soil elements (fig. 3), the current characteristics and the value of the soil would be defined by the system state. The state can represent the current condition of the land resource. Here, time and location can be vague or fuzzy when the current conditions are not clearly defined or described. An example characteristic that might be defined would be the crop output for a given soil unit.

A broader system definition including biotic elements would allow the current land resource state to represent agricultural production as a function of other internal system elements and processes. The system state would focus on defining the characteristics of important elements and describing how the state (such as the economic value of the crops grown within the system) changes when stressed by external influences, such as climate change, new cropping patterns, or removal of land from a region's agricultural base. Because these changes could also affect other elements of the system (such as soil properties, water availability, crop types and distributions), the processes that would interactively affect crop value are also represented within the system.

A broad system definition (fig. 3) requires defining the characteristics and interactions of a broad array of elements. This broad definition explicitly recognizes the spatial and temporal interactions of the elements within the system boundary and time period. A broad definition allows the key system elements to explicitly represent the system's response to change, which allows the system characteristics and resulting utility of the land resource to directly represent how the system changes in response to stressors.

A limitation of this approach is that some of the system changes are considered external factors or stressors (e.g., land use change or climate change) and are defined outside the system. For example, for a system state that defines a relationship between soil and land-resource economic productivity elements but does not include changes in climate-soil interactions, any new soil characteristics resulting from climatic change must be estimated externally and provided to the system; the system is too simplistic to represent the relationship between changes in climate and soil directly.

Perspectives on the System State

One expert divided the target land-resource system into individual land-use elements. Land uses included crop production (dryland and irrigated for food, feed, and bioenergy production), urban land use, pasture areas for animal production, wetlands, and riparian gallery forests. Each land-use element had internal subprocesses that defined the element's response to change, and the land-use elements were defined to highlight how the change affected each element individually. In a broader agricultural land-resource assessment, dryland and irrigated agriculture might be used as two aggregated elements. The state (current conditions) would then be defined and described for the aggregate element, and interactions with other elements or stressors would represent aggregate responses. In a more specific land-resource assessment, individual crops, crop-soil combinations, or other highly disaggregated elements might be defined, allowing more specific, complex interactions with other elements or stressors.

System Adaptive Capacity and Sensitivity

Defining Adaptive Capacity and Sensitivity

In addition to defining the state of the land resource system, it is important to understand and define how the system elements respond to stressors. We define two types of response: sensitivity and adaptive capacity. Sensitivity describes the overall response of a system or element to a stressor. It is framed as the response (magnitude and direction) of the target system (or each element in that system) to the stressor, either with or without adaptation. Adaptive capacity describes the adjustment of a system element to the stressor whereby the element retains its original function within the system. Adaptive capacity encompasses the system's biophysiochemical ability to respond to the stressor as well as the ability of managers of the system to recognize and manage or mitigate risk, plan and implement adaptation strategies, display financial and emotional flexibility to incorporate change, and even exhibit awareness of the stressor and the need for adaptation (Briske et al., 2015). With this definition, humans can be included as important elements of a land-resource system and may act to either enhance or constrain the system's adaptive capacity. Adaptive capacity and sensitivity indicators provide a method to characterize how system elements respond to stressors.

For the purposes of vulnerability assessment, it is critical to differentiate between an adaptive system response and a non-adaptive response. An adaptive system response to a stressor may be subtle or extreme but does not represent a fundamental change to a new system state or to a new functional response relationship. That is, the system is fully recoverable. Many biophysical models used to simulate system response to stressors inherently assume a fully adaptive system, or that all sensitivity falls within the system's adaptive capacity. The system responds to a stressor according to a deterministic relationship, but the relationship is not altered by acute or repeated exposure to the stressor. A non-adaptive response indicates that the system state has changed to a degree that it responds to a stressor in a fundamentally different way. In this case, the analyst may simulate non-adaptive responses by altering the system state to some presumed new state (and possibly new response functions) and simulating the system response from the altered state. It is also possible that the target system has an adaptive response within a certain range, but the response becomes non-adaptive beyond this range. The system may also have multiple equilibrium states, which can be determined by the nonlinear dynamics of the system or by experiments.

Perspectives on Adaptive Capacity and Sensitivity

To represent abstract components that cannot be measured directly, sensitivity and adaptive capacity are represented using one or more proxy variables and/or indicators. To represent sensitivity and adaptive capacity, changes in these proxy variables and indicators can be correlated with variables and indicators that represent the state. Adaptive system response tends to be assumed in many system models and vulnerability assessments due to the difficulty of explicitly simulating non-adaptive shifts. However, consideration of non-adaptive system response may be the focus of a vulnerability assessment.

Stressor Drivers and Pressures

Defining Drivers and Pressures

Stressors result from drivers that can be natural but are often anthropogenic in origin. An anthropogenic driver is often a societal need for food, energy, water, or land resource products or services. The driver creates a pressure on the land resource in the form of a stressor. Stressors are described by characteristics that represent the ways the stressor affects the target system. Stressors can be abiotic (e.g., climatic factors, such as heat, drought, or anoxia due to saturated soil conditions), biotic (e.g., pest factors, such as insect infestations, foliar diseases, or overgrazing), or land use (e.g., land cover, land degradation, or human actions such as irrigation, shifts in crop rotation, or residential development). Consideration of a stressor on a system implies that a normative (i.e., non-stressed) state existed prior to exposure to the stressor.

Perspectives on Drivers and Pressures

Climate change is one possible external stressor (fig. 4). In the food-energy-water nexus, land-use change from food to bioenergy products is another possible external stressor. External stressors are represented using characteristics. For example, climate change can be a stressor, and changes in rainfall intensity and timing, and maximum and minimum temperatures can be considered characteristics. These external characteristics are derived from drivers (social, economic, environmental) that exert pressures (stressors) on the target system, which in turn change the system's internal characteristics. For example, changes in rainfall and temperature characteristics (stressor characteristics) impact agroecosystems by impacting their internal characteristics and processes. These impacts are specific to each location, climate, and biophysical characteristic.

Stressor Exposure

Defining Exposure

Exposure defines the degree of stress on the elements of a target system (Anandhi et al., 2016). The degree of stress depends on the characteristics of the target system (or elements of the system) as well as the stressor. For the system, the responsiveness is characterized at the element level by the element's sensitivity, which describes the overall responsiveness of an element, as well as its adaptive capacity, which describes the portion of an element's responsiveness that is resilient or does not impact element or system function. The exposure relationships can be complex, but these relationships are critical to describing exposure in a vulnerability assessment. Exposure indicators provide a method for characterizing these relationships among stressors and a target system (Anandhi et al., 2016). Examples of exposure indicators are plant failure temperature (Anandhi and

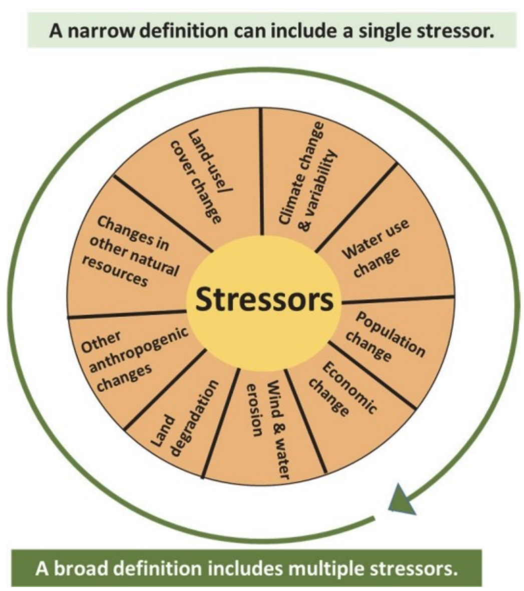

Figure 4. Definition of stressors for DEVA land resource vulnerability assessment.

Blocksome, 2017) and frost indicators (Anandhi et al., 2013a, 2013b).

Perspectives on Exposure

In a given vulnerability assessment, many exposure interactions with various system elements may be important to understand. For stressor exposure, characteristics such as proximity, duration, intensity, recurrence interval, and compounding factors are often important considerations. Climate change (driver) has important impacts on land resources through exposure to changes in temperature and precipitation (stressors), which also affect terrestrial water storage and fluxes, including soil moisture, surface and subsurface runoff, and groundwater (characteristics of system elements), that constrain the water available for irrigated and non-irrigated crops (characteristic of system response). Irrigation is influenced by plant water stress, which influences demand, and by irrigation water supply, which is influenced by factors such as irrigation water sources, irrigation methods (sprinkler, drip, and flood irrigation), and water management that regulates streamflow to meet multiple objectives of reservoirs. Considering the interactions among external stressors, including climate change, and internal system responses, such as irrigation and water management decisions, it is important to understand their combined influence on land resource exposure. For example, the irrigation water supply may be influenced by climate change, so the system's ability to adapt may be constrained by the stressor. Increasing bioenergy production to mitigate climate change may result in increased irrigation water use and increased water stress that impacts the land resources (Hejazi et al., 2015).

System Impacts

Defining Impacts

The impacts of stressors on the land-resource system may result in changes to system elements, depending on the adaptive capacity and sensitivity of the elements and exposure to the stressor. Stressors may change system elements differently or not at all. The changes may create a substantially new system state, which we call the impacted land-resource system (fig. 2).

Perspectives on Impacts

Models are commonly used to define the land-resource system impacts that result from stressors. A simple model of crop ET and soil water balance may represent the change in state (e.g., soil moisture) in response to a stressor (e.g., change in climate) at the field scale. At the global scale, the quantification and mapping of ET using global datasets is well established and can be used to represent the impact of climate shifts on vulnerable ecosystems.

System Responses to Impacts

Defining Responses to Impacts

Responses essentially allow the vulnerability assessment process to iterate using the impacted land-resource system as the new system state, returning the process to the previously defined land-resource system state (fig. 2). The new state of the impacted land resource may also change its adaptive capacity or sensitivity to compounding or future stressors, which should be considered in more extensive vulnerability assessments.

Perspectives on Responses to Impacts

Responses by decision-makers may include changes to the stressors or the system. Actions may make changes to drivers or pressures that change the function or exposure of stressors or make changes to the impacted system state that change its adaptive capacity or sensitivity to current or future stressors. Climate and land-use changes may both affect groundwater recharge and upwelling through changes to transpiration and rainfall, and these could impact irrigation water supply. Depending on the effects of irrigation water source (surface water or groundwater) and irrigation method on irrigation water use efficiency, the impacts on agroecosystems can be rather different (Leng et al., 2017), evoking different responses (e.g., political actions or management measures) that can affect drivers, pressures, state, or impacts (Bär et al., 2015). Water management may mitigate the impacts of climate change on hydrological drought (Wan et al., 2017), so considering such adaptive capability is important to assess the impacts of climate change on water available to support the land resources. An effective vulnerability assessment suggests responses to decision-makers that are likely to lead to the desired outcomes and provides a framework to assess the likely impacts that would result from changes to the stressors or the system.

Case Studies

The following six case studies were drawn from studies published prior to development of the DEVA framework. However, they each incorporate many of the DEVA elements, which we are careful to highlight, and provide concrete examples of the key concepts. In some cases, we also identify specific ways that the DEVA framework would have enhanced the analysis. In applying the DEVA framework, the analysts (ideally) would have (1) considered the full breadth of each DEVA element (such as land resource and stressor definition), (2) made conscious decisions to limit the scope and complexity of certain elements, and (3) communicated both the rationale for selecting fewer elements and components and the impact of these decisions on the vulnerability assessment results and recommendations.

Case Study 1: Climate Variability, Climate Change, and Irrigation as Stressors in the Southeast U.S.

This case study, focused on the Apalachicola-Chattahoochee-Flint (ACF) River basin (target) in the southeast U.S., demonstrates how climate variability, irrigation, and climate change (exposure and stressors) can make the land resources of this basin vulnerable (Johnson et al., 2013; Singh et al., 2015, 2016). The system was defined spatially by the 48,500 km^2 ACF boundary for the near-present condition (state). In its current state, the basin's large irrigated agriculture, rural economy, streamflows, and endangered species are intertwined and vulnerable. In a normal or wet year, irrigation does not act as a major stressor in the basin. However, droughts induced by climate variability, confounded by subsequent excessive water withdrawals for irrigation, make the basin's land resources vulnerable during dry years. Although quite detailed, this case study used a narrow definition of the target system for the land resource vulnerability assessment by including only the soil water component of the root zone, the water use component of the cropping system, the surface water and alluvial aquifer system, and a recent historical climate condition (fig. 3). A broader definition would have included socioeconomic value, chemical and biological properties, and other (than agriculture) natural resources of the system. However, even though a narrow definition of the target system was used, except for evaluating the adaptive capacity of the system, the case study adequately defined the current state, system sensitivity, drivers and pressures, exposure, impacts, and responses of water within the land-resource system.

Case Study 2: Water Use Element of a Land Resource System in the Midwest U.S.

This case study focused on the water resources vulnerability in Kansas (in the High Plains region and overlying Ogallala aquifer) as the target system (Anandhi and Kannan, 2018). This study used a narrow definition of the land-resource system (water use was the single element) to assess vulnerability using six of the seven DEVA steps. Twenty-six indicators were used to represent the target system's adaptive capacity and sensitivity and the exposure of stressors applied to the land resources. Climate and population change were the drivers. Climate change and variability were the external stressors used in this study. The stressor characteristics were used to estimate the exposure using indicators (e.g., extreme temperature change). Streamflow and ET were the indicators used to understand the state as well as the impacts on the target system (as response variables) to exposure from stressors. The correlation of the response variables to the exposure indicators was used to understand the sensitivity and adaptive capacity of the target system. The indicators were analyzed individually after normalization and aggregated to assess overall vulnerability.

Case Study 3: Land Use Element of a Land Resource System in the Midwest U.S.

This case study focused on crop production land use in Kansas (in the High Plains region and overlying Ogallala aquifer) as the target system (Anandhi et al., 2016). This study used a narrow definition of the land-resource system (land use was the single element) to assess exposure, which is one component of the DEVA framework. This study compared five approaches to estimate exposure of precipitation and temperature change and variability on land used for crop production in the region considered the "breadbasket of the world." Exposure to the external stressors (precipitation and temperature change) represented the climate change and variability drivers in this study. The stressor characteristics were used to estimate the exposure using indicators (e.g., extreme temperature change). Plant growth and development indicators (e.g., growing degree days, phenological stages) were used to understand the changes in state (impacts) of the target system. Crop yield was the response variable for the target system. The number of indicators (1 to 6) varied with the five approaches used to estimate exposure. The correlation of the response variables to the exposure indicators was validated using information on crop yield as impacted by temperature and precipitation obtained from performance tests, as well as information in the literature.

Case Study 4: Transfer of Water Rights from Farming to Domestic Water Use in the Western U.S.

This case study focused on water rights transfers in the Palo Verde Irrigation District (PVID) in California (Senay et al., 2017). The PVID comprises about 400 km^2 of farmland that is irrigated from the Colorado River using a system of dams, pumping stations, and canals (the system initial state included these flow alterations). With the growing urban population and increasing demand for domestic water use outside the system (driver), demand on the water supply has increased, which affects the PVID. The Metropolitan Water District (MWD) has devised a crop fallowing strategy (pressure) to encourage California farmers to reduce their use of the Colorado River. The fallowing program began in 2005, with MWD entering into agreements with PVID farmers on a 35-year fallowing program that pays farmers for not irrigating a portion of their land so that water will be saved and transferred to southern California for urban water use. Remote sensing-based ET data were used to monitor and assess the impact of such decisions and agreements on the land resource. Senay et al. (2017) used historical Landsat data before and after the fallowing program (1984-2014) to evaluate the spatiotemporal dynamics of crop water use in the PVID from a generated 31-year dataset of field-scale ET. The study showed that the major year-to-year fluctuations and trends in crop water use (impact) were dominated by the land and water management decisions (changes in land-use state) rather than the increasing air temperature and atmospheric water demand (climatic pressure). The fallowing program resulted in a major reduction, up to 132 million m^3 (107,000 ac-ft), in crop water use during the peak fallowing year (impact). However, the impacts of such water rights transfer from agriculture to domestic water use on other aspects of the land resource (e.g., water quality, ecosystem function) and hydrologic processes, including an assessment of system adaptive capacity, were not studied and require further investigation.

Case Study 5: Broader Definition of a Land Resource System and Stressors (Several Elements) in the Southeast U.S.

This case study is based on three studies in several states in the southeastern U.S. (Anandhi and Bentley, 2018; Anandhi et al., 2018a, 2018b). Together, these studies used a broad definition of the land-resource system (multiple elements including land use, water resources, other natural resources, climate, biological systems) and stressors (multiple elements including precipitation and temperature change, land-use change, changes in other natural resources). The components of DEVA were used in these studies. Climate change and variability (specifically, changing temperature and precipitation) and land use and land cover changes disturbed the various components of the land resources (drivers). These drivers exerted a certain pressure on the land resources (e.g., forest restoration, urbanization, land fragmentation, agricultural development, frost, warm/cold/wet/dry spells, hurricanes, droughts, sea level rise, hydrological parameters). The state of the land resource components was represented using the land resource elements' characteristics, such as structure, growth, development, quality, quantity, and/or availability. The impacts of these stressors, drivers, and pressures were represented using changes in the characteristics (e.g., changes in indicators of hydrologic alterations, biomass, yield, growth and development, mortality rates). The responses to these impacts resulted in several adaptation strategies (e.g., developing environmental flow, infrastructure modifications, introduction of new varieties). The input data for these studies were the results from a meta-analysis (synthesis and analysis of published literature) as well as 50+ indicators estimated from observed data.

Case Study 6: Weather and Climate Forcing as Stressors in Kansas Land Resources: Spring Phase

This case study focused on land resource vulnerability in Kansas as the target system (Aiken et al., 2017), defining the land-resource system by political geography (county boundaries) from 1970 to 2007. Emphasis was given to the spring phase of the cropping system as represented by winter wheat productivity, a crop that dominates the allocation of arable land in Kansas. The state of the system was represented by land allocation, on a county basis, as well as land productivity, as indicated by county-average wheat yields. These two state variables also indicated the adaptive capacity and sensitivity responses to stressors and drivers, both implicit (technology trends, market and agricultural price policy signals) and explicit (drought indicator and El Nino Southern Oscillation (ENSO) climate forcing). Stochastic analysis indicated two sectors of the land-resource system, corresponding with semi-arid (western Kansas) and sub-humid (eastern Kansas) climate regimes, an inference that was supported by regional analysis of long-term drought indicators (Zambreski et al., 2018). Adaptive capacity was indicated by trends for declining land allocation to wheat, representing land management decisions that were likely influenced by the value of winter wheat relative to alternative crop choices. Adaptive capacity was also indicated by trends in land productivity of wheat, reflecting adoption of enhanced production technology by land managers. Regression analysis provided indicators of target system vulnerability (exposure) to stressors; on an annual basis, land allocation to wheat declined by 0.6%. However, land allocation was not strongly related to weather and climate stressors (drought and ENSO indicators). Land productivity (spring phase) increased by 40 kg ha^{-1} on an annual basis, and productivity was strongly related to weather and climate stressors (drought and ENSO indicators). Modifications in the semi-arid sector of the target system are anticipated due to the development and adoption of drought-tolerant corn hybrids. Directly drilling wheat into corn stubble eliminates the ten-month fallow (non-cropped) period and increases the exposure of the spring phase of land productivity to weather and climate stressors. This non-adaptive change is likely altering the structural dependencies of the land resource system in this water-deficit region.

Knowledge Gaps

Representation of Land Resource Elements and Stressor Information in the Seven Steps

The characteristics and processes of both elements and stressors govern the land-resource system responses that can be represented in a vulnerability assessment. Often, available models are used that inherently constrain the element and stressor characteristics, perhaps in ways that do not allow key responses of elements nor interactions between elements to occur. The DEVA framework guides assessments toward first considering the important elements and stressors along with the responses and interactions that are important for the assessment, and then finding models that meet those criteria and constraints, not the other way around. This may force modelers and analysts to rethink model representations and functions to meet the goals framed by the DEVA approach.

Tools and Data Sources for Assessment of Vulnerability of Land Resources

The presentations at the ASABE AIM sessions extensively discussed available modeling tools and their application in DEVA analyses. Hydrologic and other Earth systems models are useful tools for addressing questions related to climate change and climate impacts, mitigation, and adaptation. However, some of the human components related to natural resource use and management (e.g., economics, policy) are often not represented in these models, which limits their ability to address important aspects of some DEVA applications, such as those related to the complex energy-water-land nexus. Extending Earth systems models to include human systems is critical for predicting future changes in land resources that result from interactions of human and natural systems from local to global scales (e.g., Caldas et al., 2015; Kraucunas et al., 2015).

Lack of Consistent, High-Quality Historical Observations

Despite the improved spatial coverage provided by satellite and global weather datasets, there is still a need for high-quality *in situ* datasets to downscale, bias-correct, and calibrate environmental datasets. While satellites can help collect impressive environmental data that can be interpreted reliably in a relative sense, both in space and time dimensions, the absolute magnitude typically requires bias correction and downscaling. There is a lack of *in situ* biophysical and socioeconomic datasets, such as groundwater, hydraulic, and land properties (e.g., hydraulic conductivity, perceptions on water use, energy price fluctuations). This lack can only be corrected with ground-based observations that are well distributed to cover diverse agro-hydro-climatic regions.

Recommendations for Future Work

The research literature is replete with examples of tightly focused applications of hydrologic and Earth systems models. Application of the DEVA framework to these modeling efforts has multiple benefits. The DEVA framework ensures that the context for the modeling analysis is maintained, which is critical in clarifying the intended use, and thus the appropriate approach toward evaluating, interpreting, and communicating the results (Harmel et al., 2014, 2018) of a modeling effort. The DEVA framework focuses efforts toward explicitly defining the target system boundaries, system element and stressor characteristics, stressor exposure characteristics, and system element response functions, instead of allowing these characteristics to be defined implicitly as a consequence of model selection. Finally, the DEVA framework draws attention to the differences between adaptive and non-adaptive responses to stressors, as well as natural and anthropogenic responses, that inform or alter succeeding system states and responses, which are typically not considered in traditional modeling studies. Thus, we strongly urge that studies addressing land resource vulnerabilities and responses to stressors, including those that are currently framed as hydrologic or Earth systems modeling applications, first apply the DEVA framework to ensure that all necessary elements and relationships are explicitly included in, or knowingly excluded from, the analysis.

The applicability of various indicators for specific DEVA applications should be explored. For example, an indicator perceived as useful by an agency decision-maker may be different from the indicator perceived as useful by a producer, and an indicator useful in the assessment of corn production vulnerability may be different from the assessment of grazing systems. A synthesis of indicators used in various studies to represent the elements of the DEVA framework and components of the definition of land resources and stressors would provide valuable guidance to future vulnerability assessments.

Vulnerability assessments demand ground-truthing of the results as part of an adaptive resource management framework of analysis, action, monitoring, and adaptation. We strongly recommend that government agencies at all levels continue expanding their ground observation networks to improve our understanding of the spatiotemporal dynamics of land resource drivers, responses, and indicators. Improvements are also urged in the spatial and temporal coverage and accuracy of satellite estimates. Integration of citizen-science data collection with satellite-based systems could greatly improve ground data coverage at an affordable cost. To the extent that historical records are unavailable for trend analyses, land resource studies may need to explore the possibility of adapting techniques generally used by climate scientists, such as paleo records and tools.

Conclusions

Land resources are central to understanding the relationship between humans and their environment. Land resources and vulnerability assessments are theoretical concepts that elude understanding. Due to the complexity of both vulnerability assessment and land resources (dual complexity), estimating the vulnerabilities of land resources to changes in land management or climate forcing is challenging but very important. Modeling frameworks can be useful tools. Many studies have used multiple frameworks for vulnerability assessment. This study addresses the need for clarity in defining the framework for land resources vulnerability assessment with appropriate complexity to define the important land resource system elements, processes, interactions, and feedbacks and capture the complex nature of sustainable land resources management.

A novel conceptual framework for integrated DPSIR-ESA Vulnerability Assessment (DEVA) of land resources combines the driver-pressure-state-impact-response (DPSIR) framework adopted by the European Environment Agency with the exposure-sensitivity-adaptive capacity (ESA) framework used by the IPCC to assess impacts of climate change to describe interactions between society and the environment. The DEVA framework operationalizes the process of assessing the vulnerability of a target system to external stressors. The proposed DEVA framework includes the following seven elements: (1) definition of the target system (land resource), (2) description of internal characteristics of the target system (state), (3) description of target system vulnerability indicators (adaptive capacity, sensitivity), (4) description of stressor characteristics (drivers, pressures), (5) description of stressor vulnerability indicators (exposure), (6) description of the target system response to stressors (impacts), and (7) description of modifications to the target system or stressors (responses).

The definitions of land resources and stressors were developed with multiple components. We broadly defined a land resource to include all the ecological resources of climate, water, soil, landforms, flora, and fauna, and all the socioeconomic systems that interact with agriculture, forestry, and other land uses within some system boundary. A narrow definition of a land resource has fewer elements or more simplistic representations of specific elements, while a broad definition includes multiple or more complex representations of elements.

In stating that they have applied the DEVA framework, analysts acknowledge that they have (1) considered the full breadth of each DEVA element, (2) have made conscious decisions to limit the scope and complexity of certain elements, and (3) can communicate both the rationale for these decisions and the impact of these decisions on the vulnerability assessment results and recommendations.

The DEVA framework was demonstrated with several case studies. Each case study highlighted the application of several elements of the DEVA framework to land resources in different parts of the U.S. Knowledge gaps and recommendations for future work to enhance vulnerability assessments of land resources were also identified.

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