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Rapid appraisal using landscape sustainability indicators for Yaqui Valley, Mexico

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A R T I C L E I N F O

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A B S T R A C T

An approach for rapid appraisal of agricultural landscapes was developed and applied to the Yaqui Valley, Mexico, in order to assess progress toward sustainability. Indicators were prioritized with input from stakeholders, and then data were collected to gauge progress toward targets for those metrics. This study identifies and addresses some of the practical challenges and limitations that arise when assessments must rely on readily accessible information. The sources and quality of information to determine baseline and target values and to support future monitoring are reviewed for indicators of soil quality, productivity, biodiversity, vulnerability, poverty, transparency, and economic implications of crop diversity. Appraisal results suggest land management practices that conserve and increase the efficiency of water and nutrient use contribute to achieving goals endorsed by stakeholders. And in this arid, irrigated region, risks for soil compaction and salinization must be monitored and minimized. The approach illustrates how common gaps in reliable and scale-appropriate data can be addressed by focusing on stakeholder priorities and best available information. The approach can be applied in other regions and landscapes to identify and test strategies designed to move toward increasing agricultural sustainability.

1. Introduction

1.1. Agricultural landscapes

Sustainability reflects diverse aspirational goals, which are likely to be adjusted over time with changing conditions and stakeholder perceptions (Dale et al., 2019). Thus, no single theoretical optimum can be described for sustainable landscapes (Firbank, 2005). Instead, the bio-physical and socio-economic conditions that foster progress toward sustainable agricultural landscapes fall along continuums of being more, or less, favorable for achieving a defined set of goals for a given system. Achieving progress toward sustainability thus requires farmers, consumers, and other stakeholders to first identify common goals. Within agricultural landscapes, stakeholders typically consider agriculture's effects on ecosystems and communities while also ensuring the production of food, feed, energy, materials, and other services required by society (Wu, 2013).

Agricultural landscapes encompass patterns and processes of agro-ecosystems as well as the environmental and socio-economic factors that influence them (United Nations Food and Agriculture Organization, 2018). A landscape view of agricultural systems often requires consideration of multiple spatial and temporal boundaries (Opdam

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et al., 2018). For spatial and temporal examples, individual fields have spatial boundaries that are distinct and often disconnected from sources of water for irrigation, and the rainy season may not coincide with the timing of the growing season or high crop water demand. Ideally, landscape analysis combines spatially and temporally explicit data from environmental, economic, and social dimensions to reveal relationships in agro-ecosystem patterns and processes over time such as material and energy flows, genetic diversity, and natural and human-made resources, as well as climatological and cultural settings (de Groot et al., 2002; Renetzeder et al., 2010; Groot et al., 2007). Understanding those relationships can guide decisions affecting agro-ecosystems and socio-economic management practices that are needed to achieve goals for improvement in agricultural landscapes (Dale et al., 2019; Ness et al., 2007; Kienast et al., 2009; van Zanten et al., 2014; Sattler et al., 2010).

A systems approach for assessing progress toward sustainability of agricultural landscapes (Eichler Inwood et al., 2018) integrates environmental, social, and economic factors; encourages continued stakeholder participation; accommodates a flexible, stakeholder-informed indicator suite; and allows adaptation to multiple sites and stakeholder goals. We applied such an approach in the Yaqui Valley of western Mexico to identify priority indicators for assessing sustainability with input from stakeholders (Eichler Inwood, 2018; Dale et al., 2015). Ecological indicators are used to assess the condition of the environment, to afford an early warning signal of changes in the environment, or to diagnose the cause of an environmental problem (Cairns et al., 1993). The process of selecting indicators engages stakeholders and local experts to identify and rank candidate metrics according to established criteria (Dale et al., 2019; Eichler Inwood, 2018). The underlying premise is that the selected suite of indicators informs adaptive management decisions (Lin, 2011; Roling et al., 2000; Tilman et al., 2002) by stakeholders such as farmers, community members, research and development organizations, and local and national policy-makers.

1.2. Objective

The goal of this paper is to document a rapid appraisal method for assessing progress toward sustainability of agricultural landscapes using information readily available. This approach is analogous to that of rapid ecological assessment, a means to quickly collect relevant information that identifies, defines, and prioritizes environmental conditions, which has proved to be a useful way to quickly gauge field conditions (Maragos and Cook, 1995; Starr and McCandles, 2001). The approach is applied to the Yaqui Valley in the state of Sonora, Mexico, with a focus on identifying data relevant to environmental, social, and economic goals of stakeholders. The following sections describe the study area, the methods used to analyze selected indicators or alternative metrics (proxies) for which data were accessible, results, lessons learned, limitations, and conclusions.

1.3. Background for study landscape: Yaqui Valley, Mexico

The Yaqui Valley is a useful case study for assessing progress toward sustainable agricultural landscapes because it relies heavily on irrigation and crops that are sensitive to changing temperature regimes, and is the subject of several prior studies by national and international researchers (Lobell et al., 2003; Luers et al., 2003; Addams, 2004; Ortiz et al., 2008; Christensen et al., 2006; Meza-Montenegro et al., 2013; Matson, 2012). Irrigated agricultural landscapes play critical roles in feeding growing

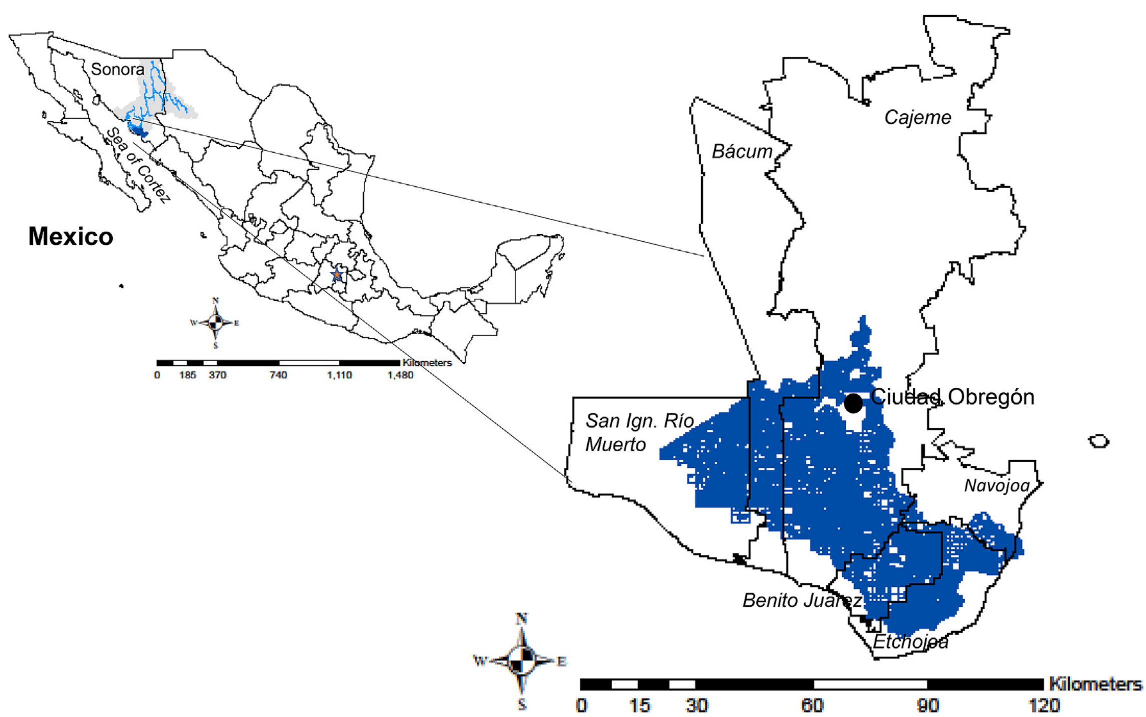

Fig. 1. Locational map of the Yaqui River and watershed (gray shading) primarily in Sonora, Mexico. The expanded view shows the Yaqui Valley Irrigation District canal system (blue lines) overlying the multiple municipalities it serves, which covers primarily Cajame including Ciudad Obregón, as well as Navojoa, Benito Juarez, Etchojoa, Bácum, and San Ignacio Río Muerto. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

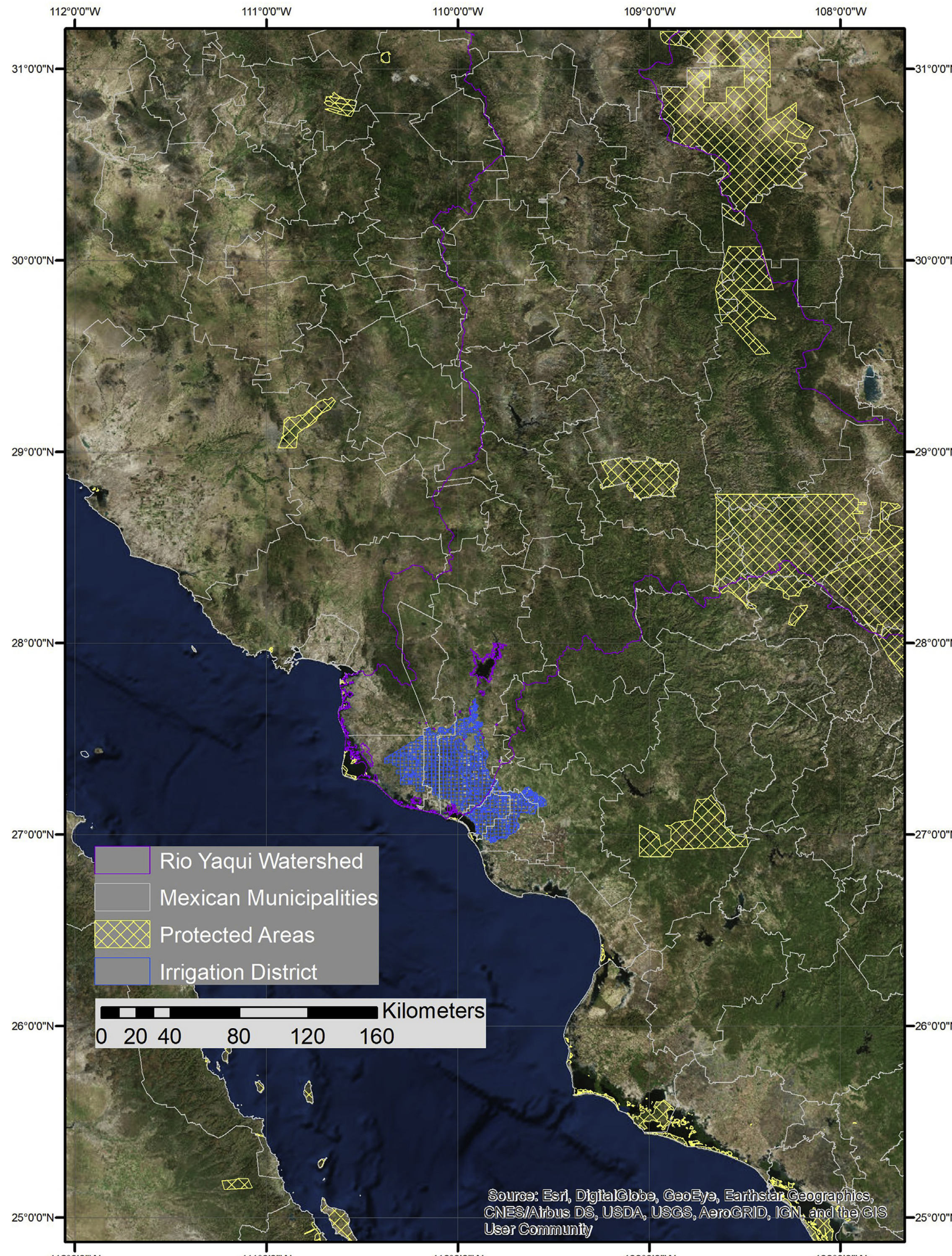

Fig. 2. The "Distrito de Riego del Rio Yaqui" (DRRY) supplies irrigation water through a system of canals (blue lines) in several municipalities (white boundaries) in southern Sonora, Mexico. The Yaqui River watershed (purple boundary) stretches far north into southern Arizona, USA. Very little natural habitat is legally protected in the region (yellow hatched areas) and includes a few small islands and coastal wetlands in the Sea of Cortez. Geographic layers (see Table 3) were applied by the authors to ESRI DigitalGlobe Basemap satellite true-color imagery. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

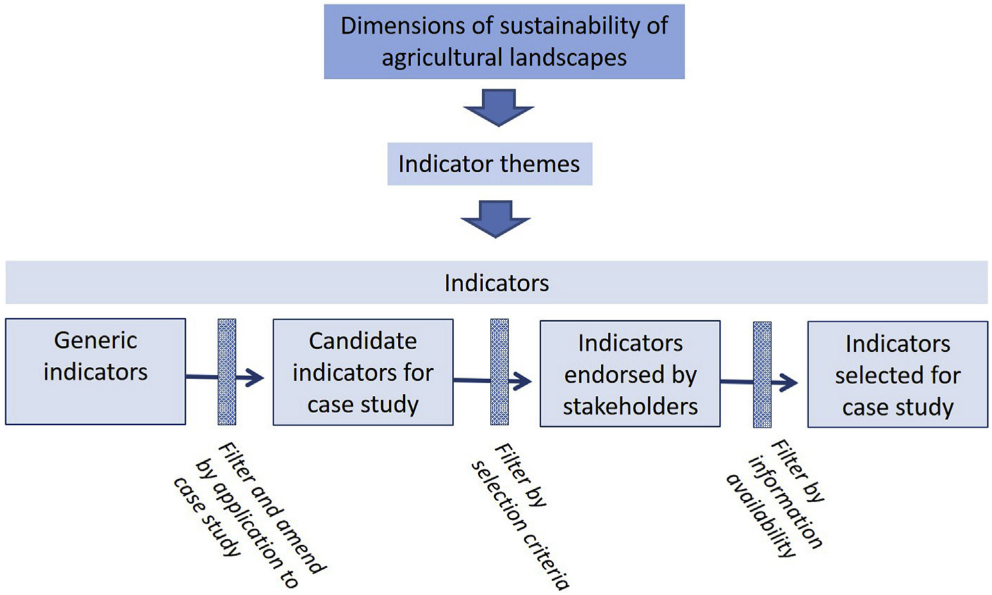

Fig. 3. Steps in selecting indicators for rapid appraisal of agricultural landscape sustainability. We identified an endorsed list of selected indicators by (a) starting with a generic list of candidate indicators, (b) determining those that are useful for the focus system, (c) consulting with stakeholder groups, and (d) determining what information is available.

Table 1
Preliminary list of themes and indicators. Meeting participants were asked to identify priorities in the three dimensions of sustainable agricultural landscapes. The list was presented in Spanish and was modified from prior work (Mcbride et al., 2011) and (Dale et al., 2013) as described elsewhere (Eichler Inwood, 2018).

Themes that fall within the three dimensions of sustainable agricultural landscapes		
Environmental	Social	Economic
• Soil Quality • Water quality • Water quantity • Climate change including greenhouse gas emissions • Biodiversity • Air quality • Productivity • Other • None	• Quality of life – Food security – Health • Work days lost – Due to injury – Other causes • Social and gender equity • Effective stakeholder participation • Risk of catastrophe • Transparency • Social acceptance (political and civil society support) • Other • None	• Trade & exports • Conservation of non-renewable resources • Jobs • Household income • Profit • Energy security • Price volatility – Food – Energy – Inputs – Products • Other • None

Table 2
Results of three Delphi decision rounds working toward consensus to retain, reconsider, or eliminate (first column status) potential indicators for the case study in the Yaqui Valley. The second column lists the average score for candidate indicators falling into each status category. Lower scores are better. Each candidate indicator was scored on a scale of 1–4 for each of four criteria. Criteria include availability of reliable data, and utility of indicator, in order to develop a list of endorsed indicators that is salient to local conditions and stakeholder priorities. The total score (min. value of 4, max. value of 16) for each indicator and from each participant were collated as an average. Lower scoring indicators were retained. The three right-hand columns reflect the number of indicators in each status category per the consensus of the Delphi participants following each subsequent round. Details available in (Eichler Inwood, 2018).

Candidate indicator status:	Average score Round 1 poll:	Nmber of indicators in each category		
		Round 1:	Round 2:	Round 3:
Retained	5.48	20	23	25
Reconsidered	6.77	14	7	0
Eliminated	7.12	11	15	20

populations but raise concerns about sustainability due to the high demand placed on freshwater resources (Kadiresan and Khanal, 2018; MacDonald et al., 2016).

The Yaqui Valley is in the southern region of the state of Sonora, Mexico, in flat desert land east of the Sea of Cortez and south of the Yaqui River (Fig. 1), that supports about 250,000 ha of irrigated agriculture, primarily planted to winter wheat (*Triticum aestivum*). The area is classified as arid hot desert (Bwh, Köppen-Geiger scheme) (Beck et al., 2018) with the coolest month occurring in January (average 17.8 C) and the hottest month in July (32.9 C) and rainfall of around 200–300 mm annually with most rainfall occurring in summer and high evaporation rates of 2,000 mm/year (Matson, 2012). The valley is known as the birthplace of the Green Revolution based on the work of Borlaug and his colleagues to improve varieties of wheat (Matson, 2012). Prior to arrival of the Spanish, the region was used for hunting, gathering, fishing, and cultivation of corn, beans and squash for thousands of years by the Yaqui Amerindians (Matson, 2012). Irrigation in the region was initiated in the early 1900s.

Today three large reservoirs form the foundation of the present Yaqui Valley society, economy, and environment, typically providing over two billion cubic meters of water storage. The dam and reservoir nearest to the cultivated area are situated upstream and northeast of the irrigation district known locally as “Distrito de Riego del Rio Yaqui” (henceforth, DRRY), which covers most of the Yaqui Valley and is administered by a cooperative organization that manages farmers’ access to reservoir withdrawals. Upstream from the DRRY, the upper Yaqui River watershed broadens to the north and east, through Sonora, and into southern Arizona in the United States (U.S., Fig. 2). The Yaqui River is nearly 400 km long and extends over 72,000 square km of diverse desert, shrub, and forest ecosystems.

Several factors are major contributors to Yaqui's highly productive, commercial agricultural landscape. In addition to hosting a world-class experiment and research center of *Centro Internacional de Mejoramiento de Maiz y Trigo* [International Maize and Wheat Research Center (CIMMYT)], the valley enjoys favorable local climate, availability of high yielding wheat varieties, large-scale irrigation, fertilizers, and pesticides, as well as supporting infrastructure and access to global markets (Matson, 2012). Specific components of the Yaqui Valley agricultural landscape have been the subject of a variety of research efforts in recent decades (Matson, 2012), including several Stanford University dissertations on topics such as nitrogen cycle and greenhouse gas emissions associated with wheat production (Addams, 2004; Ahrens, 2009; Avalos, 1997; Beman, 2006; Harrison, 2003; Luers, 2003). Such studies offer detailed information on important subcomponents of agriculture and knowledge systems unique to the Yaqui Valley (McCullough and Matson, 2016). Our case study builds on the prior research to apply a rapid assessment approach.

2. Methods

2.1. Spatial scope of the assessment

Identifying spatial boundaries requires consideration of each indicator independently. Because of the arid environment, the majority of Yaqui Valley crops are produced in the DRRY. Thus, for some indicators, the extent of land that is irrigated by DRRY provides a suitable boundary for the agricultural landscape (Fig. 1). However, the DRRY boundary is too limited for ecosystem functions and socio-economic processes that influence the Yaqui Valley from beyond the DRRY boundaries. For example, Ciudad Obregon, a city of about 400,000 residents that is the economic and social hub of the valley, is outside of the DRRY system. Information related to social and economic indicators are typically summarized by municipality (analogous to a U.S. county). Therefore, some indicators are analyzed based on administrative boundaries that overlap with DRRY functions, including the municipalities of Bácum, Benito Juárez, Cajeme, Etchojoa, Navojoa, and San Ignacio Río Muerto within the Mexican state of Sonora.

2.2. Indicator selection

We identified priority stakeholder concerns in Yaqui using the indicator selection process described by Dale and colleagues (Eichler Inwood, 2018; Dale et al., 2015). We identified an endorsed list of selected indicators (Fig. 3) by (a) starting with a generic list of candidate indicators, (b) determining those that are useful for the focus system, (c) consulting with stakeholder groups, and (d) determining what information is available.

Generic indicators within environmental, social, and economic dimensions of sustainability were derived from McBride et al. (Mcbride et al., 2011) and Dale et al. (2013) and amended for agricultural landscapes based on a review of published assessment frameworks (Eichler Inwood et al., 2018). The resulting set of themes was presented to stakeholder groups in the Yaqui Valley and used as a basis for discussions (Table 1). The research team applied criteria to rank candidate indicators (Dale et al., 2019; Eichler Inwood, 2018). Endorsed indicators are those that address the concerns of stakeholders in agricultural landscapes of the focus region. Stakeholder groups included representatives from agricultural industries, commodity organizations, farmers' unions, local environmental research faculty, international researchers (including some of the authors), farm owners, irrigation managers, plant pest and disease control specialists, agricultural outreach agents, local environmental organization members, and community members.

Stakeholders shared their perspectives on environmental, social, and economic opportunities and concerns related to the Yaqui Valley agricultural landscape during a series of meetings in March 2017. Local Yaqui Valley organizations hosted up to two dozen participants who selected the two themes with the highest priority in each of the three dimensions – environment, social, and economic – as displayed on posters (Dale and Kline, 2017) (Table 1). Participants were encouraged to suggest additional indicators and themes.

Based on prior work (Dale et al., 2015; Dale and Beyeler, 2001), we adopted four criteria for selecting indicators for agricultural landscapes: indicators should be useful to diverse stakeholders, technically effective for the location, practical in terms of obtaining indicator values, and sufficient to capture stakeholder priorities. A rating system relative to the selection criteria was developed (Eichler Inwood, 2018). The top-rated indicators are those that stakeholders recognized as a priority, are technically effective and easily measured, or can be estimated at reasonable cost.

In order to narrow the list of candidate indicators that meet selection criteria, we adopted a modified Delphi approach (Dalkey and Helmer, 1962; Linstone and Turoff, 1975; Taylor and Ryder, 2003) as detailed elsewhere (Eichler Inwood, 2018). The Delphi process involves iterative evaluation by experts to make progress toward consensus by allowing for learning and re-evaluation to occur (Dalkey and Helmer, 1962; Taylor and Ryder, 2003). This process has been recommended for selecting sustainability indicators (Wolfe et al., 2017; Dale et al., 2016; Sauvenier et al., 2005; Kampichler et al., 2010). Due to a manageable group size and uncontentious attitude, participants were not anonymous in digital questionnaires and later in conference calls to discuss the responses. As the Delphi method suggests, when ratings did not align, experts could choose to alter their score based on discussion, additional references, or new information. Better-rated candidate indicators remained in the list of indicators for discussion, while those with undisputed poor scores were eliminated (see Table 2).

2.3. Rapid appraisal

We assessed indicators in four sequential phases detailed below: (1) collect information, (2) compute values, (3) identify baselines and targets, and (4) assess progress. This rapid appraisal relies on data available through archived sources such as census data, agricultural records, and public satellite imagery.

2.3.1. Phase 1: collect information to select indicators available for assessment

To obtain the desired data about the endorsed indicators and priority themes, we searched for existing information in resources such as *Seeds of Sustainability* (Matson, 2012), peer-reviewed publications, the CIMMYT research data repository (https://data.cimmyt.org/dataverse/root/search), and Mexican government open databases and reports (https://datos.gob.mx/). We examined available information for relevance in spatial and geographic coverage (e.g., spatially explicit at a resolution that can be applied to or disaggregated for the Yaqui Valley), temporal coverage (annual or seasonal records from recent years and including, ideally, 2015, 2016, and 2017), resolution (e.g., national, state, municipality administrative unit, DRRY, or finer resolution at field or household level), reliability of the data source, and adequacy of its meta-data. Information that could contribute to determining baseline (e.g., prior year records) or target values for indicators was also identified. If data for an endorsed indicator were sparse or unavailable, further information was sought from research collaborators and stakeholders to determine potential proxy measures for those indicators. Based on this information, we selected a subset of indicators for which data were accessible to proceed with testing the assessment framework. This process resulted in seven indicators being selected for rapid appraisal in the Yaqui Valley agricultural landscape covering soil quality, productivity, biodiversity, vulnerability, poverty, transparency, and economic implications of crop diversity.

Table 3
Selected indicators, units, available data resources, and methodological approach for assessing sustainability of the Yaqui Valley, Mexico, agricultural landscape.

Dimension: Theme		Calculation approach
Environment: Soil Quality	Indicator units	Area at risk for compaction or salinization by soil type, by tenure regime; hectare (ha)
	Data resource	Digital soil map (https://datos.gob.mx/busca/dataset/conjunto-de-datos-vectoriales-de-la-carta-edafologica-1-250-000-serie-l-sonora) Map of DRRY irrigated fields (https://datos.gob.mx/busca/dataset/cuencas-de-inecc/resource/48dbec30-c836-44e4-a60b-4330c1f71a70) map map of ejidos (https://datos.gob.mx/busca/dataset/tierra-de-uso-comun–formato-shape)
	Approach	Clip soil map to DRRY map; sum area by soil type, calculate % total for each soil type; and % located in *ejido* lands (cooperative-owned)
Environment: Biodiversity	Indicator units	Protected or conservation habitat; area of perennial vegetation; ha
	Data resource	Map: CONANP 2016 (includes IUCN protected areas, 2017): http://www.conanp.gob.mx/datos_abiertos/DES/Geomatica/2016/ANPS.kmz; CONABIO NALC 2010 landcover 30m resolution
	Approach	Overlay protected areas map and land cover map with municipalities composing the DRRY
Environment: Productivity	Indicator units	Normalized Difference Vegetation Index (NDVI), unitless
	Data resource	Aqua/Terra MODIS time series 2000–2018 (250m resolution) and tools available at (https://glam1.gsfc.nasa.gov/)
	Approach	Calculate mean peak NDVI for winter cropped areas, summarize NDVI by municipality. Note: NDVI is limited to values between -1.0 to 1.0.; growing plants exhibit NDVI in the range 0.2–0.9.
Social: Acceptability	Indicator units	Vulnerability Index (social, economic, or environmental), unitless rating
	Data resource	Government table of vulnerability to climate change by municipality: theme and classification of vulnerability (very high to very low, 5 classes; using Parry & Intergovernmental Panel on Climate Change Working Group II, 2007 methodology) https://datos.gob.mx/busca/dataset/vulnerabilidad-social-economica-y-ambiental-por-municipio http://201.116.60.46/DatosAbiertos/Diccionario_de_datos_Mapas_de_Vulnerabilidad_ante_la_Sequ%C3%ADa.csv
	Approach	Create map of vulnerability by municipalities and clip to DRRY, use population data (household level) to identify intensity of vulnerability; calculate % of DRRY population in each class
Social: Transparency	Indicator units	Transparency as Corruption Perceptions Index, percent
	Data resource	Transparency International, national score (https://www.transparency.org/news/feature/corruption_perceptions_index_2017#table)
	Approach	Mexico score and rank 2012–2018
Social: Well-being	Indicator units	Social Lag (*rezago social*) Index, unitless classification
	Data resource	Government table of social lag index by municipality: classification (very high to very low, 5 classes) CONEVAL 2016 report
	Approach	Create map of social lag by municipalities and clip to DRRY, use population data (household level, CIMMYT 2015) to identify intensity of social lag; calculate % of DRRY population in each class
Economic: Risk of Catastrophe	Indicator units	Effective Number of Crop Species ($ENCS_{ha}$ and $E_{\$}$) via Shannon Diversity Index, (unitless) via production by crop, % area, pesos/ha
	Data resource	2017: List of crops by area (Junta Local de Sanidad Vegetal del Valle del Yaqui) 2016: List of crop production by area and municipality, market value (Servicio de Información Agroalimentaria y Pesquera: http://infosiap.siap.gob.mx/gobmx/datosAbiertos/ProduccionAgricola/Cierre_agricola_mun_2016.csv) Historical data: https://datos.gob.mx/busca/dataset/estadistica-de-la-produccion-agricola
	Approach	Calculate proportion of DRRY area devoted to each crop for 2016, 2017 Calculate Shannon Diversity Index for 2016, 2017, for DRRY Summarize market value and production levels for 2016 by municipality

2.3.2. Phase 2: compute values for selected indicators

Some indicators were best examined using geographic information system (GIS) tools. ArcGIS® software by Esri (version 10.5) was used to analyze spatially referenced data and prepare maps. References and links to data sources are included in Table 3. The following sections describe themes discussed with stakeholders for each dimension of sustainability with selected indicators (Eichler Inwood, 2018) shown in parentheses.

2.3.2.1. Environment: soil quality (soils at risk). The indicator for soil quality identifies soils at high risk for deterioration from agricultural activities as related to the prevailing soil type. In the Yaqui Valley landscape, concerns relate to management of certain soil types that tend to compact or have high soil salinity and thus reduce crop productivity. Conservation management employs reduced tillage and increased residue retention that improve soil quality (e.g., organic matter) (Hobbs et al., 2008), and, in the case of Yaqui Valley farms, reduces production costs and maintains yields (I. Ortiz-Monasterio, unpublished data). However, short-term or changing land tenure influences adoption of good management practices, for such practices require long-term investment of additional time or money to achieve benefits (Soule et al., 2000), and co-operatively managed fields in DRRY are typically rented to different farmers each year. Therefore, we examined the extent of soils classified as at-risk for compaction or salinization and the land-tenure regime (private versus co-operative ownership) associated with these at-risk soils for areas irrigated by DRRY.

Information on soils across southern Sonora is available as a digitized government map of major soil types, including soils at high risk for compaction and salinization. The soil map was clipped to a polygon map layer delineating DRRY irrigated cropland (excludes highways, canals and other infrastructure). The relative area of each major soil type within the DRRY and within *ejido* land (under co-operative ownership) was calculated from spatial data layers.

2.3.2.2. Environment: productivity (NDVI). Crop productivity is typically represented in terms of the yield of harvested product per area, which correlates to aboveground biomass and health of crops. Several indices provide a proxy for aboveground biomass at scales of hectares to square kilometers (Silleos et al., 2006). The normalized difference vegetation index (NDVI) has advantages as an indicator of yield for landscapes including ready access to seasonal global data coverage from multiple satellite sources such as MODIS, LANDSAT, and Sentinel-2, ensuring future monitoring capability, as well as spatial scalability. NDVI is calculated as (Lobell et al., 2003; Tucker, 1979):

$$\frac{(NIR - Red)}{(NIR + Red)} = NDVI \tag{1}$$

resulting in a range of -1 to 1, where NIR is the near-infrared spectral reflectance (wavelength peak about 842 nm) and Red is the spectral reflectance of the red band (wavelength peak 665 nm). We used NDVI as a proxy for productivity of winter-cropped land (primarily wheat and some safflower, *Carthamus tinctorius*) in the Yaqui Valley. Pre-calculated NDVI products were accessed for MODIS time series data (2003–2018; 250 m resolution) using the VISNAV-LULC 2010 general crop mask available in the interactive Global Agricultural Monitoring System (GLAM) toolset (https://glam1.gsfc.nasa.gov/), which incorporates atmosphere corrected Global Inventory Modeling and Mapping Studies (GIMMS) NDVI (Tucker et al., 2005) in order to examine NDVI for 2016 and 2017 as well as seasonal trends in NDVI over the past 15 years.

2.3.2.3. Environment: biodiversity (area of conserved and perennial vegetation). Biodiversity was identified as an important theme for sustainability in the Yaqui landscape during stakeholder workshops (Eichler Inwood, 2018). A local conservation group shared their goals for increasing biodiversity, especially of native macro-flora and -fauna associated with the local desert landscape. Assessing biodiversity with direct sampling of sites sufficiently representative of the case study landscape is not feasible for the rapid appraisal employed.

According to stakeholder workshop participants, there are no areas managed to conserve native desert habitat in the DRRY. Therefore, to assess potential biodiversity across the Yaqui landscape, we examined areas of legally protected habitat and perennial vegetation in the region by overlaying DRRY boundaries and *Comision Nacional de Areas Naturales Protegidas* [National Commission of Protected Areas] maps, as well as 2010 land cover data layer for the region (30m resolution; CONABIO 2010).

2.3.2.4. Social: acceptability (indices of vulnerability to climate change). Indicators of acceptability describe stakeholders' level of satisfaction with socio-economic and environmental conditions and perceived impending changes of those conditions. Such perceptions are difficult to quantify. A proxy for acceptability is provided by indices of vulnerability interpreted in view of the coupled human-environment system, which includes prevailing stresses and perturbations, sensitivity to exposure, coping capacities, and the potential for system adjustments (Turner et al., 2003). In the Yaqui Valley, issues of water availability and temperature extremes are priorities of stakeholders (Eichler Inwood, 2018). High nighttime temperatures and droughts reduce wheat yields (Ortiz et al., 2008; Prasad et al., 2008; Lobell and Ortiz-monasterio, 2007) and are associated with climate change stressors (Schoups et al., 2012). Given the arid environment, extreme rainfall events often cause destructive flooding, and the frequency of floods associated with cyclone activity in this region has increased (Zuñiga Tovar and Magaña Rueda, 2018). The Mexican government applied the Intergovernmental Panel on Climate Change (IPCC) approach (Parry, 2007) to estimate climate vulnerability based on "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes" (Preston et al., 2007). The Mexican government database contains indices of economic, social, and environmental vulnerability by municipality for 2015, which we used for assessing the Yaqui Valley.

Climate vulnerability was evaluated using GIS with the following steps. First, we summarized geo-referenced household population data for residents within the DRRY (K. Sonder, unpublished data). Population data were clipped to DRRY polygons that were buffered to include all households or villages within 300 m of irrigated land (excluding Ciudad Obregon), resulting in total population of approximately 55,000. Then the Mexican government map of climate vulnerability for 2015 by municipality (https://datos.gob.mx/busca/dataset/vulnerabilidad-social-economica-y-ambiental-por-municipio) was applied to the DRRY population data. Finally, we calculated the total number of residents living within the DRRY under each of five classes of vulnerability, ranging from very low to very high vulnerability.

2.3.2.5. Social: acceptability (index of transparency). Transparency of institutional and financial transactions is a concern for stakeholders in Yaqui Valley (Eichler Inwood, 2018). No proxy indicator data for transparency within the Yaqui Valley was deemed acceptable because of the low resolution or difficulty with interpretation of available data. Information on transparency for Mexico as a whole was available from the Transparency International Corruption Perceptions Index, which "ranks 180 countries and territories by their perceived levels of public sector corruption according to experts and businesspeople" (Transparency International, 2017). The Mexican national chapter of Transparency International compiles a separate National Index of Corruption and Good Governance with summaries at the state level (Transparencia Mexicana, 2011). Data on the rate of participation in elections by each federal voting district (2012, 2018) were also considered. As a placeholder, we use the Corruptions Perception Index scores (on a scale of 0–100) for Mexico from 2012-2018 (available from www.transparency.org).

2.3.2.6. Social: well-being (social lag index). A proxy measure for social well-being is available from the Mexican government statistics database as the *rezago social* index, which is a measure of the degree of social lag for the region relative to the overall population of Mexico (CONEVAL, 2015). This index compiles statistics about access to water, sanitation, healthcare, electricity, education, and the quality of housing and provides a measure of conditions for the DRRY relative to other households in Mexico. However it is not a measure of poverty *per se* because it does not incorporate indicators of income and food (Andrés-Rosales et al., 2018). Applying the same population mapping used for the vulnerability indices, we determined the proportion of residents living at each social lag classification by applying the government rating (by municipality) to households within DRRY for census years 2010 and 2015.

2.3.2.7. Economic: risk of catastrophe (index of crop diversity and market diversity). Because wheat, as complemented by a few other crops, such as maize (*Zea mays*), chickpea (*Cicer arietinum*), and safflower, dominates commercial agriculture in Yaqui landscapes, stakeholders acknowledged the potential social and economic risk related to catastrophic crop loss from pests, diseases, drought, or other climatic events (Eichler Inwood, 2018). For a proxy of economic risk related to crop diversity, we selected a common expression of diversity, the Shannon diversity index (H') (Shannon, 1948; Spellerberg and Fedor, 2003) calculated as:

$$H'_{ha} = -\sum_{i=1}^{s} (p_i \times ln\, p_i) \tag{2}$$

where p is the proportion of hectares planted in the i^{th} crop species, and s is the number of crop species (Gotelli and Chao, 2013). The H' can be expressed as the effective number of crop species ($ENCS_{ha}$, (Aguilar et al., 2015)) using

$$ENCS_{ha} = e^{H'} \tag{3}$$

where e is the exponential constant approximated at 2.718 (Gotelli and Chao, 2013). $ENCS_{ha}$ indicates the number of crop species planted to equal areas that would give the equivalent H'. Diversity of agricultural market value can be calculated likewise using the same equations but replacing hectares with pesos, resulting in $H'_{\$}$ and $ENCS_{\$}$ that express

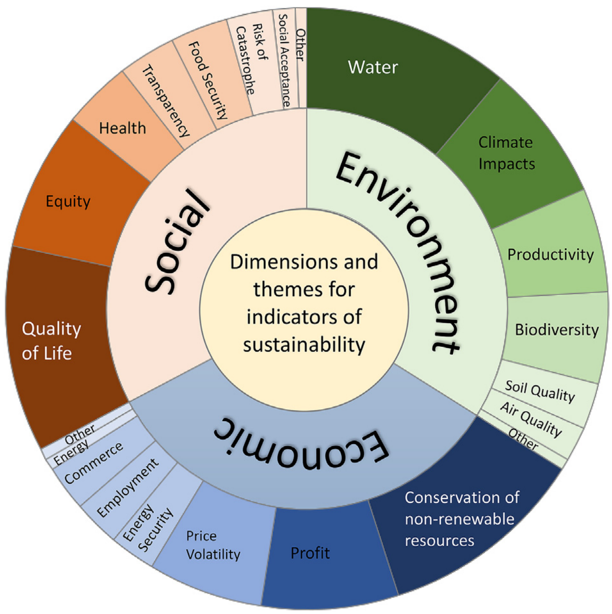

Fig. 4. Visualization of local stakeholder priorities for indicator themes within social, environmental, and economic dimensions for Yaqui Valley, Mexico. The size of each segment is proportional to the number of stakeholders who prioritized that indicator theme relative to others within the same dimension. Conservation of non-renewables includes soil and water conservation issues per stakeholder input. Water has been combined into one segment that includes water quality and quantity. Quality of life includes health and food security, as well unspecified concerns.

the markets' dependence on the diversity of crop species.

We summarized the crop production data and analyzed crop diversity using equation (1), as the relative proportion of the Yaqui Valley planted to each major crop. The 2016 harvest year information is from municipal records and applies to the six municipalities of the valley, including a minority of production areas outside of the DRRY (available at http://infosiap.siap.gob.mx), for the data could not be disaggregated to the DRRY alone. These values were compared to data from 2005. In contrast, 2017 data are from DRRY irrigation applications (records obtained from Junta Local de Sanidad Vegetal del Valle del Yaqui) and, therefore, apply only to production from DRRY irrigated lands.

Market values associated with each crop were available for the 2016 production year by municipality, and we ranked these in terms of the reported average market value-per-hectare, as well as variability in value across municipalities. These data were compared to records for the 2005 production year. Yield and market value data by crop were not available for 2017.

2.4. Phase 3: Identify baseline and target values for indicators

Where possible, we identified baselines and targets for indicators based on literature or historical records, knowledge of the landscape, and priorities discussed with stakeholders (Eichler Inwood, 2018). Identification of baseline, or reference values, for each indicator can require significant research efforts that are beyond the scope of a rapid appraisal. Wherever data were available, we determined baseline values for indicators based on archived data from the last 5 to 15 years. Targets values or desired trends for each indicator are determined with stakeholders during the indicator selection process. These targets can remain somewhat flexible as the cycle of adaptive management (Walters, 1986; Willams and Brown, 2012) repeats to incorporate new knowledge of the appraised landscape or comparable landscapes. Those indicators that use indices have established minimum and maximum values from which baseline and targets are inferred, however discussion with stakeholders is needed to identify near-term and locally relevant targets, as well as sub-populations who are poorly represented by the indices.

Table 4
Values obtained for indicators in the Yaqui Valley landscape are shown relative to baseline and target values, where available.

Indicator	Baseline (year)	Assessed Value (year)	Target	Progress
Soils at risk for compaction or salinization (ha)	n/a	71,992 ha[a] *34,897 in ejido land*	n/a	Data needed
Mean peak winter-crop NDVI (unitless)	0.653 (mean 2003–2015)	0.733 (2016)	0.8	+++
Protected habitat within DRRY (ha)	0	0 (2016)	increased[e]	[d]
Vulnerability (% of population at best index category)				
Social	unknown	57.3 (2015)	100	Data needed
Environmental	unknown	0 (2015)	100	[d]
Economic	unknown	71.2 (2015)	100	[c]
Social lag (% of population at best index category)	80.9 (2000)	42.7 (2015)	100	–
Transparency (%)	35 (2014)	28 (2018)	increases	–
$ENCS_{ha}$ (unitless)	3.8 (2006)	4.1 (2017)	12[b]	[c]

ENCS: Effective number of crop species by ha.
[a] Equivalent to about 33% of DRRY.
[b] For example, similar climate and irrigation regime of southern California has $ENCS_{ha}$ of 12.
[c] Positive progress toward target.
[d] Concerning trend or status relative to target.
[e] Additional stakeholder input should be sought to create a quantitative target.

2.5. Phase 4: compare assessed indicator values with baseline and target values where available

We evaluated computed indicator values relative to baseline and target values and highlighted progress toward landscape sustainability goals. Baseline values can also show whether indicators reveal deteriorating conditions.

3. Results

3.1. Indicator selection

Stakeholders in the Yaqui Valley shared their perspectives for environmental, social, and economic opportunities and concerns related to agricultural landscapes (Fig. 4). Secure and sufficient water from the reservoir is necessary for irrigation, drinking, household use, and salt intrusion management; thus, water is a primary concern for all in the community. Agriculture, led by wheat production, is the main business of the Yaqui Valley. Therefore, improvements to environmental and social conditions must also consider agricultural profit and continuation of access to markets and a comparative advantage for local producers. A desire to compete in a variety of export markets influences many farmers' management decisions and, given the growth of specialty markets for socially and environmentally responsible production, provides an opportunity for co-benefits related to environmental protection and social responsibility.

The priorities expressed by consulted stakeholders are reflected in the size of each of the themes shown in Fig. 4. While it was relatively easy to agree on important indicator themes, selecting specific indicators within each theme was more challenging and required criteria and an iterative process (see Methods). The ratings from an initial poll of experts (Table 2) resulted in removal of 11 candidate indicators

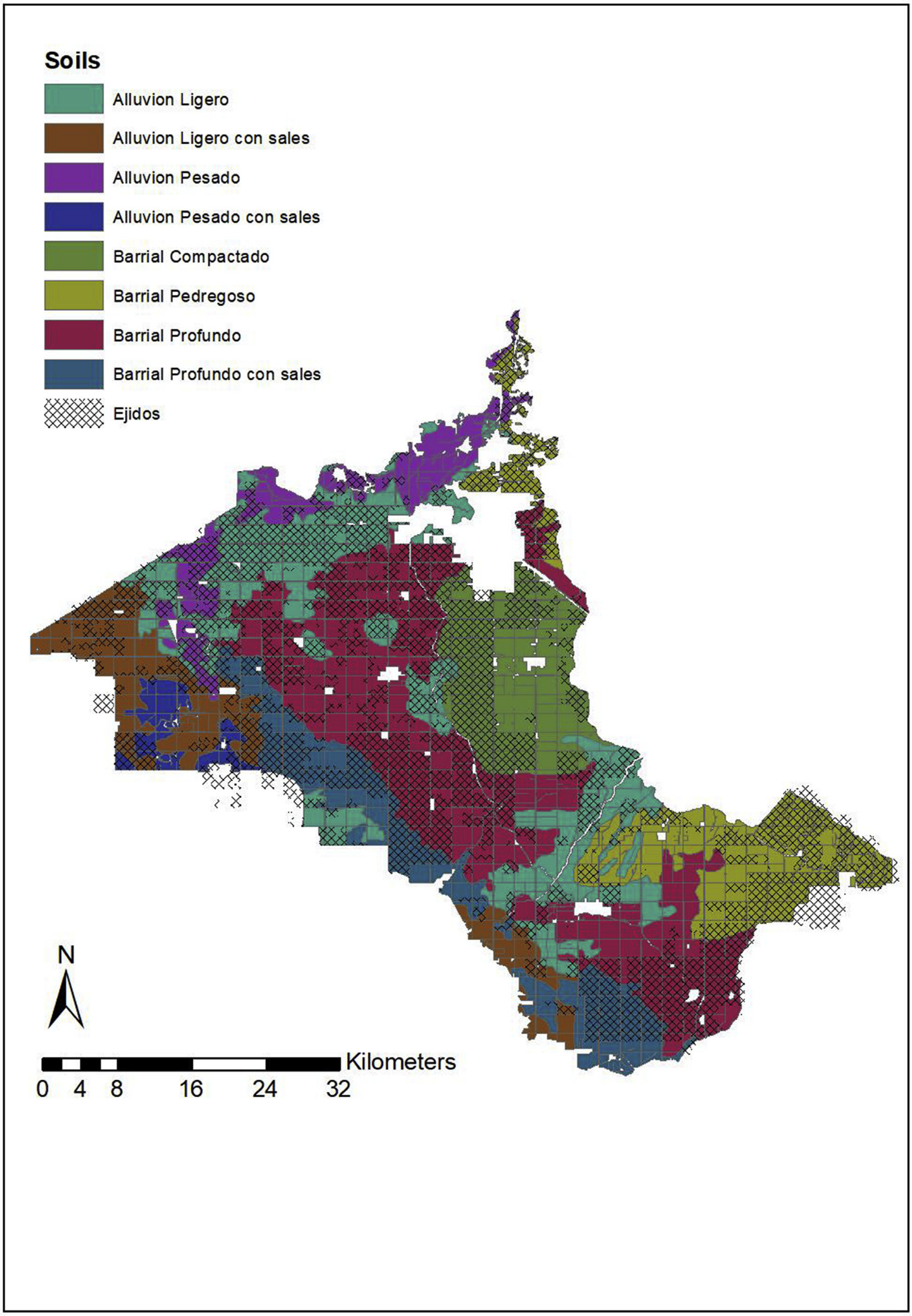

Fig. 5. Eight soil types are found within the Yaqui irrigation district, of which about half is owned by *ejido* communities (hatched areas) and mostly rented to large-scale industrial farm businesses. Soil types that have a high risk for compaction (*Barrial compactado*) or salinization (*con sales*) require careful management in order to remain productive. White represents areas of non-agriculture or population dense locations. Created by authors, see source citations in Table 3.

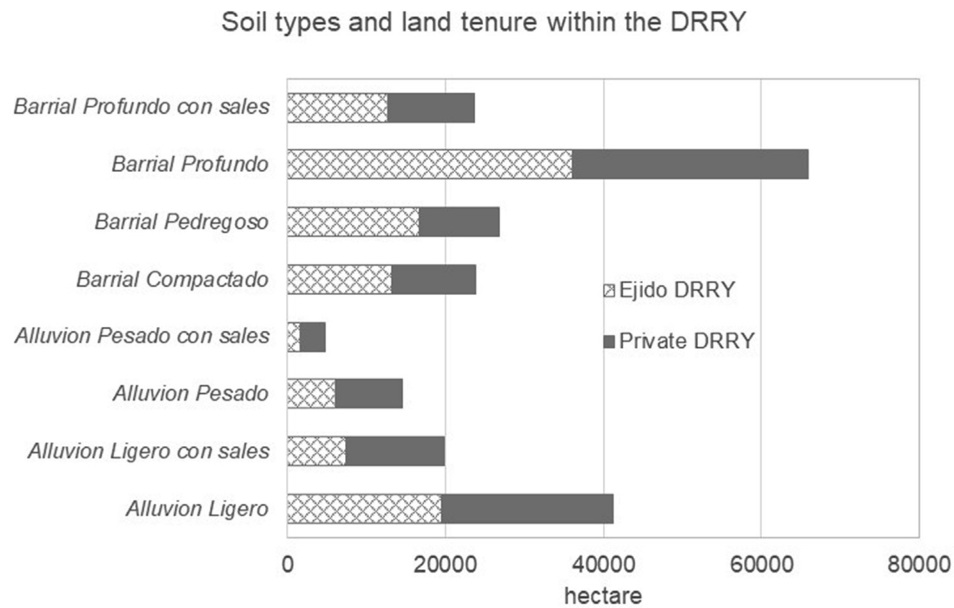

Fig. 6. Total area of each type of soil is shown for the DRRY and compared to the area under *ejido* ownership. See source data in Table 3.

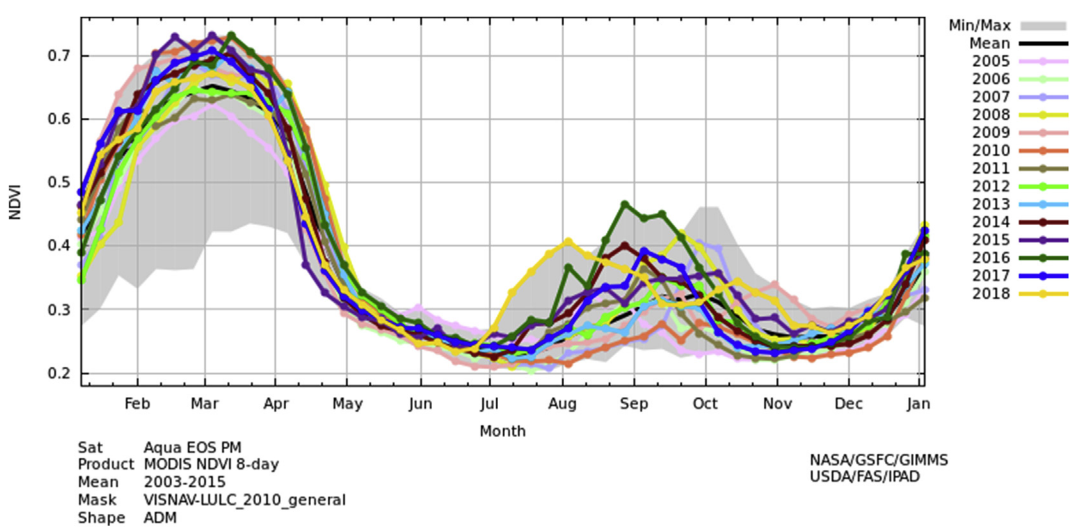

Fig. 7. Regional NDVI for cropped areas (using the GLAMS tool) peaks for winter crops during mid-February to mid-March and for summer crops in late August to late September in the Yaqui Valley, after applying the VISNAV-LULC crop mask to the regional time series for MODIS satellite data (https://glam1.gsfc.nasa.gov/).

(typically with a total score of 7 or higher), while 14 candidate indicators warranted additional discussion to determine if they would be retained, and twenty others were widely considered as useful (scoring between 4 and 5). No specific score or quartile was established as a threshold for inclusion or elimination because flexibility was required to identify indicators that could be sufficient while also being practical given available data. The most common factor for not endorsing indicators was the lack of readily available data. In some instances, the terminology or suggested units was modified to better reflect concerns or data specific to the Yaqui Valley. One digital survey, two conference calls, and two rounds of email communications yielded a list of 25 endorsed indicators (Appendix A). Practical considerations for rapid measurement resulted in a final list of selected indicators for the rapid assessment, as described below and listed in Table 3.

3.2. Rapid appraisal of indicators toward more sustainably managed landscapes

The indicator values for annual or seasonal data from 2015-2017 are discussed below relative to baseline (historical) or target (desired future) indicator values (Table 4). Indicators are organized in subtitles according to sustainability dimension (environmental, social, economic), theme (e.g., soil quality), and indicator. The spatial and temporal resolution of available data varies. We do not aggregate or collapse indicators into a summary number or index as it is preferable to allow decision makers to interpret each indicator. The context is very important for interpreting the appraisal, and therefore the method is better suited to monitoring one landscape through time rather than comparing disparate landscapes.

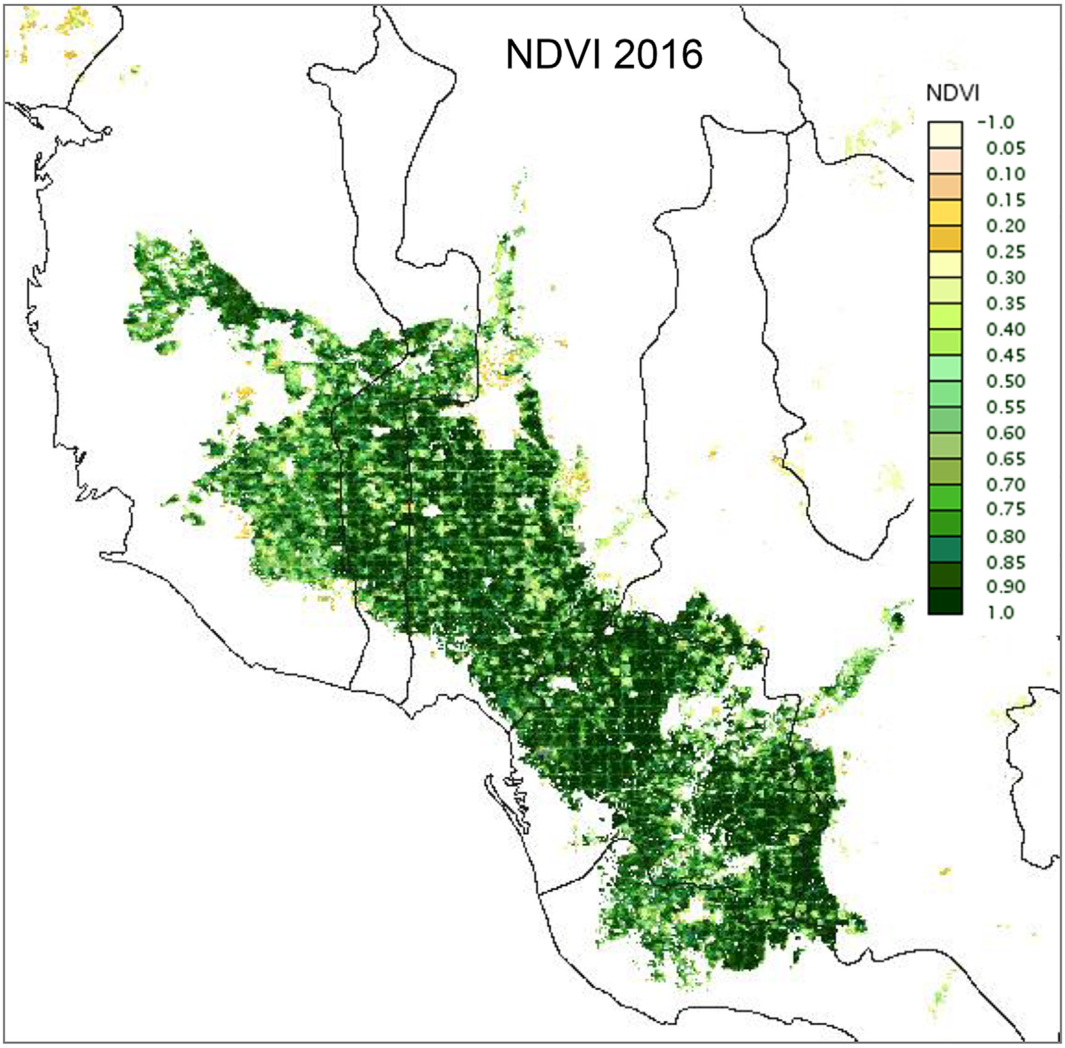

Fig. 8. NDVI on March 5, 2016, shows crops at near-peak growth stage throughout the Yaqui and Mayo Valley municipalities (black lines) as indicated by dark green pixels (based on MODIS satellite imagery, https://glam1.gsfc.nasa.gov/). Non-cropped areas are shown as white. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 9. The fields within DRRY are primarily flood-irrigated through a system of canals. The canals and canal margins are maintained by removing vegetation to facilitate drainage. Outside of fruit orchards and walnut plantations, little perennial shrub or tree cover is observed within the district. (Photo by S. Eichler).

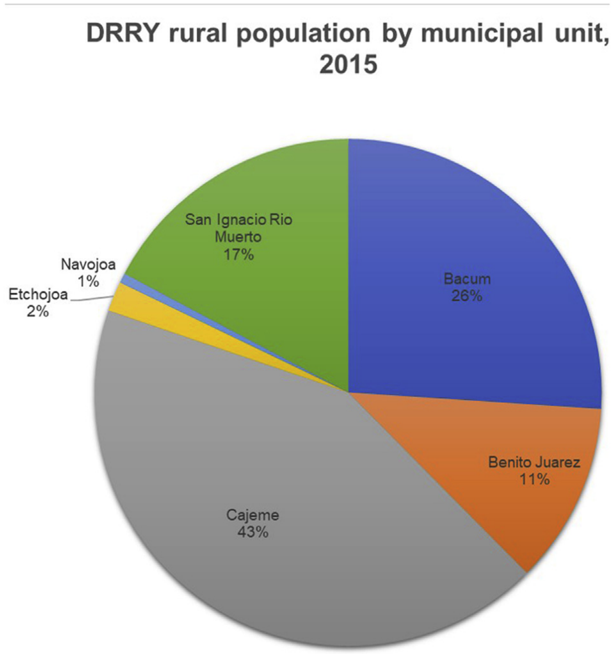

Fig. 10. Approximately 55,000 rural residents of the DRRY are primarily found within Cajeme and Bacum municipal boundaries. See sources listed in Table 3.

3.2.1. Environment: soil quality-area of soils at risk for compaction or salinization

High risk soils represent about a third of the DRRY irrigated area while a little over half of the area (excluding roads, canals and other non-irrigated surfaces) contains the three most desirable soils for agriculture: silt loam (*alluvion ligero*, 19% of DRRY by area), clayey silt (*alluvion pesado*, 7%), and deep clay (*barrial profundo*, 30%) (Fig. 5). Specific agricultural management practices improve productive potential of certain soils especially soils with salts (*con sales*, those having conductivity above 4 dS/m) and easily compacted soils (*compactado*), which are considered to be poor soils for agriculture (Lobell, 2005).

Soils with high concentrations of salts represent about 22% of the irrigated land (Fig. 6). To avoid further salinization and to maintain their productive potential, these soils require periodic leaching with clean water, which requires larger irrigation water volume relative to soils without salts, in addition to other agronomic practices such as careful selection of crops and application (type, timing, placement, form) of agronomic nutrients. Agricultural decisions over multiple seasons and in response to low water availability need to consider a crop's sensitivity to increased soil salt content. For example, almond (*Prunus dulcis*) and citrus tree (*Citrus spp.*) crops are sensitive, and maize and alfalfa (*Medicago sativa*) are moderately sensitive, whereas wheat and safflower are moderately tolerant of some salts (USDA ARS, 2015).

Barrial compactado soils represent 11% of the DRRY and have a high risk for compaction. Compacted soils benefit from conservation agriculture practices that reduce tillage to retain and build soil organic matter through crop residue management and rotations (Hamza and Anderson, 2005), the use of improved machinery (lighter equipment, flotation tires), mechanical treatments (e.g., periodic knife or chisel plow), crop and management choices that reduce the number of machine passes required per season, or controlled field traffic to facilitate semi-permanent bed and furrow patterns. In total, about one-third of the DRRY contains soil classes at higher risk for degradation (*con sales* or *compactado*), calling for specialized management to maintain or improve productivity (Moreno-Ramos et al., 2014).

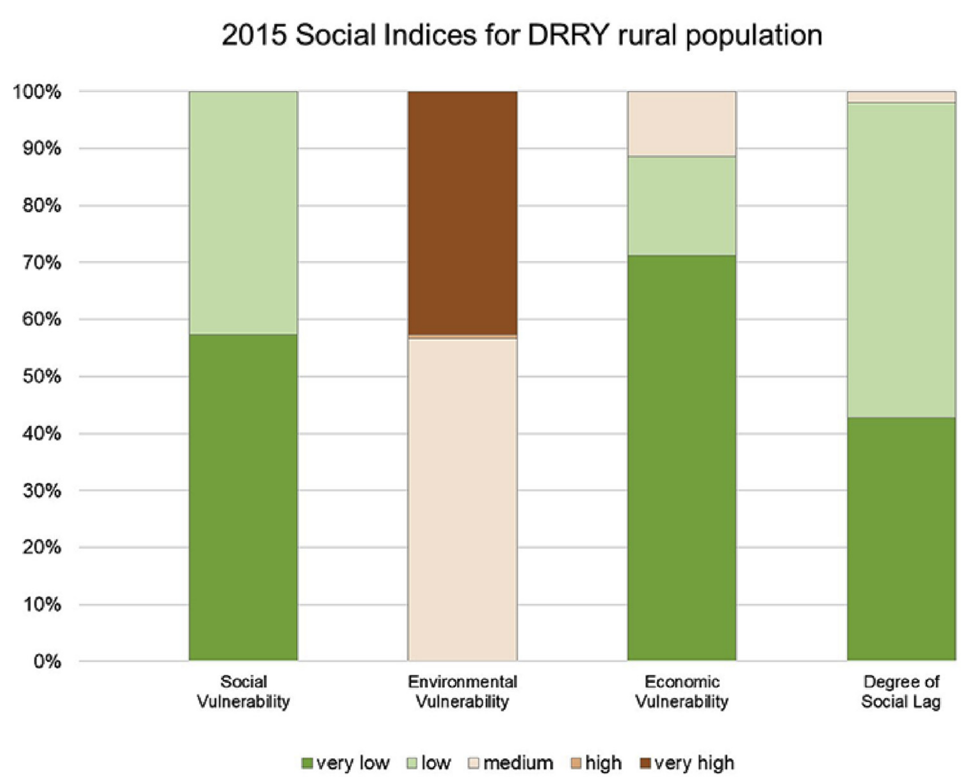

Fig. 11. Mexican government classification for indices of social, environmental and economic vulnerability to climate change and social lag are shown by percent of the rural DRRY residents. See sources in Table 3.

Table 5
Transparency International Corruption Perceptions Index and ranking for Mexico (on a scale of 0–100, where 0 is highly corrupt whereas 100 is very clean) relative to 180 countries.

	2012	2013	2014	2015	2016	2017	2018
Score	34	34	35	31	30	29	29
Rank	105	106	103	111	123	135	138

Conservation agriculture practices such as residue retention and reduced tillage have been used regularly on a small portion of the DRRY area despite improving long-term yield stability (Ortiz et al., 2008), in part due to land-tenure patterns. About half (51.4%) of the DRRY is *ejido* land (Fig. 5). Soil types within *ejidos* are representative of the DRRY as a whole (Fig. 6). Because much of the *ejido* land is rented to private farmers on an annual basis, unlike privately owned and managed land, there is little incentive to invest or adjust practices in order to generate long-term improvements in soil quality (Matson et al., 2012). Thus, policy incentives or programs that reduce the costs associated with adoption of conservation agriculture are particularly useful if focused on areas with high risk soils, especially those within *ejidos*.

High soil quality in agricultural systems relates to maintenance of high productivity without soil or environmental degradation and is evaluated using chemical, physical, and biological metrics (Govaerts et al., 2006). Prior work in the DRRY has shown that poor soils can be highly productive under good management practices (Lobell et al., 2002). An effective remote sensing technique for determining soil quality is useful and more cost-effective than an extensive and expensive physical sampling regime. One such proxy indicator is the proportion of land under conservation agriculture management. Because conservation agriculture affects soil physical properties such as organic matter content, moisture penetration and retention, aggregate structure, and vegetative material retained on the soil surface (Hobbs et al., 2008; Govaerts et al., 2006; Verhulst et al., 2011; Fuentes et al., 2012) as well as arthropods (Rivers et al., 2016), efforts have been made to identify areas of conservation agriculture through satellite spectral imagery (e.g. Daughtry et al., 2006) as an indicator of soil quality (Watts et al., 2009). Methods for seasonal remote sensing of conservation agriculture areas are not yet well-calibrated (Watts et al., 2009) and are still under development for the Yaqui Valley (K. Sonder, personal communication). However, in-field percent residue retention post-harvest correlates with satellite data in other areas of commercial production in Mexico and could be used in future appraisals to identify areas of conservation agriculture (Ortiz-Monasterio et al., 2007). A target could be application of conservation agriculture on all soils *con sales* and *compactado* so that management practices reduce risks for compaction and salinization. As remote sensing methods evolve, there may be opportunities to estimate soil organic matter (SOM) across landscapes, though presently these methods involve specialized airborne sensors and substantial calibration efforts (Denis et al., 2014; Hbirkou et al., 2012; Lacoste et al., 2014) and, thus, were not considered for the present rapid appraisal approach. Diverse management factors are known to influence soil SOM changes in the Yaqui Valley. Information about effects of different management practices should be shared in a timely manner with local farmers, and technical assistance on SOM management options should continue to be part of farmer-outreach efforts.

3.2.2. Environment: productivity-seasonal peak NDVI

NDVI is useful for monitoring crop conditions and forecasting yields (Becker-Reshef et al., 2010). NDVI indicates the stage of crop growth and hence the planting season so that areas under differing crops such as winter wheat, fall maize, or summer soybean (*Glycine max*) can be identified (Lobell et al., 2003). Satellite-derived NDVI is related to direct measurements of the fraction of photosynthetically

Table 6
Agricultural production from the top 25 crops for 2016 by area and market values for the Yaqui Valley (based on data available from Mexico's *Servicio de Información Agroalimentaria y Pesquera*). Data were reported for each of the municipalities that have some area in the DRRY: Bácum, Benito Juárez, Cajeme, Etchojoa, Navojoa, and San Ignacio Río Muerto, which includes some areas outside of DRRY. Yields and market values are calculated from tonnage, harvested area, and market value by crop for each municipality. Scientific names were added according to FAO (FAO, 2010). Note: crop yields for food or feed versus seed crop are listed separately as reported by source; soybean production in 2016 was anomalous for the decade as water resource limitations prevent its double cropping under most recent years.

2016 Crop	Total harvest (ha)	Average yield (ton/ha)		Average value (pesos/ha)		Rank by harvest area	Rank by $/ha
		Mean	SD[a]	Mean	SD[a]		
Wheat *(Triticum aestivum)*	221022	6.6	*0.4*	23833	*1.1*	1	26
Soybean *(Glycine max)*	48957	2.2	*0.2*	15100	*1.2*	2	33
Safflower (*Carthamus tinctorius)*	24797	2.6	*0.2*	17144	*2.2*	3	31
Corn *(Zea mays)*	20061	7.5	*1.0*	24040	*3.9*	4	25
Potato *(Solanum tuberosum)*	7783	33.1	*1.8*	218271	*42.0*	5	4
Wheat, seed	6229	6.3	*0.2*	39073	*3.1*	6	22
Bean *(Phaseolus vulgaris)*	5100	1.4	*0.3*	19563	*2.9*	7	29
Sorghum *(Sorghum bicolor)*	4352	5.6	*0.8*	21110	*3.1*	8	28
Chickpea *(Cicer arietinum)*	3370	2.4	*0.1*	32776	*3.7*	9	24
Soybean, seed	3300	2.3	.	22475	.	10	27
Green chile *(Capsicum spp. (annuum))*	1974	28.8	*16.4*	201492	*134.1*	11	6
Zucchini *(Curcurbita spp.)*	1526	17.1	*3.9*	120797	*33.0*	12	13
Red tomato (Lycopersicon esculentum)	1185	82.6	*30.0*	494484	*195.1*	13	2
Green tomato *(Lycopersicon esculentum)*	827	18.7	*3.4*	80287	*34.2*	14	16
Corn, cob	575	11.9	*2.1*	41307	*14.4*	15	21
Watermelon *(Citrullus lanatus)*	556	42.2	*0.3*	118657	*3.4*	16	14
Cotton *(Gossypium spp.)*, (on-the-seed weights)	420	4.0	*0.5*	46498	*8.9*	17	20
Onion *(Allium cepa)*	393	37.1	*5.2*	150755	*8.6*	18	8
Cucumber *(Cucumis sativus)*	363	132.6	*44.3*	610828	*233.1*	19	1
Broccoli *(Brassica oleracea var. italica)*	292	19.3	.	160875	.	20	7
Lettuce *(Lactuca sativa)*	282	28.6	*3.3*	138472	*19.3*	21	11
Sorghum, seed	155	5.0	.	17820	.	22	30
Pastures and grasslands	130	17.9	*11.4*	11888	*7.3*	23	35
Brussels sprouts *(Brassica oleracea var. gemmifera)*	89	18.0	.	206600	.	24	5
Sunflower *(Helianthus annuus)*	80	1.9	.	15620	.	25	32

[a] Standard deviation of up to six reporting municipal subunits of the DRRY; not available for crops reported from only one municipality.

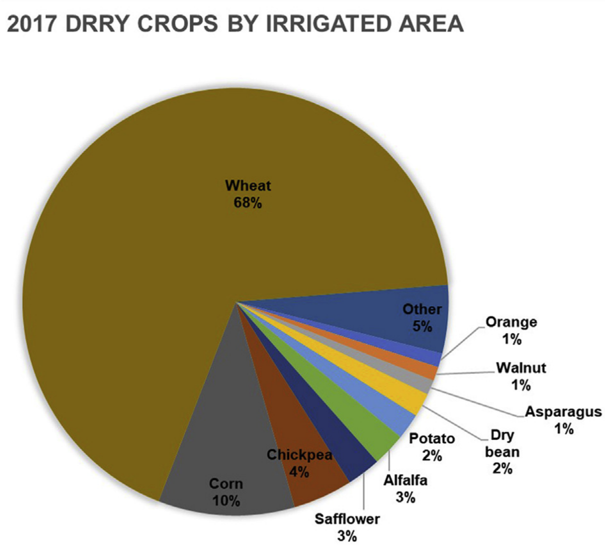

Fig. 12. The percent of irrigated DRRY land planted in ten primary crops (total area approx. 250,000 ha) in 2017. Wheat occupies two-thirds of the crop production area in the Yaqui Valley although 63 other crops are also grown. The proportion of other crops is provided in Fig. 13. Source: *Junta Local de Sanidad Vegetal del Valle del Yaqui.*

active radiation and is used in estimating grain yields at regional scale (Lobell et al., 2003). NDVI is linearly correlated to grain production, but the relationship has sensitivity limitations and is more accurate below a threshold of about 4 ton/hectare of wheat grain (Skakun et al., 2017). Wheat yields in DRRY often surpass that threshold. Other remote sensing tools are available for estimating yields beyond that threshold (Lobell et al., 2003, 2015) but require ground control points and detailed geo-referenced yield data resources for calibration. However, for estimating productivity of the suite of crops across the landscape relative to historical productivity, NDVI is an adequate and readily accessible indicator. And many Yaqui Valley farmers are already familiar with NDVI as a result of local outreach efforts that promoted the use of hand-held sensors for improved nitrogen fertilizer management.

Peak NDVI for winter crops in the DRRY occurs late-February to mid-March (Fig. 7). Mean peak NDVI for 2016 (0.733; Fig. 8) and 2017 (0.709) were very near to the mean winter peak for regional NDVI over the period 2003–2015 (0.653). A comparison of reported 2016 average wheat yield to mean peak-season NDVI by municipality showed a weak positive linear correlation ($R^2 = 0.329$, data shown elsewhere (Eichler Inwood, 2018)). This relationship could indicate that the high-yielding fields in DRRY were surpassing the threshold for which NDVI accurately predicts grain yields or other limitations. Similar high productivity, and thus yields, could be expected for 2017 in the absence of late season crop losses; however, yield data were not available at the time of this appraisal.

In the case of productivity as measured by NDVI across the landscape, a reasonable baseline is mean peak NDVI for each season, averaged over several growing seasons. A hypothetical crop yield maximum would exhibit peak NDVI of about 0.8 for 250 m resolution (Becker-Reshef et al., 2010), which provides a target value for the context of Yaqui Valley production practices. That is, maintaining the indicator value for productivity between the historical mean and the hypothetical maximum may be the target on a seasonal and annual basis. This indicator is most useful for projecting poor crop yield—for example, from landscape stresses such as extreme weather, disease, or input limitations. In the context of the Yaqui landscape's high productivity, an alternative could be to calculate the relative proportion of the DRRY that achieves seasonal mean to maximum NDVI during a growing season. Reliable data sources and additional analysis are required in order to assess how landscape productivity relates to agricultural inputs and farm profitability; two concerns identified by stakeholders.

3.2.3. Environment: biodiversity-legally protected habitat areas and perennial vegetation

Not surprisingly for an area devoted to agriculture, the DRRY contains no formally protected conservation habitat (Fig. 2). However, conservation lands often do not represent ideal habitat for maintaining native biodiversity because they are often located in areas that are less desirable for development (agriculture or otherwise) and likely differ from predevelopment habitat in the landscape (Scott et al., 2001). Some of the nearby coastal wetlands and shrub islands in the Sea of Cortez are reserved as migratory bird and forest animal habitat within municipalities overlapping DRRY. Legally protected areas exist to the north and east of the DRRY, within and along the upper Yaqui watershed, although some of the stakeholders suggested that monitoring and enforcement were insufficient to fulfill conservation goals.

The amount of perennial vegetation that could provide refugia for beneficial macro-organisms in the DRRY is minimal and virtually undetected using 30m resolution land-cover data, although patches of such vegetation can be observed directly. Perennial shrub land cover occurs nearby, outside of the DRRY. Aside from small walnut (*Juglans spp.*) and citrus tree groves managed as cash crops, perennial cover in or adjacent to cropland in DRRY is difficult to detect by remote sensing because trees occur almost exclusively along roadways or adjacent to households. Shrub or groundcover is arranged in a narrow band along field margins and canals in the DRRY (Fig. 9). Unlike perennial hedgerows, which serve an important habitat and biodiversity function, the field margins within the DRRY and canal banks are routinely cleared of perennial vegetation during canal maintenance. Land-cover data show no forest or shrub cover within the DRRY at 30m resolution (CONABIO NALC 2010).

Using the area of protected habitat as an indicator of potential biodiversity assumes there is a link between protected habitat and actual biodiversity even though that relationship is not always well-documented (Chape et al., 2005; Geldmann et al., 2013). The current conditions, without designated conservation area within the DRRY, may be considered a baseline value, and additional stakeholder input is needed to determine a target value although at least one local organization has set specific goals to establish native habitat along both sides of the main road between the airport and city as well as to establish a Sonoran Desert botanical garden as a potential tourist attraction (personal communication, Fundación Ambiental del Valle Del Yaqui, 2016). Such targets, focused on native desert habitat, appear reasonable compared to other options considered.

In some other contexts, the benefits of perennial vegetation are significant when >20% of the landscape supports non-crop species, and this benefit accrues even when there are fragmented habitats (Tscharntke et al., 2002). A target of 20% (Tscharntke et al., 2002) of the agricultural landscape would represent approximately 44,000 ha of perennial land cover in the DRRY area. It seems highly unlikely that extensive perennial vegetative cover, even in hedgerows, would be acceptable given local water resource limitations. Establishment of perennial vegetation outside of the DRRY could provide some of the desired aesthetic and cultural value described by stakeholders but is less likely to provide cropping system benefits such as biological pest control and pollination. Revegetation of headwater areas of the Yaqui River watershed, and effective enforcement to control disturbances within legally protected areas, could provide conservation habitat and help regulate water flow. However changes in vegetation would likely alter the water yield (Brown et al., 2005) and thus would require careful selection of appropriate species for revegetation strategies.

The advantages of using national data to monitor conservation areas are the low cost and ready access. However, the coarse spatial resolution

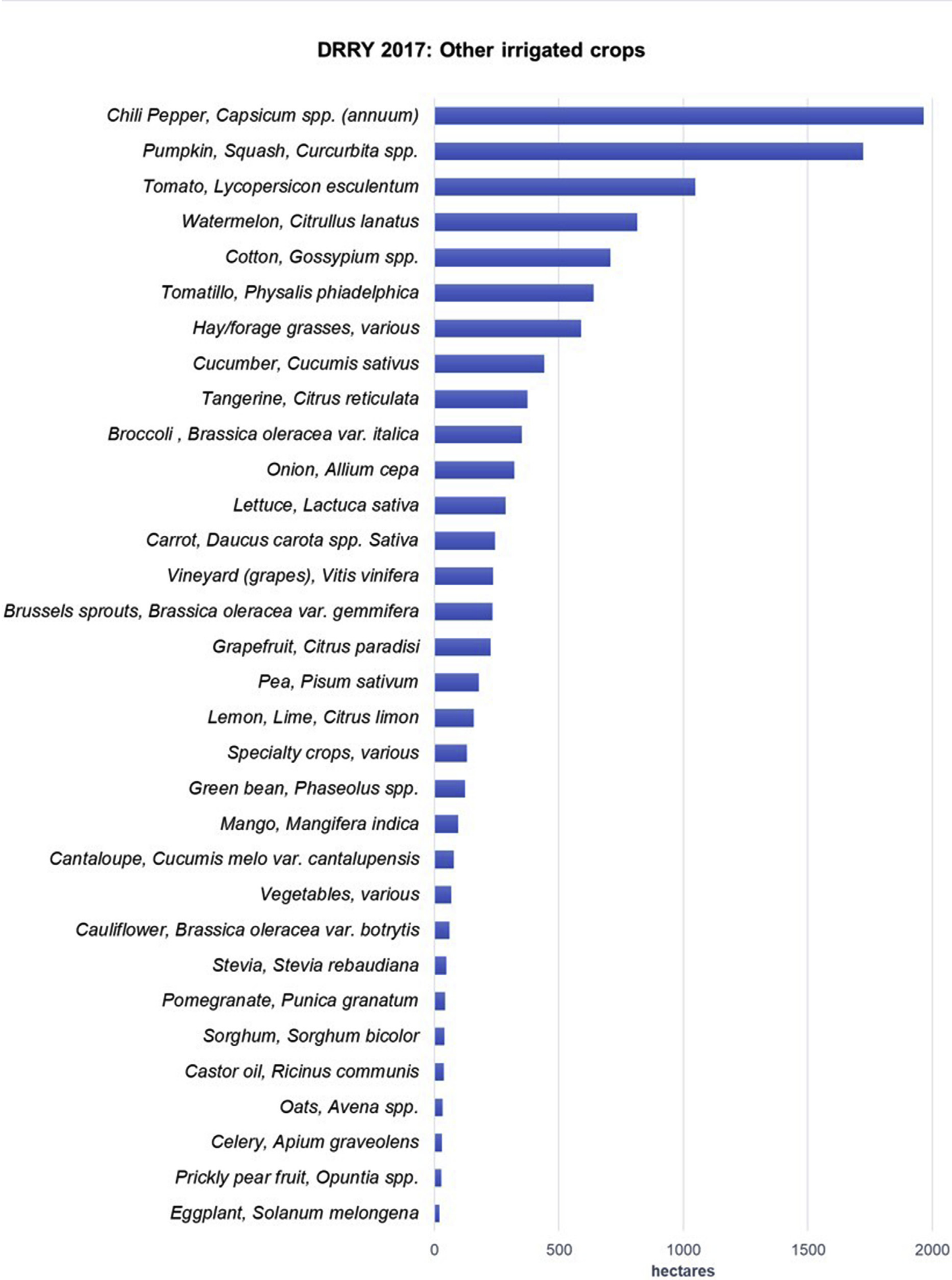

Fig. 13. Other crops depicted in Fig. 12 that are grown on 5% of the DRRY in 2017. Crops grown on less than 20 ha are not shown here. Source: Junta Local de Sanidad Vegetal del Valle del Yaqui.

of data and the need for assumptions regarding the relationships between officially declared conservation areas, actual area of conserved habitat, and benefits accrued by species of concern create challenges for interpretation. Therefore, working with local initiatives and monitoring their progress in establishing native habitat in designated areas is a recommended alternative.

3.2.4. Social acceptability: government index of vulnerability to climate change

Social acceptability can be related to vulnerability to climate change, which takes into account exposure (presence of a climate hazard), sensitivity (responsiveness of a system to the hazard), and adaptive capacity (ability to manage exposure and/or sensitivity, or cope with adverse impacts (Preston et al., 2007);). Climate vulnerability ratings provide a summary measure of how exposure and sensitivity create a potential impact, which may be ameliorated by the communities' adaptive capacity. The rural population within the DRRY in 2015 consisted of about 55,000 people who resided in portions of six municipalities (Fig. 10), primarily Cajeme and Bácum. Using the Mexican government's census-based indices (based on IPCC 2007 approach to estimating vulnerability to climate change), the vulnerability of this population was classified as low (43%) or very low (37%) relative to other regions of Mexico (Fig. 11). Similarly, over three-quarters of the rural population reside within municipalities considered to have relatively low economic vulnerability. In contrast, environmental vulnerability is medium, high, or very high for the area (57%, <1%, and 43% respectively). The logical target is to achieve 'very low' vulnerability status for the entire population for each of the indices. Continued input from local stakeholders including government, agro-industry representatives, and residents is needed to identify programmatic changes to help address environmental vulnerability.

Use of national indices for the social-themed indicators offers advantages and disadvantages for the assessment. It is advantageous to have readily available data that are defined and bracketed within five rating categories and that are likely to be updated periodically using a consistent methodology. However, linkages between local conditions, choices, and indicator value is not transparent. And because the indices are relative to the rest of the nation, future ratings for the Yaqui Valley could be influenced more by changes in other parts of Mexico than by actual change in local conditions. Better documentation and analysis of the underlying data are required for future application and interpretation of the indices.

Other options include undertaking site-specific assessments, but this is also costly and time-consuming (Tate, 2013). Other methods for determining vulnerability related to climate change have been used. For example, Luers and others (Luers et al., 2003) calculated vulnerability of DRRY farmers to temperature stressors and market fluctuations based on wheat yield variations. They estimated adaptive capacity as a function of soil type and management level. This approach to vulnerability focused on yields of the primary crop, and the methods are data intensive and site-specific. The climate change vulnerability indices, based on an established procedures and periodic census data, therefore offer advantages for this rapid appraisal.

3.2.5. Social acceptability: Corruption Perceptions Index

The Mexican chapter of Transparency International maintains some information on transparency by state including a survey on the prevalence of bribes required prior to receiving public service, but an estimate of transparency was not available by municipality. The National Index of Corruption and Good Governance shows deteriorating conditions for the state of Sonora with a drop of 2.9% from 2001 to 2010 (Transparencia Mexicana, 2011). Results from a more recent survey are not yet available. A placeholder measure for transparency is the Corruption Perceptions Index, comparing scores and rankings for 2012–2017 (Table 5). The index is based on a compilation of multiple surveys and sources that capture attitudes toward public sector corruption including bribery, diversion of public funds, integrity in the public sector, nepotism in government, effective prosecution of corruption, adequacy and enforcement of anti-corruption laws, and legal protection for journalists and whistleblowers. The Corruption Perceptions Index for Mexico has deteriorated in the last five years, falling from a high of 35 in 2014 to 2018's score of 28. For comparison, the top-ranking nations of New Zealand and Denmark achieved scores of 89 and 88 respectively, whereas the U.S. received a score of 75 for 2017. The declining trend in Mexico is consistent with stakeholder concerns over a lack of transparency in how development funds for the Yaqui Valley were utilized as well as concerns that safety and security were deteriorating (Eichler Inwood, 2018). Some stakeholders expressed pessimism that government officials would be effective at improving delivery of agriculture support services. Furthermore, stakeholders need data in a form and scale that they can understand (e.g. by specific project and municipality).

The goal for transparency is to reverse recent trends and increase confidence in government. Transparency goals include improved reporting of funding received from all sources for local projects, and how the funds are used. Published annual audit results would be a positive step to allow interested stakeholders to verify how money is allocated and spent for each project, each year, by municipality.

An alternative indicator of transparency may be voter participation records (Taecharungroj et al., 2019), which are summarized by the Mexican government for federal elections in 2012 (Instituto Federal Electoral, 2013) and 2018 (Instituto Nacional Electoral, 2019). These data show that voter participation across Sonora's 7 federal voting districts ranges from 46.4-59.7% and was lower than the national average in both 2012 and 2018. Many social and economic conditions affect voter participation rates, and more research is recommended to understand how voter participation is linked to transparency and perceived corruption. Likewise, while examples of assessing local governance capacity exist (Wilde et al., 2009; da Cruz et al., 2015), these too require investments in data collection and a separate participatory process that are beyond the scope of the rapid appraisal approach.

3.2.6. Social acceptability: government index of social lag

The degree of social lag (relative access to social services) is very low or low for the DRRY population based on 2015 data (Fig. 11). To put the index in perspective, municipalities with very low, low, and medium social lag correspond to 5, 12, and 25% of the population being without refrigeration and having 2, 3, and 4% of persons over age 15 who are illiterate—based on two of several statistics contributing to the index. It is important to note that social and economic ratings are likely skewed by Ciudad Obregon statistics being derived from data for the region that includes the municipality of Cajeme, which contains urban areas that are not part of the DRRY rural population. An advantage of using an index is the availability of data and an implied preferred status, which in this case is to expand the 'very low' social lag level classification to all residents of the Yaqui Valley. A limitation is that future changes will occur relative to the rest of Mexico, so an understanding of underlying data is important for interpretation.

3.2.7. Economic: diversity of crops by area planted and market value

In 2016, crops were harvested from 353,974 ha in six municipalities of the Yaqui Valley (includes minor areas outside of DRRY), at a total value of 10.8 billion pesos (about 524 million US dollars using December 1, 2016, exchange rate of 20.776:1). Of this total amount, 62% of the area and 48.5% of value was attributed to wheat grain production (Table 6). Similarly in 2017, requests for irrigation allocations were primarily for wheat (67.8% of DRRY, Fig. 12), followed by maize (10.4%), and the remaining 21.8% divided among 53 other crops (Fig. 13) excluding double cropped fields (about 4500 ha, data not shown).

The calculated Shannon diversity index for crops by area was nearly identical at 1.42 and 1.43 for 2016 and 2017, respectively, despite different information sources. These values correspond to $ENCS_{ha}$ of 4.19 and 4.15 for 2016 and 2017, respectively. This $ENCS_{ha}$ for the Yaqui Valley is equivalent to having just 4 crop species planted to 88,500 ha each. This lack of spatial diversity is due to the predominance of wheat within the DRRY and is much lower than the $ENCS_{ha}$ in southern California (ranging from 9-12) but is similar to that of the grain belt in Illinois (Aguilar et al., 2015). The $ENCS_{ha}$ baseline for Yaqui Valley municipalities was 3.8 for 2006 (data not shown). The comparison shows that $ENCS_{ha}$ has improved slightly over the course of a decade. An alternative perspective is given by calculating diversity of the market value (rather than spatial diversity using hectares), which results in a value of $ENCS_{value} = 7.00$ for 2016.

While wheat production was by far the most important crop in terms of total economic value for the area, it had a relatively low value per unit of land at about 23,800 pesos per hectare (US$1146/ha using 12/01/2016 exchange rate) when compared to other crops in the valley for 2016. In 2005, wheat was valued at only 8,827 pesos per hectare (US$840/ha using 12/01/2005 exchange rate of 10.08:1USD, not adjusted for inflation). The higher value in 2016 is a result of both higher market price/ton and higher average yields (data not shown). Wheat ranks 26th in market value per hectare of production in 2016 (Table 6). However, the variability in value among municipalities is also low (standard deviation = 1.14), implying that consistent markets for wheat are similarly accessible through the region and, thus, the risks are relatively low (Harwood et al., 1999). In contrast, potatoes (*Solanum tuberosum*) are ranked 5th in market value per hectare but have high variability (standard deviation = 42.05). Value per hectare is highest among fresh vegetable and specialty crops (including potatoes), which also had greater variability in value, perhaps because these crops often require higher overhead (e.g., maintenance of screen-houses, post-harvest processing, and storage) and involve greater risks (Popp and Rudstrom, 2000). Specialty crops have limited markets and intense competition that can provide opportunities for high profits or result in big losses. Additional research and stakeholder discussion are needed to identify target levels of crop diversity that achieve acceptable risk while improving economic resilience throughout the landscape.

In the Yaqui Valley, risk of catastrophe can be interpreted as risk to agricultural productivity, which is related to high temperatures during the early growing season that often dramatically reduce wheat yields (Prasad et al., 2008; Lobell and Ortiz-monasterio, 2007). Therefore, local trends in global warming could destabilize wheat production, which is the economic basis of Yaqui Valley agriculture. This risk is mitigated to some extent due to the ongoing research and development of new varieties of wheat designed to tolerate higher temperatures. Thus, diversity in wheat varieties planted each year should also reduce risk. The advantage of using crop diversity as a proxy for crop-related economic risk is that data on production and value by crop are likely to exist at local and regional scales as a matter of course, although this information is not always archived in a national or international repository; so accessibility often relies on local contacts.

4. Discussion

Collectively, information on environmental, social, and economic indicators increases understanding about ways to progress toward sustainable agricultural landscape goals. Advances are needed in all dimensions, while building capacity for learning and adaptation, to enable continual improvements in response to evolving conditions and goals (Dale et al., 2019). Information on particular indicators relative to baseline and target conditions can be used to gauge whether progress is being made or to help identify practices that improve conditions as discussed below.

It is fundamental that the appraised indicators are meaningful and useful in decisions made about advancing toward goals. As the suite of indicators was developed, some proposed indicators were discarded due to lack of data or because available data was limited and not technically effective for a landscape appraisal. The process of discerning indicators provides an opportunity for learning by stakeholder participants. Future appraisals therefore may become iteratively more data-driven and representative of community concerns.

Results of this rapid appraisal suggest that there are opportunities to improve soils through conservation agriculture in order to reduce risk of compaction and salinization and to improve soil quality. Productivity throughout the DRRY irrigated land, as indicated by NDVI, has been maintained at a high level during the past 18 years with a few exceptions during drought years. To address water concerns expressed by stakeholders, efforts should focus on improving water- and nutrient-use efficiency while maintaining yields. Additional stakeholder input is needed to determine whether NDVI as a proxy for landscape productivity remains a useful indicator or if it requires modification.

Protected native habitat is absent within the DRRY. Beyond the increased aesthetic value from native flora desired by stakeholders, the lack of perennial vegetation could limit efforts to support organisms that are beneficial to crops, such as native pollinators and insect pest predators or parasites. There is an opportunity to develop corridors of native plants along certain types of field margins, although concerns for rodent pest control, water flow management, and water use must be addressed. Marine, mangrove, and forest conservation areas, although located outside the DRRY, should be evaluated to determine how they might best be managed to achieve stakeholder goals.

Indicators of social sustainability considered in this study include indices of relative vulnerability related to climate change, as well as poverty and transparency. The analysis suggests that reducing environmental and economic vulnerability to climate change can be achieved by increasing the diversity of crops and continued investment to identify low-risk and high-value production options that are adapted to the local conditions, including crop options that help remediate compacted or saline soils and that are tolerant to drought and salinity. Making crop insurance available for more crops, including alternative varieties that improve water- and nitrogen-use efficiency, can encourage farmers to increase overall system diversity and rotations, thereby reducing economic risks associated with catastrophic crop loss. Other economic indicators such as rate of bankruptcy claims, land consolidations, or years-in-business should be explored to provide a more robust appraisal of economic sustainability for an agricultural landscape.

The exclusion of some indicators for the rapid appraisal is of note. Indicators were most often not considered because of the paucity or absence of information. For example, additional data are needed to more fully address several concerns identified by Yaqui Valley stakeholders (Eichler Inwood, 2018). We were unable to access data on reservoir volume, water charge rates, and irrigation releases, which are key issues in this arid landscape. The Valley's contribution to, and effects from, global climate change are concerns recognized by farmers, businesspeople, local researchers, and other Yaqui Valley stakeholders. No suitable information was readily available to estimate fossil energy dependence, which is linked to social, environmental, and economic priority themes including air quality and health, greenhouse gas (GHG) emissions, and crop production costs. Data related to pesticide use via a container collection program were not yet available but could help address priorities related to reducing negative health impacts associated with pesticide exposure. The social indices and data identified do not effectively address goals related to improving gender and educational equity that were discussed during stakeholder workshops (Eichler Inwood, 2018). Specific calculations and meta-data for vulnerability indices were not available from the government, making it difficult to verify what data and criteria were applied in these municipalities to establish the vulnerability ratings. A scarcity of reliable, historical indicator data influences interpretation of outcomes, as well as the ability of stakeholders to use results in decision-making, a key purpose of conducting an assessment of the agricultural landscape.

While adaptation to climate change is a priority that encourages diversification of crop genetic resources through use of heat tolerant and drought resistant varieties, indicators for climate impacts or climate and weather data were not included. In future iterations of the appraisal, we suggest considering indicators of adaptation to climate change such as area planted to drought resistant varieties, as well as practices that will reduce or reverse greenhouse gas emissions such as area managed by precision fertilization, organic certified, or regenerative farming techniques.

In addition to limitations discussed earlier for each indicator, several general limitations to the Yaqui rapid assessment are acknowledged. A more comprehensive assessment involving additional indicators, finer resolution of data, or site-specific measurements was not possible due to the limited resources for field work. It would be helpful to collect additional information from the Yaqui Valley and use it to conduct a detailed assessment of progress toward sustainability to determine the costs and benefits of that additional information. Additional research is warranted to identify the principal social, economic, or cultural drivers for the expressed priority themes. Furthermore, testing the rapid appraisal process in other agricultural landscapes would offer additional insights for improving the process. Because there can be different numbers of themes and indicators within each dimension, we suggest using an analysis approach that is designed to solve complex decision problems that involve several attributes, inaccurate and/or missing data, group decision-making, and expert judgment (Bohanec et al., 2013) and lack of balance within dimensions. For example, Multi-Attribute Decision Support System (MADSS) models require aggregation of indicator themes within dimensions prior to evaluating the overall progress toward sustainability (e.g., see (Parish et al., 2016)).

Even with the paucity of available information, this rapid appraisal of the progress toward sustainable agricultural landscapes in the Yaqui Valley offers a launching point for stakeholder engagement and decision-making processes for landscape management. In light of the information gained from the rapid appraisal, stakeholders may refine or amend the suite of indicators or seek additional data resources. Increased familiarity with the terminology, opportunities and limitations of a rapid appraisal toward landscape sustainability may improve stakeholder engagement and encourage knowledge sharing around local, high-priority themes.

Future steps envisioned for this appraisal process would aim to collect feedback from stakeholders on the results and recommendations documented here. Proposals should be developed by local stakeholders to conduct necessary research and fill gaps in data for priority measures. Our study focused on agricultural landscape management issues for the DRRY due to the location of the CIMMYT research center in DRRY and their established relationships. We did not try to include the neighboring irrigation districts–the autonomous Yaqui region to north and the Rio Mayo irrigation district to the south–which fall under separate management. However, the recommendations may be relevant for those and other districts. Other future steps should support monitoring to evaluate which practices are most effective in advancing priority goals. Ideally, local agricultural outreach professionals would help stakeholders identify management practices that address areas of continued concern. With further engagement of stakeholders, it is likely that additional or different indicators will be deemed appropriate. Regardless of changes to data availability and assessment results, the *process* of engaging with stakeholders to consider desired future conditions in the Yaqui Valley landscape is likely to lead to greater appreciation of how current practices affect future outcomes.

5. Conclusion

The utility and limitations of a rapid appraisal process are documented based on accessible information relevant to agricultural landscapes. The approach is best suited to examination of a given landscape over time rather than comparing two disparate landscapes. Many practical challenges must be met to assemble data sufficient to understand a suite of landscape indicators. We demonstrate how results can be derived from readily available data despite several limitations.

The approach can be generalized to diverse landscapes in a variety of development contexts and provide information in a user-friendly format that can be periodically updated. The potential to learn from experiences and modify indicators in future appraisals is another advantage of the approach. The appraisal method can be used by non-experts with basic internet access to public databases. If the appraisal is repeated periodically, it will provide an adaptable basis for monitoring trends regarding issues of local concern, while highlighting areas in which better data are needed. Because indicator data are not collapsed into a single index, there are opportunities to gain contextual knowledge of driving factors affecting landscape sustainability, thus allowing stakeholders to prioritize local policy or farm management needs. Participation in rapid appraisals can improve awareness among community members of social and environmental conditions, trends, and how perspectives and concerns vary across segments of society. The Yaqui Valley process generated information and discussion that help stakeholders consider agricultural management decisions in view of broader community and landscape goals.

The Yaqui Valley case reinforces the idea that improving sustainability of agricultural landscapes requires time and commitment to work with communities. An advantage of using the rapid appraisal method is that stakeholders can revisit the priority level of indicator themes as new participant voices are heard and reevaluate the usefulness, technical effectiveness, practicality and sufficiency of selected indicators, particularly as new data resources become available.

Declaration of competing interest

The Authors declare no conflicts of interest.

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Appendix

Endorsed indicators, identified through an iterative compilation of stakeholder priorities and expert opinion, that can be used to assess progress toward sustainability within the agricultural landscape of Yaqui Valley, Mexico, are listed with preferred units of measurement.

Dimension	Theme	Endorsed Indicator	Preferred Unit
Environment	1. Soil quality	Soil organic matter	Kilogram (kg)/hectare (ha) or % soil organic matter
		Area of compaction	ha or % of irrigation district
	2. Water	Nitrate concentration or export (in or from drainage canals)*	Concentration: mg/L; export: kg/ha/year
		Minimum reservoir volume needed to ensure valley-wide single crop	m^3
		Quality of drinking water	Contaminates monitored and levels remain below thresholds of impact on human health
	3. Climate Change	CO_2 equivalent emissions (CO_2, N_2O, CH_4)	ton CO_2 eq/year relative to total harvested yield estimates
	4. Biodiversity	Habitat areas for taxa of concern	ha
	5. Air Quality	Total particulate matter less than 2.5 μm diameter ($PM_{2.5}$) or 10 μm diameter (PM_{10})	$\mu g/m^3$
		Tropospheric ozone	ppb
	6. Productivity	Yield	g C/m^2/year (relative to total ha harvested)
		Nitrogen use efficiency or Nutrient use efficiency	Percent of fertilizer recovered in grain
Social	7. Social Well-being	Employment	# of full-time-equivalent jobs related to agriculture; unemployment rate
		Household income	$/day; on-farm and off-farm generated if available
	8. Social acceptability	Transparency	Corruption Perceptions Index (Transparency International)
		Vulnerability	Climate Vulnerability Monitor (DARA and the Climate Vulnerable Forum. 2012.)
	9. Health	Pesticide use	Liters (or $ spent) per ha per year or per kg of production
	10. Risk of catastrophe	Crop diversification to reduce risk from extreme events	% area planted in wheat; % of crop area planted to resilient varieties (to be defined through discussion with local stakeholders)
Economic	11. Energy security	Fuel price volatility	Standard deviation of monthly percent price changes over one year (e.g., diesel fuel)
		Energy security for vital operations	Percent of water needs supplied by local power
	12. External trade	Trade volume	$ (net exports or balance of payments)
	13. Profit	Return on investment (ROI)	% (net investment/initial investment)
		Net present value	$ (present value of benefits minus present value of costs)
	14. Fossil energy dependence	Edible Energy Return on Investment	Ratio of fossil energy input to food energy harvested
	15. Conservation of non-renewable resources	Area managed with soil tests that support agriculture decisions	Number of ha, number of farmers
		Water productivity	Ratio of grain yield (kg/ha) to seasonal water use (m^3/ha)

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