Environmental Sustainability and Conventional Agriculture: An Assessment of Maize Monoculture in Sinaloa, Mexico Using Multicriteria Decision Analysis and Network Analysis

by

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ABSTRACT

Sinaloa, a coastal state in the northwest of Mexico, is known for irrigated conventional agriculture, and is considered one of the greatest successes of the Green Revolution. With the neoliberal reforms of the 1990s, Sinaloa farmers shifted out of conventional wheat, soy, cotton, and other commodities and into white maize, a major food staple in Mexico that is traditionally produced by millions of small-scale farmers. Sinaloa is now a major contributor to the national food supply, producing 26% of total domestic white maize production. Research on Sinaloa's maize has focused on economic and agronomic components. Little attention, however, has been given to the environmental sustainability of Sinaloa's expansion in maize. With uniquely biodiverse coastal and terrestrial ecosystems that support economic activities such as fishing and tourism, the environmental consequences of agriculture in Sinaloa are important to monitor. Agricultural sustainability assessments have largely focused on alternative agricultural approaches, or espouse alternative philosophies that are biased against conventional production. Conventional agriculture, however, provides a significant portion of the world's calories. In addition, incentives such as federal subsidies and other institutions complicate transitions to alternative modes of production.

To meet the agricultural sustainability goals of food production and environmental stewardship, we must put conventional agriculture on a more sustainable path. One step toward achieving this is structuring agricultural sustainability assessments around achievable goals that encourage continual adaptations toward sustainability. I attempted this in my thesis by assessing conventional maize production in Sinaloa at the regional/state scale using network analysis and incorporating stakeholder values through a multicriteria decision analysis approach. The analysis showed that the overall sustainability of Sinaloa maize production is far from an ideal state. I made recommendations on how to improve the sustainability of maize production, and how to better monitor the sustainability of agriculture in Sinaloa.

For Beatrice

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Chapter 1

INTRODUCTION

Sinaloa, a coastal state in the semiarid north of Mexico, produces 26% of the nation's white maize (Gobierno del Estado de Sinaloa, 2010), a staple of the Mexican diet (Galarza Mercado, et al., n.d.). This important role in satisfying national food supply is relatively new for Sinaloa: it produced almost no commercial maize before 1990 (Servicio de Información Agroalimentaria y Pesquera (SIAP), 2010). Today, Sinaloa is the national leader in maize production, modeling its irrigated, mechanized production methods after the conventional agriculture model of the United States (Aguilar Soto, 2004). Maize, however, is a resource consumptive crop with potential for environmental degradation, made evident in the U.S. Corn Belt (Brye, Norman, Bundy, & Gower, 2000; Clay, 2004; Kessavalou, Doran, Powers, Kettler, & Qian, 1996; Patzek, 2008; Sampson & Knopf, 1994). Yet, farmers, citizens, and governments in Sinaloa are not seriously considering the effects of maize cultivation on its natural resources or on other economic sectors. Neither are they considering if current practices will allow for maize production – or agricultural production in general – to continue over the long-term. In other words, Sinaloa is not considering the sustainability of maize production.

Sustainability assessment considers the economic, social and ecological components of a system (Gibson, 2006). Research on maize in Sinaloa to date has focused on social, economic, and agronomic elements of production (e.g. Aguilar Soto, 2000; Aguilar Soto, 2004; Aguilar Soto & Maya Ambía, 2007; Díaz Valdés, 2006; Díaz Valdés, Pérez D., N. W., López G., A., Partidas R., L., & Suárez, Y. E., 2008; Maya Ambía & Ponce Conti, 2010; Ojeda-Bustamante, Sifuentes-Ibarra, & Unland-Weiss, 2006), with little focus on environmental impacts or social justice (de Ita Rubio, 2003; Díaz Coutiño, 2007). In the 1980s, Wright (2005) studied the social inequities associated with agricultural modernization and excessive pesticide use in Sinaloa's commercial vegetable sector, calling attention to the need for further analysis and systemic change in the agricultural sector. Furthermore, studies on Sinaloa's biodiverse coastal ecosystems have revealed the presence of toxic agrochemicals (Carvalho, Fowler, & Readman, 1996; Green-Ruiz & Páez-Osuna, 2001, 2003; Federico Páez-Osuna, Ramírez Reséndiz, Ruiz Fernández, & Soto Jiménez, 2007), calling attention to the need for further research on how Sinaloa's agricultural sector interacts with and impacts the environment. As the state's most important crop in terms of surface area and production (SIAP, 2010), maize is a key starting point for understanding the relationship of contemporary agriculture to the environment in Sinaloa.

Research Questions and Objectives

Environmental analysis is an essential step toward fully assessing the sustainability of agriculture in Sinaloa. The discourse on agricultural sustainability has focused on the advantages of alternative agriculture and the disadvantages of conventional agriculture. Yet, the two modes of production espouse "fundamentally divergent paradigms" and values (Beus & Dunlap, 1990, p. 591). Agricultural alternatives such as organic farming or biodynamic farming are designed around values such as environmental stewardship, holism, and community, while conventional agriculture is designed around the values of efficiency, centralization, specialization, and productivity (Beus & Dunlap, 1990; Hansen, 1996). Thus, to assess their sustainability with the same criteria is to compare apples and oranges. Conventional agriculture is currently the dominant mode of food production and is highly institutionalized through government subsidies, large-scale purchasers, and international markets (Clay, 2004). There is a need to address the sustainability of conventional agricultural systems in a more flexible manner to identify context-specific, feasible, and practical transitions to a more sustainable system. Part of achieving this is incorporating stakeholder perceptions and needs. My thesis assesses the sustainability of the state's most important commercial crop, maize, focusing on the environmental component of the system at the state/regional scale in attempt to fill the gaps of sustainability assessment for conventional agriculture and environmental analysis of agriculture in Sinaloa. I seek to answer the following research questions:

1. What are the critical environmental concerns addressed by sustainability assessments of agricultural systems?
2. What is the relevance of such concerns for conventional maize production in Sinaloa?
3. How can stakeholder values be incorporated into a sustainability assessment?
4. What is the current level of environmental sustainability for the maize sector in Sinaloa?

I applied Multicriteria Decision Analysis (MCDA) as the assessment method, and network analysis for system analysis. Using the best knowledge, data, and tools available to me, I identified stakeholder concerns, environmental indicators of sustainability, their current and ideal states, and justifications for how they were assessed. The results call attention to environmental questions in need of further research. Finally, I made recommendations on moving toward a more sustainable agricultural system.

Study Area: Sinaloa, Mexico

Sinaloa is a state located on the Pacific Northwest coast of Mexico, 22˚31' to 26˚56' North latitude and 105˚24' to 109˚27' West longitude. Its area is 58,092 km^2. The mean elevation is 344 meters, though more than half the state is below 150 meters. Most of Sinaloa can be classified as coastal lowlands. The eastern border rises into the *Sierra Madre Occidental* Mountains. The climate in most of Sinaloa is warm and sub-humid with an average annual temperature of 23.8˚C (75˚F; Schmidt Jr., 1976). Annual precipitation is about 80 cm, with most precipitation falling in the summer monsoon season (Comrie & Glenn, 1998; Liebmann, et al., 2008). Soils are mostly eutric regosols, luvisols, verticals, and cambisols.

Sinaloa is biodiverse, with 424 bird species, 143 mammals, and 122 documented amphibians and reptiles (Sarukhán & García Méndez, 2003). The native vegetation of the coastal plains is mainly thorn forest, while the foothills host deciduous tropical forest and low deciduous forest. The native montane vegetation is oak forest and pine-oak forest (Schmidt Jr., 1976). Along the coastline are sandy beaches, dunes, mangroves, estuaries, and lagoons (Carvalho, et al., 1996; Federico Páez-Osuna, et al., 2007). Sinaloa's coast is also an important economic asset, supporting a major shrimp and fishing industry (Trujillo Félix & Gaxiola Carrasco, 2010) as well as tourism and recreational activities that attract national and international visitors (Cruz-Torres, 2004; Gobierno del Estado de Sinaloa, 2010; Rubio Rocha & Beltrán Magallanes, 2003). The coast also supports high species diversity, providing sanctuary for migratory birds, as well as refuge, feeding, and reproductive grounds for endangered species such as turtles, crocodiles, and jaguars (Carvalho, et al., 1996; Rubio Rocha & Beltrán Magallanes, 2003).

Sinaloa has a long history of large-scale agriculture. In the nineteenth century, it was one of the first states in Mexico to modernize, with infrastructure for irrigation and greater concentration of land ownership than other parts of the country (Nakayama Arce, 1983; Ortega Noriega, 1999). In the 1930s, the federal government invested in new irrigation infrastructure for Sinaloa, finishing in 1948 (Ortega Noriega, 1999). Vegetable commodity production expanded in the 1950s and 1960s, and Sinaloa became a major competitor with United States producers (Schmidt Jr., 1976). Sinaloa is noted as one of the greatest successes of the Green Revolution (Wright, 2005). Today, Sinaloa hosts a population of 2,652,451 people, of whom 151,944 are farmers (Gobierno del Estado de Sinaloa, 2009a). Agriculture occupies 25% of the state's landscape (Gobierno del Estado de Sinaloa, 2009b) and represents 14.9% of Sinaloa's GDP. Most agriculture in the state is irrigated with surface water channeled from 11 river dams (Gobierno del Estado de Sinaloa, 2009a).

The large-scale, conventional maize production of Sinaloa represents an enormous departure from traditional small-scale, rain-fed maize cultivation typical in the rest of Mexico (Aguilar Soto, 2004). Sinaloa did not historically produced maize on a commercial scale. Prior to 1990, the dominant crops of Sinaloa by surface area were sesame, safflower, and a rotation of soy and wheat. Starting in 1990, maize production in Sinaloa expanded rapidly, going from 140,727 ha planted in 1989 to a peak of 606,917 ha in 2008 (SIAP, 2010). This expansion was a result of federal neoliberal economic reform in the late 1980s that eliminated price protections for all commodity crops but maize and beans. This, and new high-yielding seeds varieties adapted to Sinaloa's growing conditions led commercial growers in Sinaloa to start planting maize under irrigation. Maize is now a monoculture in Sinaloa during the winter growing season (Eakin, Bausch, & Sweeney, submitted).

Cultivating transgenic plant varieties is not legal in Mexico. The Sinaloa state government allowed Monsanto to plant a small experimental plot with transgenic maize in 2010 (Beltrán, 2010), but in 2011 the secretaries of SAGARPA (*Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación*; Secretary of Agriculture, Livestock, Rural Development, Fishing and Food) and SEMARNAT (*Secretaría de Medio Ambiente y Recursos Naturales*; Secretary of the Environment and Natural Resources) denied permission for a 100 ha pilot plot of transgenic varieties (Pérez U., 2011).

Chapter 2

LITERATURE REVIEW

Theoretical Approaches

Sustainability. At its most basic, sustainability is defined as “meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development (WCED), 1987). Burkhardt (1989) argued that sustainability is a moral obligation “direct[ing] us toward resolving difficult practical problems in future-directed research and technology development, conservation/preservation strategies, and institutional design” (p. 126). The field of sustainability science seeks to “[improve] society’s capacity to use the earth in ways that simultaneously ‘meet the needs of a much larger but stabilizing human population,… sustain the life support systems of the planet, and… substantially reduce hunger and poverty’” (Clark, 2007, p. 1737, quoting The National Research Council Policy Division Board on Sustainable Development, 1999).

Sustainability is committed to collaboration between researchers and stakeholders to produce knowledge that is ”both technically sound and socially acceptable,” or, socially robust (Sarewitz, et al., n.d., p. 13). Stakeholders are the various people associated with the decision process in question (Lahdelma, Salminen, & Hokkanen, 2000). The field of sustainability is use-inspired, “defined by the problems it addresses rather than by the disciplines it employs” (Clark, 2007, p. 1737). Sustainability problems are “important, real world challenges that are complex requiring systems dynamics thinking, not yielding to easy solutions or optimal tradeoffs, and are best understood in the context of specific places although their impact and scale of operation may vary in both space and time" (Miller, Muñoz-Erickson, & Redman, 2011, p. 179). Sarewitz, Kriebel, Clapp, and colleagues (n.d.) emphasized linking knowledge to action for sustainability by seeking intervention points rather than merely characterizing a problem.

Gibson (2006) observed that the impetus for sustainability is driven by demands for improvements to current conditions that are not viable over the long term. He identified normative criteria for sustainability, or sustainability principles on which to base those improvements: socio-ecological system integrity, livelihood sufficiency and opportunity, intragenerational equity, intergenerational equity, resource maintenance and efficiency, socio-ecological civility and democratic governance, precaution and adaptation, and immediate and long-term integration. These principles can be applied to any sector in which environmental, social, and economic components intersect, and has become an important lens for considering critical issues such as energy, urban development, resource management, and agriculture.

Agricultural sustainability. There are many reasons to be concerned about the sustainability of agriculture, such as natural resource depletion, pollution, fluctuating food prices, corporate concentration in the food and agriculture industries, the obesity epidemic, and others (Table 1). Many of these problems are associated with conventional agriculture, characterized as "capital-intensive, large-scale, highly mechanized agriculture with monocultures of crops and extensive use of artificial fertilizers, herbicides and pesticides, with intensive animal husbandry" (Hansen, 1996, p.120, citing Knorr & Watkins, 1984). Conventional agriculture has been described as centralized, competitive, specialized, exploitative, and dominant of nature. The term "conventional agriculture" is often used to refer to mainstream U.S. agriculture (Beus & Dunlap, 1990).

The concept of conventional agriculture was developed to contrast with alternative agricultural approaches and to justify the need for alternatives (Hansen, 1996). "Alternative agriculture" is an umbrella term for organic, biodynamic, regenerative, and low-input agriculture, as well as agroecology, permaculture, best management practices, and maximum economic yield, all of which are associated with the idea of agricultural sustainability (Beus & Dunlap, 1990; Dahlberg, 1991; Hansen, 1996; Keeney, 1989). While these alternative approaches to agriculture are diverse, they have much in common. For alternative agriculturalists, agriculture is about more than food sufficiency and environmental stewardship; it is "a form and manifestation of culture" that "must contribute to cultural and natural vitality by maintaining and promoting democracy, community, and care" (Burkhardt, 1989, pp. 116, 122). They favor significantly reducing synthetic agrochemical use, energy use, technology, and food processing, while advocating for smaller farms, greater farm and regional self-sufficiency, conserving natural resources, direct sales to consumers, and farming as a way of life (Beus & Dunlap, 1990; Burkhardt, 1989). They all "agree that

Table 1

Sustainability Principles and Agricultural Concerns

Sustainability Principles (Gibson, 2006)	Agricultural Sustainability Concerns	References
Socio-ecological system integrity	Yield capacity	Badgley, 2007; Roberts, 2008; UNEP, 2009
	Animal welfare	Singer & Mason, 2006; Pollan, 2006; Schlosser, 2002
	Environmental degradation	Berry, 1977; Carson, 1962; Lal, et al., 2003; McNeely & Scherr, 2003; Pretty, 1995; UNEP, 2009; Uri, 1999a
	Altering global nutrient cycles	Vitousek, et. al., 1997
	Greenhouse gas emissions	Oenema, Kuikman, & Velthof, 2001
	Agrochemical use	Carson, 1962; Lal, et al., 2003; Pretty 1995; Uri, 1999a
Livelihood sufficiency and opportunity	Declining rural livelihood viability	Cochrane, 2003; Lal, et al., 2003; Lyson, 2004; Schlosser, 2002
	Farm subsidies	Myers & Kent 2001; Roberts, 2008
	Worker rights	Clay, 2004; Schlosser, 2002
	Corporate concentration in the agriculture sector	Berry, 1977; Fitzgerald, 2003; Lyson, 2004; Roberts, 2008
	Land concentration, farm size	Berry, 1977; Roberts, 2008; Lyson, 2004
Intragenerational equity	Loss of local/traditional knowledge	Altieri 1995; Berry 1977; Morales, 2002; Wilken, 1987
	Aging farmer population	Hollis, 2005
	Undernourishment	Roberts, 2008; UNEP, 2009
	Obesity epidemic	Nestle, 2002; Roberts, 2008
	Diet related disease	Horrigan, Lawrence, & Walker 2002; Nestle, 2002; Schlosser, 2002
	Fluctuating food prices	UNEP, 2009
	Food safety	Horrigan et al., 2002; Redman, 2007; Schlosser, 2002
	Inequitable terms of trade	Clay, 2004
	Food deserts	Winne, 2008

Table 1 continued

Sustainability Principles (Gibson, 2006)	Agricultural Sustainability Concerns	References
Intergenerational equity	Projected population rise	Kendall & Pimentel, 1994; UNEP, 2009
	Environmental degradation	(see above)
	Natural resource depletion	Berry, 1977; Lal, et al., 2003; UNEP, 2009
	Biodiversity loss	Altieri, 1999; Morris & Winter, 2002; Scherr & McNeely, 2008
	Loss of local/traditional knowledge	(see above)
	Climate change	Roberts, 2008; UNEP, 2009
Resource maintenance and efficiency	Natural resource depletion	(see above)
	Overproduction	Cochrane, 2003
	Energy use in agriculture	Pimentel & Pimentel, 2008; Pretty, 1995
	Loss of cultivable land	UNEP, 2009
Socio-ecological civility and democratic governance	Corporate concentration in the agriculture sector	(see above)
	Land concentration	(see above)
Precaution and adaptation	Biotechnology	Garcia & Altieri, 2005; Pretty, 2001
	Projected population rise	(see above)
	Food safety	(see above)
Immediate and long-term integration	Definition of agricultural sustainability	Douglass, 1984; Hansen, 1996
	Sustainability assessment	see Table 2

industrial agriculture is unsustainable over the long term," meaning that sustainability in agriculture is a call for basic change within the sector and beyond (Dahlberg, 1991, p. 338).

In his analysis of the concept of agricultural sustainability, Hansen (1996) identified two broad interpretations:

> …sustainability interpreted as an approach to agriculture developed in response to concerns about impacts of agriculture, with motivating adherence to sustainability ideologies and

> practices as its goal; and sustainability interpreted as a property of agriculture developed in response to concerns about threats to agriculture, with the goal of using it as a criterion for guiding agriculture as it responds to change. (Hansen, 1996, p. 117)

He further categorized interpretations of agricultural sustainability as ideology, a set of strategies, the ability to fulfill a set of goals, and the ability to continue into the future. Looking at conceptual and methodological barriers for using sustainability concepts to guide change in agriculture, Hansen (1996) found that using sustainability as an approach to change has been hampered because prescribed approaches have been too specific, views of conventional agriculture are distorted, and because of the use of poor logic. To further convolute the concept and objectives of agricultural sustainability, conventional agricultural interests now use the same vocabulary and images used by alternative agricultural interests to frame their objectives and products as environmentally friendly, and even sustainable (e.g. ADM, 2011; Monsanto, 2010; Renewable Fuels Association, 2010). The result is that sustainable agriculture is poorly defined in concept and practice, with definitions being too specific, too vague, or biased toward one end of the conventional-alternative spectrum or the other.

The negative characterization of conventional agriculture is not without reason. Yet, the productive capacity of alternative agriculture has also been questioned with fears that it may not be a viable, or even sustainable approach to food production on a large scale. The idea of “high yield conservation” posits that alternative methods have lower yields than conventional systems, and therefore require bringing more land into agricultural production to produce the same amount of food, implying an increase in deforestation, erosion, and other negative outcomes (Clay, 2004; Devine & Furlong, 2007; Goklany, et al., 2002; Mäder, et al., 2002). Implicit in this argument is that population will rise (such as the oft-referenced population projection of nine billion people by 2050 (Alexandratos, 1999)), and that current eating patterns will remain constant, necessitating even higher yielding agricultural approaches that are assumed to be technologically driven (Fedoroff, et al., 2010). However, dietary changes, especially reducing meat consumption in favor of a more plant-based diet, could decrease pressure on agricultural land (Helms, 2004; Pimentel & Pimentel, 2003). Still, an expansion in biofuel crops could increase pressure on agricultural land.

Contrary to the high yield conservation hypothesis, some studies have shown that the productive capacity of alternative practices is comparable to and perhaps better than conventional agriculture (Badgley, et al., 2007; Pimentel, Hepperly, Seidel, Hanson, & Douds, 2005; Pretty, et al., 2006). An idea gaining traction is "sustainable intensification," which is producing more food per land unit while reducing the environmental impacts of production with strategies such as reduced tillage, integrated pest management, agroforestry, and precision agriculture, among others (Godfray, et al., 2010; Matson, Parton, Power, & Swift, 1997; Pretty, 1997). Regardless of alternative agriculture's productive capacity, or potential dietary changes, building the social and human capital (e.g. farmer skills and knowledge, consumer demand for alternatively-farmed produce) as well as institutions (e.g. local markets) needed for the large-scale implementation of alternative agriculture will take time. It is unrealistic to expect that all conventional farmers –many of whom struggle financially or have little economic motivation to switch (Rosset & Altieri, 1997; Webster, 1997)– will adopt alternative management approaches for the sake of sustainability in spite of existing institutions that provide incentives for the status quo (Godfray, et al., 2010; Hendrickson & James Jr., 2005; Tilman, Cassman, Matson, Naylor, & Polasky, 2002), such as agricultural subsidies (Myers & Kent, 2001), or the agricultural treadmill (Cochrane, 2003). Until those incentives change, if we want to improve the sustainability of agricultural production we need to stop focusing on what makes conventional agriculture unsustainable; this is already well-documented (Table 1).

To meet the sustainability criteria of intragenerational equity and livelihood sufficiency and opportunity (Gibson, 2006), agriculture must produce enough food to feed the human population. Conventional agriculture thus contributes to sustainability in terms of human food provisioning because it has increased aggregate world food production (Pretty, 2008), raising the world average per capita food availability, even with a doubling of the population since the 1950s (Alexandratos, 1999). At this stage in the long journey toward sustainability, it is unrealistic to imagine that some form of conventional agriculture is not a critical part of producing a sufficient amount of food at national and global scales given the current population size.

While still building capacity for the expansion of alternative agriculture in terms of land use, institutions, and human capital, one of the many important steps toward agricultural sustainability is to reduce the environmental impacts of conventional agriculture. We need to put conventional agriculture on a sustainable trajectory by framing it as a system interacting in the environmental, social and economic spheres, and continually identifying tangible ways for farming to become more sustainable. Indeed, sustainability literature highlights that in the pursuit of sustainability "there is no end state to be achieved"; it is a process of continual adaptation (Gibson, 2006, p. 172; Miller, et al., 2011; Pretty, 1997). One way to gain a better understanding of how conventional agriculture interacts with the surrounding environment and to identify the most effective ways to improve its sustainability is through sustainability assessments designed to capture the issues of greatest concern.

Of the definitions for sustainable agriculture, a few have encompassed the many forms of agriculture while calling attention to sustainability values and their systemic nature. Douglass (1984) defined agricultural sustainability by the characteristics of environmental stewardship, the achievement of food sufficiency, and community. Similarly, Rasul and Thapa (2003) pointed out that there are "three basic features of sustainable agriculture: (i) maintenance of environmental quality, (ii) stable plant and animal productivity, and (iii) social acceptability" (p. 174). Another definition focused on these issues was provided by the American Society of Agronomy (ASA, 1989) defining sustainable agriculture as:

> …one that, over the long term, enhances environmental quality and the resource base on which agriculture depends, provides for basic human food and fiber needs, is economically viable, and enhances the quality of life for farmers and society as a whole. (ASA, 1989, p. 15)

According to Hansen's (2006) typology of agricultural sustainability interpretations, the focus on these three issues defines sustainability as the ability to fulfill a set of goals and the ability to continue.

For this project I adopted those elements of the ASA's definition of sustainable agriculture that are within the scope of environmental sustainability: long-term enhancement of environmental quality and natural resources, and the provisioning of basic human food needs. The criterion of long-term enhancement of environmental quality and natural resources aligns with Gibson's (2006) sustainability criteria of resource maintenance and efficiency and socio-ecological system integrity. The criterion of the provisioning of basic human food needs aligns with Gibson's criteria of livelihood sufficiency and opportunity, and intra-generational equity. The other components of the definition – provisioning of human fiber needs, economic viability, and quality of life – are very important for understanding the sustainability of maize production in Sinaloa, however, they are beyond the scope of this project.

Measuring Agricultural Sustainability: Indicator-Based Assessment

Assessing the sustainability of agricultural systems is key to implementing policies and practices that increase sustainable land use (Sadok, et al., 2009). Sustainability assessments are often accompanied by "attempts to define sustainability objectives, to identify appropriate indicators, to apply sustainability considerations in scenario building, community mapping, multicriteria evaluations, lifecycle and flow analyses, and a host of other tools to assist decision-making in complex circumstances" (Gibson, 2006, p. 171). Many sustainability assessments are indicator-based. An indicator is a proxy or measure of an issue of interest that is difficult to monitor directly (Rigby, Woodhouse, Young, & Burton, 2001). According to Sands and Podmore (1993) the primary objective of an environmental sustainability assessment "is to identify, integrate and quantify diverse phenomena that represent the 'state of the environment' for agricultural systems" (p.74); in other words, select appropriate qualitative and quantitative indicators that identify system drivers and system outcomes.

Indicator selection is a complex task. An indicator must be theoretically and contextually appropriate (Rigby, et al., 2001); it must communicate and measure the issue of interest and contribute to the system analysis (Van Cauwenbergh, et al., 2007); and it must be meaningful to stakeholders. However, once a potential indicator is identified, the information associated with the indicator is a serious constraint. Often, there is no existing data for an ideal indicator; it may never have been collected at the location and scale of interest; if data has been collected it may be outdated or difficult to access; or there may not be enough information to interpret the available data. In many cases, due to timing and funding constraints of research, the assessment team does not have the option of collecting the data that would be most relevant to the assessment, and therefore must settle on an indicator for which data already exists. Because there are often multiple potential indicators for a variable, it is important to explain why each indicator was selected and what it communicates about the sustainability of the issue it is intended to measure. Indicator selection is an essential step in sustainability assessment that must be done carefully and thoughtfully to ensure the right combination for analysis, meaning, and relevance.

Once system indicators are selected and current state data are collected, the system is assessed for its sustainability by comparing the current state of the indicators to sustainable reference values or ranges that reify sustainability principles, such as those identified by Gibson (2006). Establishing scale and location-appropriate sustainable states for each indicator is challenging. For many issues, sustainability problems have been identified, but poorly defined, making it difficult to know what the sustainable state would be. For example, land use is a major consideration for agricultural sustainability. A large land area dedicated to a monoculture is widely acknowledged to be environmentally unsustainable (Benton, Vickery, & Wilson, 2003; Pretty, 2008; Rosset & Altieri, 1997). But what constitutes a large area of monoculture? Does the unsustainability of a monoculture vary by crop, tract shape, location, and surrounding land uses? There is no single correct answer to these questions. Thus, a sustainable state (also referred to as an ideal state or level, desirable state, or target value) is a matter of interpretation; it can be generated by comparing it to another system, identifying a threshold, applying a legal value, seeking expert knowledge, or a combination of these options (Van Cauwenbergh, et al., 2007).

While researchers typically provide justifications for the sustainability values they use, these can be challenged and debated, because a single sustainable level for all indicators often does not exist. For example, according to the sustainability ideals of organic farming, synthetic nitrogen fertilizer should not be used (Lotter, 2003). However, it increases production, thereby increasing the food supply, which is good for social sustainability. This tradeoff suggests that, rather than a single amount of nitrogen use being sustainable, there is a range of use – zero to accommodate organic ideals, up to a permissible amount to aid production– that may be considered sustainable. Van Cauwenbergh and colleagues (2007) identified the various kinds of ideal states as maximum or minimum target, threshold, regional average, trend, and between sector comparisons.

I reviewed twenty-eight diverse assessments of agricultural systems in diverse locations and at varying scales, from farm level assessments in Asia to an international assessment of environmental impacts in North America (Table 2). Most of the assessments I reviewed are indicator-based, with different assessment objectives, such as sustainability, soil quality, farm management, and others. I paid particular attention to the analytical framework and evaluation method in each assessment. The primary motivation for the review, however, was to identify the environmental variables of greatest concern to sustainability that are most relevant to the case of Sinaloa, and how indicators for these variables were selected and assessed.

While assessment objectives and methodology vary, there were a few shortcomings characteristic of all of the assessments reviewed that need to be addressed. First, in terms of objectives, many agro-environmental sustainability ideals are based on the values of alternative approaches to agriculture (e.g. organic agriculture, biodynamic agriculture, agroecology, etc.), which were established in reaction to the excesses of conventional agriculture (Beus & Dunlap, 1990; Dahlberg, 1991; Hansen, 1996). In order to make the assessment useful and relatable to stakeholders, the assessment should use metrics appropriate for the mode of production, and consider a range of sustainable values/states that contributes to achieving multiple sustainability principles. Second, the results of sustainability assessments are characteristically a numerical value, a categorical variable (low, medium, high, etc.) or some other brief, semi-quantitative value. These values, however, are often not meaningful outside of the context of the decision making process. Indicators and their sustainability score are the product of a careful and complex decision process that factors in sustainability principles, scientific knowledge, context, missing data, stakeholder motivations and values, and system dynamics. The decision process is part of the results as much as the aggregated sustainability score, and should be reported as such.

Finally, in terms of methodology, many assessments do not establish the relationship of each indicator to sustainability. In other words, sustainability is more complex than a distance-to-target evaluation for individual indicators (Van Cauwenbergh et al., 2007). Rather, each indicator has a unique function in the sustainability of a system, and their values are linked not just in the sustainability score, but also systemically. Part of establishing an indicator's relationship to sustainability is identifying how stakeholders value the variable that the indicator represents. This is important because sustainability is a values-driven concept. The values represented (e.g. the values of the researchers, scientific consensus,

Table 2

Assessments reviewed

Analytical Framework	Reference	Objective	System Assessed	Evaluation Method
Driving force-state-response (DSR)	Hansen et al., 2001	Environmental impact of organic farming	National: Denmark	Organic compared to conventional
DSR	Flores Martinez et al., 2005	Environmental assessment	National: Mexico	Trends
DSR	OECD, 2001	Environmental performance of agriculture	International: OECD countries	Compare with earlier OECD work
Environmental Sustainability Index (ESI)	Sands & Podmore, 1993	Environmental sustainability of irrigated agriculture	Agronomic scale (physical extent of the crop and homogeneity of the agricultural management practices employed)	Compare to a best case scenario based on physical environment; compare systems to each other and over time
Farmer Sustainability Index (FSI)	Taylor et al., 1993	Sustainable farm production practices	Farm: cabbage farmers in Malaysia	Weighted indicators by research team; sustainable thresholds established by research team
Indicator of sustainable agricultural practice (ISAP)	Rigby et al., 2001	Develop indicators of Environmentally sustainable agriculture practices	Farm	Indicators weighted according to sustainability principles from literature
Life Cycle Assessment (LCA)	Kim et al., 2009	Estimate county-level environmental performance for continuous corn cultivation	County: U.S. Corn Belt	Compare corn stover production to corn grain production
Framework for Assessing the Sustainability of Natural Resource Management Systems (MESMIS)	Perales Rivas et al., 2000	Identify and evaluate critical points for reaching sustainability of the South Sinaloa agro-forestry-pasture system	Regional: South Sinaloa	Compare traditional system and innovative system
MESMIS	Perez-Grovas, 2000	Sustainability of coffee production systems	State: Chiapas	Compare traditional coffee cultivation to organic cultivation

(Table 2 continued)

Analytical Framework	Reference	Objective	System Assessed	Evaluation Method
MESMIS	López-Ridaura et al., 2002	Evaluate peasant natural resource management systems	Farm/region	Monitor over time
Multistage methodological framework	López-Ridaura et al., 2005	Systems analysis phase of sustainability assessment	Multi-scale: Michoacán	(None)
Rasul & Thapa, 2003 (original)	Rasul & Thapa, 2003	Sustainability of conventional and ecological agriculture systems	Small communities: Bangladesh	Compare conventional with ecological agriculture
Scale, technique, and composition effect theory	Vilas-Ghiso & Liverman, 2007	Explore trends in input use in the Mexican agricultural sector post-NAFTA	National: Mexico	Trends over time
Sequential Ecological Framework	Carter, 2002	Soil quality for sustainable land management;	National: Canada	Average soil organic matter in local conditions; critical levels of soil organic matter
Simplified version of *indice de calidad de agua* (ICA) (Index of water quality)	SEMARNAT. n.d.	Anthropogenic affects on water quality	National: Mexico	Indicators weighted by research team; classification scale (excellent condition to strong negative impact)
Stockle et al. framework (original)	Stockle et al., 1994	Relative sustainability of farm system	Farm	Indicators scored and weighted by research team
Sustainability Assessment of Farming and the Environment (SAFE)	Van Cauwenbergh et al., 2007	Sustainability in agriculture systems	Farm/region/ state	Reference values/thresholds
Walter & Stützel, 2009 (original)	Walter & Stützel, 2009	Sustainability of agriculture	Field/county	Distance to target/ severity ratio
(None)	Bindraban et al., 2000	Land quality	Continental; national; regional	Distance to target
(None)	de Ita Rubio, 2003	Effect of NAFTA in Sinaloa	Sinaloa agriculture	(None)
(None)	de Vries et al., 2002	Heavy metals	Dutch agroecosystems	Critical load threshold
(None)	Doran & Zeiss, 2000	Soil health & sustainability	Farm level soil	(None)
(None)	Instituto Nacional de Ecología (INE), 2009	Air quality	City	Thresholds established by the Secretaria de Salud

(Table 2 continued)

Analytical Framework	Reference	Objective	System Assessed	Evaluation Method
(None)	Krishna, 2002	Soil mineral deficiency & nutrient acquisition in crop production	Farm: crop production	Estimation of elemental contents in different plant tissues
(None)	Paetz & Wilke, 2005	Soil sampling; determining soil characteristics for agriculture	Field	(None)
(None)	Pimentel et al., 1995	Erosion and agricultural productive capacity; economic costs of erosion	National: erosion in U.S.	Compare conservation techniques to conventional techniques; economic bottom line
(None)	Vaughan, 2003	Environmental impact of NAFTA	National: Mexico	Change since implementation of NAFTA
(None)	Vaughan, 2004	Environmental impact of NAFTA	International: North America, mostly Mexico	(None)

stakeholders, government, etc.) change not only the results, but also how useful and relevant the assessment is perceived by those to whom it matters most: the stakeholders, who are in the position to influence progress toward sustainability. While stakeholder input is encouraged in sustainability assessment (Gibson, 2006), none of the assessments in my review used stakeholder input in the evaluation process, the phase of the assessment in which this relationship is established.

Alternative approaches to indicator-based assessments are needed to confront these shortcomings. My study is an example of one such alternative. I employed a combination of MCDA (Lahdelma, et al., 2000; Lootsma, 1999; Triantaphyllou, 2000) and network analysis (Scott, 2000) in an indicator-based assessment of the environmental sustainability of conventional maize production at the state/regional scale in Sinaloa, Mexico.

Environmental Sustainability Variables for Agriculture

In order to gain a better understanding of the methods of agricultural sustainability assessments and the issues or variables of greatest concern to agricultural sustainability, I reviewed twenty-eight diverse assessments of agriculture (Table 2). I noted each environmental indicator, and categorized them by general theme: water, soil, inputs, ecosystems, atmosphere, yields, land, and pests and disease (Appendix C). From these themes, I identified twelve broad environmental variables to address in my assessment of conventional maize production in Sinaloa: soil quality; erosion; water quality; irrigation; nitrogen fertilizer; pesticides; fossil energy; agricultural land; pests and disease; ecosystems; greenhouse gas emissions; and crop yields. I elaborate on each of these variables below.

Soil quality. Soil quality is "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Doran and Zeiss, 2000, p. 4). Soil quality is recognized as one of the most important issues of agricultural sustainability (Lal, 1991), with soil organic matter (SOM) as perhaps the single most important issue of soil quality (Carter, 2002; Clay, 2004; Weil & Magdoff, 2004). It reflects on the agricultural sustainability criteria of long-term enhancement of environmental quality and natural resources because it is a natural resource that contributes greatly to environmental quality by supporting plant life, cycling nutrients, sequestering carbon, filtering water, and supporting the plants that provide for basic human food needs.

SOM is typically composed of organic molecules from plant litter, animal litter, and detritus. Its composition is highly variable and as yet poorly understood. The increased use of synthetic fertilizer starting in the 1950s drew focus away from the importance of SOM because its role in plant growth was understood only in terms of nutrient supply (Weil & Magdoff, 2004). By the 1990s, however, interest and appreciation for SOM was reestablished because of its important role in the global carbon cycle and its stimulatory effects on plant growth: it enhances nutrient supply, soil structure, cation exchange capacity, water retention, carbon and nitrogen levels, and microbiological soil processes (Chen, Nobili, & Aviad, 2004).

Erosion. A major challenge for conventional agriculture is topsoil loss from erosion, which affects soil quality. In the U.S. for example, the rate of soil formation is about 1 ton per hectare (T/ha) per year, while the rate of soil loss on croplands is 17 T/ha per year from erosion (Pimentel, et al., 1995), though rates vary widely. Erosion negatively affects soil quality by reducing soil depth, nutrient supply, organic matter, and water retention capacity, all of which may lead to dramatic decreases in yields (Fernandez-Reynoso, 2008). Erosion occurs when soil is exposed to energy from wind or rain (Pimentel & Pimentel, 2008). The occurrence of erosion degrades environmental quality and natural resources because the essential resource of soil is being depleted when erosion occurs. Conventional agricultural lands are susceptible to erosion because of repeated tilling and lack of consistent vegetative cover (Pimentel, et al., 1995), though topography, land surface slope, and local climatic conditions play an important role in erosion as well. This detracts from the provisioning of basic human food needs because erosion results in lower yields. In conventional agriculture, fertilizers and irrigation are used to compensate for erosion and the resulting reduction in soil quality, but these inputs "create pollution and health problems, destroy natural habitats, and contribute to high energy consumption and unsustainable agricultural systems" (Pimentel, et al., 1995, p. 1117). Furthermore, eroded soil particles often enter water systems, which can lead to eutrophication, siltation in harbors and channels, wildlife habitat loss, and increased water treatment costs, among other environmental costs (Pimentel, et al., 1995).

Irrigation. Water is necessary for producing food to meet the agricultural sustainability criteria of the provisioning of basic human food needs. The source and efficient use of water are important to the sustainability of agricultural systems. Agriculture accounts for 70% of annual global water use. Water use is a dominant theme in maize production because it is a water intensive crop: one hectare that yields 7 tons of maize transpires around 4,000 cubic meters (m^3) of water (Pimentel, et al., 1995). In the U.S., for example, maize requires approximately 14 million liters, or 14,000 m^3 of water per hectare (Pimentel, et al., 2008). Because of the high demand for water in maize production, it is sometimes cultivated under irrigation in areas with low rainfall, such as Sinaloa.

89% of the land devoted to maize production in Sinaloa is irrigated (SIAP, 2010), making irrigation highly relevant to its sustainability. Irrigation relates to sustainability in terms of water source, availability, quality, and efficient use, which are part of the agricultural sustainability criteria of long-term enhancement of environmental quality and natural resources.

While irrigation can increase yields and contribute to consistent production levels, when fields are not set up for proper drainage irrigation can also lead to soil salinization, which decreases soil quality, and may decrease yields (Lee & Howitt, 1996), demonstrating how interrelated many of the assessment variables are. In a rain fed agricultural system, these issues would not be as relevant; the concern would be annual precipitation and its variability and unpredictability. As a major concern for agriculture in terms of availability, quality, source, and efficient use, water was the variable most represented by indicators in the agricultural assessments reviewed.

Water quality. In addition to water use, water quality is essential for agricultural sustainability because agriculture and all life depend on the long-term quality of natural resources such as water. Agricultural activities have the potential to seriously impact water quality through erosion, nutrient loading, and agrochemical contamination (Doran & Zeiss, 2000; Pimentel, Acquay, et al., 1992). There is ample evidence in the U.S. Corn Belt that agrochemicals have contaminated groundwater aquifers, rivers, and lakes (Spalding, et al., 2003; Verstraeten, Carr, & Steele, 1999), which can be harmful to humans and natural ecosystems. This has led to serious downstream impacts, such as the famous hypoxic (oxygen-depleted) water mass known as the “dead zone” in the Gulf of Mexico. Hypoxic events negatively impact coastal economic activities, such as fishing (Rabalais, Turner, & Wiseman Jr., 2002). Hypoxia is one of many symptoms of eutrophication, which is “an increase in the rate of production and accumulation of carbon in aquatic systems” (Rabalais, et al., 2002, p. 237). Eutrophication is a natural process that occurs when nutrients accumulate in a water body, promoting plant and algal growth. Cultural eutrophication occurs as a result of high nutrient loading (primarily nitrogen and phosphorus) from human activities such as agriculture, which can deoxygenate the water, reduce light infiltration, change species composition, and impair water use (Perry & Vanderklein, 1996).

Nitrogen fertilizer. Synthetic nitrogen fertilizer, an important input for conventional agriculture, is one of the major contributing factors of the yield gains achieved during the twentieth century. Its use has made it possible to produce food on marginal lands, and has dramatically increased food production in many parts of the world (Allison, 1973; Tilman, et al., 2002). While it contributes to sustainability in terms of food sufficiency and land use efficiency, nitrogen fertilizer also presents a host of challenges to sustainability in terms of energy use, nitrogen cycling, and greenhouse gas emissions. These negative outcomes of nitrogen use are related to the other assessment variables of irrigation and water quality: problems with water quality are often driven by nitrogen runoff from agricultural fields. Excessive nitrogen fertilizer use is often a result of inefficient management practices related to timing, placement, and rate of application (Millar, Robertson, Grace, Gehl, & Hoben, 2010). Nitrogen fertilizer production is the most energy intensive aspect of conventional agriculture, requiring natural gas, a fossil fuel, for its manufacture (Pimentel & Pimentel, 2008). Excessive nitrogen fertilizer use "diminishes stratospheric ozone, promotes smog, contaminates drinking water, acidifies rain, eutrophies bays and estuaries, and stresses ecosystems" (Socolow, 1999, p. 6001). Over-applying nitrogen fertilizer also leads to emissions of nitrogen oxides (NO_x) such as nitrous oxide (N_2O), a potent greenhouse gas (Tilman, et al., 2002). Understanding the tradeoffs among yield gains, fertilizer management, N_2O emissions, and environmental impacts are essential for sustainably using nitrogen fertilizer (Millar, et al., 2010). It can negatively impact the long-term enhancement of environmental quality and natural resources such as water, but contributes to agricultural sustainability in terms of the provisioning of basic human food needs. It is worth noting that, while phosphorus is widely applied to maize crops in other regions (Clay, 2004), maize growers in Sinaloa generally do not apply it, so I did not include it in this assessment.

Pesticides. Pesticides are substances that are used to kill organisms such as insects, animals, weeds, and fungi that are harmful to cultivated crops and animals. They include insecticides, herbicides, and fungicides (OECD, 1997). There are naturally occurring pesticides, such as *Bacillus thuringiensis* (BT), as well as inorganic or chemical pesticides. Chemical pesticides existed before World War II, but they were not widely available to farmers until the advent of the organochlorine chemical DDT, whose insecticidal properties were discovered in 1939 (Weinzierl, 1994). In Mexico, intensive use of pesticides began in the mid-1940s to increase production and meet the quality requirements of the export market (González-Farias, 2003). Farmers embraced pesticides because of their low cost and effectiveness; they reduced crop losses to insects, rodents, weeds, fungi, and disease, and reduced labor. Today, pesticides are still widely used in conventional farming systems. By the 1990s, approximately 2.5 million tons of pesticides were used worldwide to destroy pests (Pimentel, Acquay, et al., 1992). According to one estimate, pesticide use in Mexico reached almost 120,000 tons per year by 1995 (González-Farias, 2003). Most alternative farming approaches reject the use of pesticides, opting for Integrated Pest Management (IPM), a suite of strategies including biological controls and crop rotation that decrease reliance on chemical inputs (Cowan & Gunby, 1996; Devine & Furlong, 2007; Morales, 2002).

Pesticide use varies greatly by crop, region, and mode of production. In U.S. maize production, herbicides and insecticides are widely used and have increased dramatically over time. For example, herbicide use in 1964 was less than 12 kilograms per hectare (kg/ha) of maize, and by the early 1990s herbicide application had reached almost 100 kg/ha of active ingredients (Clay, 2004).

There are many sustainability concerns related to pesticide use, including impacts on wildlife, ecosystems, biodiversity, water contamination, and human poisonings (Uri, 1999). It is estimated that 25 million people are poisoned (Alavanja, Hoppin, & Kamel, 2004), and 200,000 people die from pesticide exposure globally each year (Wilson & Tisdell, 2001). Pesticides indiscriminately kill crop pests and beneficial organisms such as pollinators, decomposers, and natural pest enemies (Weinzierl, 1994). Pests can develop resistance to chemical pesticides, which ultimately increasing the number of pests, promote new pests, and therefore increase the use of toxic pesticides (Clay, 2004; Cowan & Gunby, 1996; Douglass, 1984; Wilson & Tisdell, 2001). Some pesticides, particularly organochlorine pesticides, persist in soils, sediments, and biota, increasing risks for environmental damage and risks to human health (Carvalho, et al., 1996). Another problem related to pesticide use is the proper disposal of pesticide containers. Each year in Sinaloa, approximately 500 tons of empty plastic pesticide containers must be disposed of (Cruz, Siller, Cárdenas, & Guzmán, 2006). Like nitrogen fertilizer, pesticides can detract from agricultural sustainability in terms of long-term enhancement of environmental quality and natural resources, but contributes to the provisioning of basic human food needs. Thus, it is important to understand the tradeoffs among yield gains, environmental impacts, and pesticide management approaches in order to sustainably use pesticides.

Fossil energy. Fossil energy has dramatically transformed food production by reducing human labor and increasing production. Pimentel and Pimentel (2008) pointed out that in U.S. maize production, 25% of total fossil energy use is comprised of machinery and fuel, which reduce human and animal labor. The other 75% is used to increase maize productivity, primarily in the manufacture of synthetic fertilizers and pesticides. Thus, one of the most effective ways to reduce fossil energy use in the agricultural sector is to reduce chemical input use. On-farm fuel consumption has become more efficient since the 1980s in response to energy prices, as conventional farmers made technical and managerial changes to improve productivity and efficiency (Cleveland, 1995). There is, however, still room for improvement. Wind and Wallender (1997) suggest changing furrow flow rate, irrigation time, and reducing fertilizer application as strategies for reducing on-farm fossil-fuel use. Cole and colleagues (1997) recommend "expand[ing] the use of minimum tillage, irrigation scheduling, solar drying of crops, and improved fertilizer management" (p. 223).

No-tillage and reduced tillage, often referred to as conservation tillage, represent not just reduced energy use, but a set of cultural practices developed to conserve natural resources and sustain satisfactory yields. Energy savings associated with conservation tillage depend on the balance of soil structure, fertilizer use, pest incidence, and pesticide use. Conservation tillage involves "leaving at least thirty percent of the previous crop residue on the soil surface after planting" (Lal, Eckert, Fausey, & Edwards, 1990, p. 207). The various approaches to conservation tillage include minimum tillage, chisel plowing, plow-planting, ridge tillage, and no-tillage (Lal, et al., 1990). Reduced tillage and no tillage also has the added benefit of increasing soil organic matter, which increases soil quality (Franzluebbers, 2004).

Fossil energy use was not widely included in the assessments of my literature review. However, it is a proxy for farm management, mechanization, and technology. While mechanization is primarily understood as a substitute for human and animal labor, it can also be a substitute for land because in some circumstances it permits more production per land unit, in other words, higher yields (Conforti & Giampietro, 1997). On the other hand, mechanization requires large fields to be viable, and therefore is more associated with extensive agriculture (i.e. a monoculture produced on a large land area) than intensive agriculture (high output from a small land area).

Depending on management, mechanization can negatively affect production. For example, in the past it was a common practice to plow, disk, and harrow maize fields before planting, however, it is now known that this practice leads to soil erosion, kills beneficial soil organisms, and degrades soil structure (Clay, 2004). Some regard natural resource preservation as an unnecessarily high standard for performance in agriculture. In this line of thinking, technology is regarded as a substitute for other natural resources (e.g. fertile soil) to maintain output. Cases of stagnating yields in places such as the United States, Japan and Holland, however, suggest that there are diminishing returns for technology use in agriculture (Douglass, 1984). Fossil fuel is a non-renewable resource that has contributed significantly to our capacity to provide for basic food needs, yet its inefficient use across sectors diminishes the long-term enhancement of environmental quality and natural resources. Because of the centrality of fossil fuels to the technologies of conventional agriculture throughout the production cycle (fertilizer production, input application, machinery production and operation, transport, etc.) as well as their role in greenhouse gas emissions and the debate on biofuels, they warrant special consideration for sustainability (Pimentel & Pimentel, 2008).

Agricultural land. Land quality, land tenure, and land use distribution have become major concerns for the future of agriculture. These concerns are related to climate change (Ramankutty, Foley, Norman, & McSweeney, 2002); global population rise, and increasing international food needs (Godfray, et al., 2010; Tilman, et al., 2002). Land use change is another critical concern. Farmland is converted to other uses such as urban development (Alig, Kline, & Lichtenstein, 2004; Hasse & Lathrop, 2003), while more marginal land in forests, grasslands, and wetlands is converted to agricultural use (DeFries, Foley, & Asner, 2004; Monfreda, Ramankutty, & Foley, 2008). Rising land values are leading to land concentration and fewer farmers (Levins & Cochrane, 1996). Finally, the quality of agricultural land is being degraded as a result of agricultural activities such as tillage and irrigation that may result in soil erosion, compaction, nutrient depletion, and salinization (Doran & Zeiss, 2000).

Devoting land to agricultural use is necessary to meet the agricultural sustainability criteria of providing for basic human food needs, however, the arrangement and management of crops can have significant effects on sustainability. A large land area devoted to a single crop –a monoculture– is problematic for the long-term enhancement of environmental quality and natural resources in terms of biodiversity, soil quality, yields, and agrochemical use. First, deforesting land, planting a monoculture, and fragmenting the natural landscape dramatically reduce biodiversity above and below the soil, thereby reducing soil quality and increasing dependence on synthetic fertilizers to maintain productivity (Rosset & Altieri, 1997). Next, large monocultures are prone to pests and disease, which decrease yields, encouraging increased pesticide use and pesticide dependence (Pimentel, Acquay, et al., 1992; Wilson & Tisdell, 2001). These negative outcomes of agricultural land use can be minimized through management changes. For example, alternative approaches seek to minimize crop loss to pests and chemical use through management techniques such as crop rotation and polyculture that support greater biodiversity and improve soil quality and yields (Altieri, 1999, 2002; Pretty, 2008).

Sinaloa maize is produced as a conventionally managed monoculture. To assess its environmental sustainability, it is important to weigh the tradeoffs among food needs, industrial needs, and the extent to which the negative outcomes of conventional agricultural land use are manifest or will emerge in Sinaloa, while recognizing that land management choices can maximize or minimize the potential for these problems to be manifest in the future. To arrive at meaningful conclusions about the sustainability of agricultural land use in Sinaloa would require an in-depth study on land use alone.

Pests and disease. The variable of pests (insects, rodents, birds, weeds, fungi, etc.), and disease was the least represented in my literature review. Yet this variable can seriously affect agricultural productivity. For example, it is estimated that insects, weeds, and disease lead to a 37% reduction in yields of food and fiber crops in the U.S. (Pimentel, Acquay, et al., 1992). Thus, this variable is key to the agricultural sustainability criteria of provisioning basic human food needs. Pest incidence may also serve as an indicator of imbalances in the crop management system. Pest infestation can be a result of farm management, such as continuously growing the same crop without rotation, or a lack of diversity in agricultural fields (e.g. monoculture). In these cases, when a pest or disease does strike, aside from chemical defenses, there is little to stop the infestation from spreading to the entire crop, which can result in devastating losses. To control pests and disease and reduce crop losses, pesticides have been used in increasing quantities across the globe (Pimentel, Acquay, et al., 1992; Tilman, et al., 2001). Crop pests and disease can thus indirectly impact the long-term enhancement of environmental quality and natural resources because they provoke pesticide use, depending on the management approach.

Another way to deal with crop pests is through preventative management. Traditional farmers have a number of techniques for preventing pest infestation, such as site selection, field concentration/arrangement, crop rotation, soil management, planting and harvesting time, intercropping, biological control, and organic repellent use (Morales, 2002). As Morales (2002) learned from her research with traditional Cakchiquel farmers in Guatemala, "curative pest control activities [such as pesticide use] were largely unnecessary in the traditional maize. The important question to address was why herbivorous insects do not reach pest status [in traditional systems] in the first place" (p. 146). Monitoring pests and disease is an important way to understand farm management, an agroecosystem, and its sustainability.

Ecosystems. An ecosystem may be defined as "a biotic community and its abiotic environment functioning as a system" (Odum & Barrett, 2005, p. 516). Though there are many kinds of ecosystems (natural, urban, agricultural, etc.), my focus for this variable is Sinaloa's native terrestrial ecosystems and coastal aquatic ecosystems. Terrestrial and aquatic ecosystems provide a host of benefits for people, including oxygen production, water filtration, food production, flood control, climate regulation, pollination, genetic diversity, nutrient cycling, aesthetic beauty, recreation, and many others. These are often referred to as ecosystem services (Bennett, Peterson, & Gordon, 2009). These services are critical to human life and are the foundation of economic activities such as timber, tourism, fishing, and agriculture.

For example, Pimentel, Stachow, and others (1992) call attention to the importance of genetic diversity as an ecosystem service provided by and necessary for agriculture, pointing out that agriculture "depend[s] on the 10 million natural species for production and sustainability. The continued viability of agriculture and forestry also depends on wild relatives of the cultured species for genetic resources used in plant breeding to improve crop and forest productivity" (p. 357). Natural ecosystems also play an essential role in watershed maintenance (CRZFSM, et. al., 2002), which is critical for agricultural systems that depend on surface water irrigation, and for the people whose lives depend on those watersheds. Natural ecosystems are critical to the sustainability of agriculture.

"Landscape-level decisions are essential to address [agricultural] sustainability" (Keeney, 1989, p. 102). At a regional scale, the composition of land uses, human and ecological communities, and ecosystems (e.g. land in forests, grasslands, cities, riparian areas, agriculture, etc.) can greatly impact ecosystem functioning (including food production), and therefore sustainability in terms of ecological integrity, environmental quality, and natural resources (Benton, et al., 2003; Forman, 1995). Land use decisions invariably present sustainability tradeoffs that are often hidden or implicit (Bennett, et al., 2009; Foley, et al., 2005). Food provisioning is an important service provided by an agroecosystem, however, land in agriculture can have tremendous impacts on surrounding ecosystems, both terrestrial and aquatic, and diminish their ability to provide other important ecosystem services (Matson, et al., 1997). First, converting land from native vegetation to agriculture reduces the number of ecosystem services provided (carbon sequestration, water filtration, biodiversity, etc.; DeFries, et al., 2004). Second, this conversion can dramatically alter the hydrologic cycle (Gordon, Peterson, & Bennett, 2007). In most agricultural systems, there is less vegetative cover, thus exposing the soil to erosion, reducing soil percolation and infiltration, and compacting the soil through mechanical tillage. The result is "increasing overland flow volumes, peak runoff rates, and potential pollutant delivery to riparian areas" (CRZSFM, et al., 2002, p. 163). Agricultural runoff usually contains fertilizers, pesticides, and eroded soil, which can result in fish kills from eutrophic or hypoxic conditions, and leads to the accumulation of chemicals and heavy metals in sediments, water bodies, and biota. Accumulation of agrochemicals and heavy metals has been found in Sinaloa's coastal lagoons (Carvalho, et al., 1996; Green-Ruiz & Páez-Osuna, 2001, 2003).

Both terrestrial ecosystems (forests, grasslands, etc.) and aquatic ecosystems (rivers, estuaries, wetlands, mangroves, lagoons, etc.) are essential considerations for sustainability. Yet, they are very complex, and require a great deal of investigation to gain a meaningful understanding of their function, how they affect agriculture, and how agriculture affects them. In addition, all the ecosystems in Sinaloa are human-managed to some degree. The issues of governance and the coordination of economic and social activities associated with ecosystem management are also important factors for sustainability. This level of depth is very difficult to capture in a sustainability assessment, however, sustainability assessments can call attention to key components in need of further research.

Greenhouse gas emissions. Agriculture is a major source of anthropogenic greenhouse gas (GHG) emissions and contributor to global climate change. This impacts the long-term enhancement of environmental quality and natural resources, as climate change is projected to affect our ability to produce food in the future (Ramankutty, et al., 2002; Tilman, et al., 2002). Though estimates are uncertain, agricultural emissions of GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are thought to account for a third of anthropogenic radiative forcing (Cole, et al., 1997), which is the amount of energy that is out of balance in the Earth's energy budget. It has been calculated that 83% of greenhouse gas emissions associated with food occur at the farm level (Weber & Matthews, 2008). For example, large amounts of CH_4 are emitted by livestock, primarily ruminants such as cows (Grant, Smith, Desjardins, Lemke, &

Li, 2004). N_2O is produced by soil bacteria in the processes of denitrification and nitrification, and exacerbated by synthetic nitrogen fertilizer application (Amos, Arkebauer, & Doran, 2005). Agriculture can also sequester CO_2 through management practices such as soil restoration, recycling organic waste, decreasing fallow periods, planting cover crops, and practicing agroforestry. Farm level GHG emissions can be cut by reducing tillage, controlling for erosion, minimizing fertilizer use, and improving irrigation management (Amos, et al., 2005; Cole, et al., 1997; Grant, et al., 2004). In other words, management practices that improve soil quality, water quality, and water use efficiency also help mitigate GHG emissions and increase sustainability.

Crop yield. Yield represents the capacity of an agricultural system to provide for basic human food needs. Crop yield is a measure of the weight or volume of a crop harvested per unit of land (e.g. bushels/acre, tons/hectare). It is commonly used to measure agricultural output in conventional cropping systems because it captures three critical concerns: productivity, land-use efficiency, and capital investment efficiency (Clay, 2004).

Yet, yield is also a proxy for the relationship among environmental resources (seed variety, soil quality, climate, water availability, etc.), socio-economic conditions (farm management, farmer skills, land tenure, access to markets, etc.), and productivity (Bindraban, Stoorvogel, Jansen, Vlaming, & Groot, 2000). Yield thus represents a complex system of relationships, and many sustainability tradeoffs. For example, Conforti and Giampietro (1997) point out that, as we seek to increase food production, among the tradeoffs of land use and land management are fossil energy and biodiversity. Higher yields in conventional agriculture are most frequently achieved with external chemical and mechanical inputs that require fossil energy directly and indirectly. The development and use of these inputs require financial capital, such that agricultural production reflects economic investment rather than ecological capacity (Wright, 2005). In addition, there are diminishing returns past a certain threshold of use, and their indiscriminate use has resulted in environmental degradation (Pimentel, et al., 2005; Pretty, 2008; Rosset & Altieri, 1997; Tilman, 1999).

Yield is not the only measure of agricultural productivity. Many alternative approaches aspire to support biodiversity, promote soil quality, cycle nutrients, and provide other ecosystem services in addition to producing food (Scherr & McNeely, 2008). These goals also serve to enhance resilience in the face of ecological and economic shocks, ensuring a consistent harvest if not a record breaking one. For example, Rosset and Altieri (1997) describe the agroecological approach to productivity as a function of:

> …the interactions between the various biotic and abiotic components [of an agroecosystem]. By assembling a functional biodiversity it is possible to initiate synergisms, which subsidize agroecosystem processes by providing ecological services such as the activation of soil biology, the recycling of nutrients, and the enhancement of beneficial arthropods and antagonists. Agroecological technologies do not emphasize boosting yields under optimal conditions as the Green Revolution technologies do, but rather *they ensure constancy of production under a whole range of soil and climatic conditions*… What is important, however, is to focus not on particular technologies, but on an assemblage of technologies that incorporate crop diversity, legume-based rotations, integration of animals, recycling, and use

> of biomass and residue management. (Rosset & Altieri, 1997, p. 6. emphasis added)

Agroecology emphasizes ecological yield capacity rather than economic yield capacity. In addition to food and ecosystem services, agriculture can provide sense of place, and be a source of tradition, culture, and identity for a community (Lyson, 2004). How production is understood and valued is a complicated but critical variable for agricultural sustainability.

Chapter 3

METHODS

Fieldwork

In July 2010, I conducted interviews in Spanish with twenty-six stakeholders and experts (Kontic, 2000) from different sectors of the Sinaloa maize system. These stakeholders and/or experts include farmers, agronomists, university researchers, government employees, environmentalists, and representatives of farmers' associations, all of whom have a stake in Sinaloa's environment, maize production, or both. I prepared a general interview outline to ensure topics of interest were introduced during the conversation. The interviews informed me of each interviewee's background, expertise, and stake in Sinaloa maize production and environment. Some, such as farmers and agronomists, had a greater interest in agricultural sustainability, while others, such as environmentalists, had a greater interest in environmental sustainability. The interviews also provided perspective on production decisions and norms in the Sinaloa context.

Stakeholder ranking of variables and recommendations. I administered a simple questionnaire to stakeholders in my interviews and at a meeting of agronomists for a total of forty-one responses. The questionnaire was in Spanish, and was comprised of twelve broad agro-environmental sustainability variables based on my literature review and the prominent environmental sustainability concerns of conventional agriculture: erosion, soil quality, water quality, pest and disease incidence, yields, terrestrial ecosystem, aquatic ecosystem, nitrogen fertilizer, irrigation, fossil energy, pesticides, and agricultural land use (Appendix D). The stakeholders, according to their opinion and experience, numerically ranked the variables by their importance to the sustainability of maize production in Sinaloa. I interpreted the results of the stakeholders' rankings with MCDA.

On the questionnaire, I also asked stakeholders to identify specific indicators for each sustainability issue that would be useful to them and relevant to the case of Sinaloa, if any occurred to them. I selected indicators for the sustainability assessment based on this feedback as well as data availability. There was also space for comments and/or recommendations on what to include in the assessment of maize production, not limited to agro-environmental sustainability.

Indicator Selection and Data Sources

I selected indicators for the agro-environmental sustainability assessment based on stakeholder feedback from interviews and the questionnaire (Appendix E), as well as data availability. I derived data for the ideal states of the indicators from the literature, best management practices for Sinaloa, sustainability principles, and/or expert opinion. I collected data for the current states of the indicators from primary and secondary sources. Secondary data were collected from government agencies and academic literature focused on the region. Mexican government agencies such as the Sinaloa state government, CONAGUA (*Comisión Nacional de Agua*; National Water Commission), INEGI (*Instituto Nacional de Estadística y Geografía*; National Institute of Statistics and Geography), SEMARNAT (*Secretaría de medio ambiente y recursos naturales*;

Secretariat of the Environment and Natural Resources), and SAGARPA (*Servicio de Información Agroalimentaria y Pesquera*; Agriculture and Fishery Information Service) provide statistics for agricultural production, management practices, and the state of the environment and natural resources in Sinaloa. There is a limited body of literature about agricultural production and the environment in Sinaloa, which also provided data and local perspective for the assessment.

Primary data were collected by Eakin, Appendini, Perales and others (2009) via survey and semi-structured interviews. In the 2009-2010 growing season, they surveyed 449 maize farmers in irrigation district 010 near Culiacán, Sinaloa, representing 2.37% of irrigation users in the irrigation district (SEMARNAT & CONAGUA, 2009). A cluster sampling strategy was employed, in which five irrigation *módulos* (administrative units of farmers with water rights within the district) were randomly selected, and within them, respondents were selected at random for the survey from a list of módulo members provided by each módulo, stratified by landholding size. The number of respondents in each módulo was roughly proportional to the módulo's size. My interviews with local experts both confirmed the accuracy of secondary data and filled in data gaps. I interpreted the indicator data using MCDA.

Network Analysis

Network analysis (Scott, 2000), based on graph theory, is a method for analyzing the influence that each system component has on the other system components. In the context of environmental sustainability assessment, influence represents activity or passivity of each indicator in the system. A system component is active if it exerts influence over other components. It is passive if it has little or no influence on other indicators, and is greatly influenced by other indicators. Influence is important to measure because it helps identify key intervention points for systemic change.

I used an impact matrix (Godet, 2001) to identify the activity (influence) or passivity (no influence) of each system variable (agro-environmental sustainability variable). The purpose of the impact matrix is to identify whether a system variable has influence on the other system variables. In the impact matrix, each indicator is listed along both the rows and columns. I identified whether each row item influences each column item using a binary measure of relations: 0 represents no influence, and 1 represents influence. Only direct influence, not indirect influence, was considered.

Visualizing the impact matrix helps to understand links among indicators, and identify patterns of influence and feedback loops. To do this, I analyzed the impact matrix with UCINET (Borgatti, Everett, & Freeman, 2002), a software program for network analysis, then generated a centrality diagram, a type of system graph, with NETDRAW (Borgatti, 2002; see Figure 1). According to network theory, being in an advantageous or central position within a network is one form of influence. In a network diagram, the closer a variable is to the center, the more influence it has. I analyzed two basic types of advantage: high degree, and high betweenness. With degree, the more ties a variable has to other variables, the more advantaged they are. I focused on Freeman out-degree centrality, which is when a variable has ties extending toward other variables (as opposed to in-degree centrality, which is when a variable receives many ties). Out-degree connections reflect direct influence. They are indicated in Figure 1 by arrows extending from one actor to other actors. For betweenness, I analyzed Freeman betweenness centrality, which means that when a variable is in the geodesic pathway between other pairs of variables, it is in a favored position because the pairs of variables must go through the variable to connect with each other (Hanneman & Riddle, 2005). Betweenness is a measure of indirect influence in the system.

These qualities of influence are important for understanding system dynamics. It may seem redundant in light of the stakeholder weighting, however, this process reveals different information about the system that is important for sustainability assessment. For example, if hypothetically the stakeholders ranked aquatic ecosystem as their highest priority because of a valuable but threatened fishery on the coast, rather than simply recommending a reduction of nutrient levels in the coastal waters, we could examine the network analysis and see that fertilizer application and high erosion rates influence the coastal ecosystem. We could then recommend changes in the source of the nutrients– farm level fertilizer application and erosion– in order to improve the sustainability of the aquatic ecosystem and the system at large. Network analysis is a useful tool for understanding system dynamics and making practical recommendations to improve the sustainability of a system.

Data Assessment: Multicriteria Decision Analysis (MCDA)

Sustainability assessment is increasingly considered a decision-making strategy (Sadok, et al., 2009). Gibson (2006) highlights the important role of assessment for decision-making processes, emphasizing that sustainability assessments must oblige decision-makers to consider core sustainability requirements. He also points out that assessment criteria must reflect local ecosystems, institutions, and preferences through "informed choices" of stakeholders. These elements of assessment –defining decision criteria in terms of sustainability and incorporating context-specific criteria through stakeholder engagement– are embodied in the MCDA method.

I interpreted the results of the questionnaire and the variable indicators with MCDA (Lahdelma, et al., 2000; Lootsma, 1999; Triantaphyllou, 2000). MCDA "aims to develop methods and tools to assist with decision-making, particularly in terms of the choice, ranking or sorting of options (alternatives, solutions, courses of action, etc.) in the presence of multiple, and often conflicting criteria" (Sadok, et al., 2009, p. 775). It provides a method for "weighting individual variables on the basis of existing empirical research and theory" (Eakin & Bojórquez-Tapia, 2008, p. 114). It has not previously been applied to a study of agricultural sustainability at the regional scale. The importance of weighting the system indicators lies in the fact that the system components almost never carry equal weight in a real system, whether the weight reflects stakeholder values as in this study, environmental management principles, or any other normative or functional standard.

Engaging stakeholders arguably provides the stakeholders with a greater sense of ownership in the research results, which is important for research that is intended to be relevant across sectors (Robinson & Tansey, 2006). The MCDA method is collaborative, or transdisciplinary. In transdisciplinary research, "knowledge and values from outside the realm of science are integrated into the research process" (A. I. Walter, Helgenberger, Wiek, & Scholz, 2007, p. 325). With MCDA, researchers and stakeholders co-produce the concept of sustainability for the system in question. MCDA provides a mechanism for incorporating stakeholder values in sustainability assessment, and describes the relationship of each indicator to sustainability through value functions. MCDA describes sustainability (*S*) mathematically as a relationship between weights and the current state of the diverse factors that contribute to sustainability.

Defining weights. To obtain the weights, stakeholders ranked the agricultural sustainability issues on the questionnaire from 1 to 12 (1 being the most important to Sinaloa maize production, and 12 being the least important). Because the ordinal scale cannot be used for mathematical operations, for each questionnaire response I transformed the ordinal scale to weights (w_{ij}) in a scale with ratio properties, which Noh and Lee (2003) established as a valid transformation:

$$w_{ij} = \frac{1}{n}\sum_{k=i}^{n}\frac{1}{k} \qquad (1)$$

where i is the index of variables, j is the index of stakeholders, n is the number of variables, and k is the rank of the sustainability variable assigned by the stakeholder.

After calculating the variable weights for each questionnaire response, I aggregated the weights by taking the geometric mean of the weights for each variable, then normalizing the geometric means so that the sum of the weights of all twelve sustainability variables is equal to 1.

Distance to the ideal point. I assessed the sustainability of Sinaloa maize production using the technique known as the distance to the ideal point. This technique is based on the notion of the "ideal point," which is an abstract condition possessing the most desirable values for each indicator (Lootsma, 1999; Szidarovsky, Gershom, & Duckstein, 1986). To determine the distance to the ideal or sustainable point for each indicator, I identified the current state and ideal state by consulting the literature and local experts.

The distance of the current state of each indicator to a sustainable state is embodied in a value function (Beinat, 1997) that represents the relationship of the indicator to sustainability (Appendix F). Value functions facilitate the comparison of indicators in different units by normalizing their values to a dimensionless scale from 0 (anti-ideal condition) to 1 (ideal condition). In each value function, the abscissa represents the units of the indicator in their natural scale, and the ordinate represents the current state of the indicator as related to sustainability in the dimensionless scale.

To identify the appropriate value function for each indicator, I consulted the literature. To identify the value functions that could not be found in the literature, I presented generic value functions to experts who identified the appropriate curve. I developed the value functions in a Microsoft Excel (2008) file and adjusted them to best fit the expected behavior of each indicator in relation to sustainability. This method should have wide applicability, however, the specifics of the quantitative assessment are specific to Sinaloa.

I coded the numerical value of each indicator in the dimensionless scale according to its distance from sustainability as far, close, or very close to a sustainable state. A value between 0 and 0.49 is categorized as far from a sustainable state. A value between 0.5-0.75 is close to a sustainable state. A value of 0.76-1 is very close to a sustainable state. This categorization follows the Weber-Fechner's Law of Psychophysics (Bojórquez-Tapia, Cruz-Bello, Luna-González, Juárez, & Ortiz-Pérez, 2009; Lootsma, 1999; see Appendix G).

Aggregation. In the final step, the normalized weights of all stakeholders ($w_i^{'}$) were combined with the value of each indicator in the dimensionless scale ($x_i^{'}$) to determine the aggregate environmental sustainability score of the Sinaloa maize system (*S*):

$$S = \sum_{i=1}^{n} w_i^{'} x_i^{'} \tag{2}$$

(Lootsma, 1999).

Chapter 4.

RESULTS

Network Analysis

The network analysis of Freeman out-degree centrality (Table 4) and Freeman betweenness centrality (Table 5) of the system impact matrix (Table 3) revealed that the most active or influential system components are agricultural land, pesticides, and irrigation (Figure 1). Agricultural land is almost two standard deviations higher than the mean out-degree. This variable has even greater betweenness, over two standard deviations higher than the mean. Thus, agricultural land is very influential in the system. This is because devoting land to agriculture, or a specific crop, greatly impacts land management and input use. Yield has average degree and high betweenness, which means that yield does not have high direct influence, but does have high indirect influence. The most passive, or least influential system components are aquatic ecosystem, water quality, and terrestrial ecosystem; these are sinks in the system that receive all the impacts.

Table 3

Impact matrix. Rows and columns list the twelve agro-environmental variables in the same order. Rows display influence (1) or non-influence (0) on each column.

	Soil quality	Irrigation	N fertilizer	Water quality	Agrcultur-al land	Pesticides	Erosion	Aquatic ecosystem	Pest incidence	Terrestrial ecosystem	Fossil energy	Crop yield
Soil quality	0	0	1	0	1	0	1	0	0	0	0	1
Irrigation	1	0	0	1	1	0	1	1	0	1	0	1
N fertilizer	1	0	0	1	0	0	0	1	0	0	1	1
Water quality	0	0	0	0	0	0	0	1	0	0	0	0
Agricultural land	1	1	1	0	0	1	1	0	1	1	1	0
Pesticides	1	0	0	1	0	0	0	1	1	1	1	1
Erosion	1	0	0	1	1	0	0	1	0	0	0	1
Aquatic ecosystem	0	0	0	0	0	0	0	0	0	0	0	0
Pest incidence	0	0	0	0	0	1	0	0	0	0	0	1
Terrestrial ecosystem	1	0	1	0	1	1	1	0	0	0	0	1
Fossil energy	0	1	0	0	0	0	0	0	1	0	0	0
Crop yield	0	1	1	0	1	1	0	0	0	0	0	0

Table 4

Freeman's Out-Degree Centrality

Variable	Freeman's Out-Degree Centrality
Agricultural land	8
Pesticides	7
Irrigation	7
Fossil energy	6
Erosion	5
Nitrogen fertilizer	5
Soil quality	4
Yield	4
Terrestrial ecosystem	2
Pest incidence	2
Water quality	1
Aquatic ecosystem	0
Mean	4.2
Standard deviation	2.45

Table 5

Freeman Betweenness Centrality

Variable	Freeman Betweenness Centrality
Agricultural land	15.683
Yield	11.567
Pesticides	11.126
Irrigation	9.560
Nitrogen fertilizer	4.060
Soil quality	3.676
Fossil energy	3.626
Pest incidence	2.393
Erosion	2.310
Terrestrial ecosystem	1.000
Water quality	0.000
Aquatic ecosystem	0.000
Mean	5.417
Standard deviation	4.984

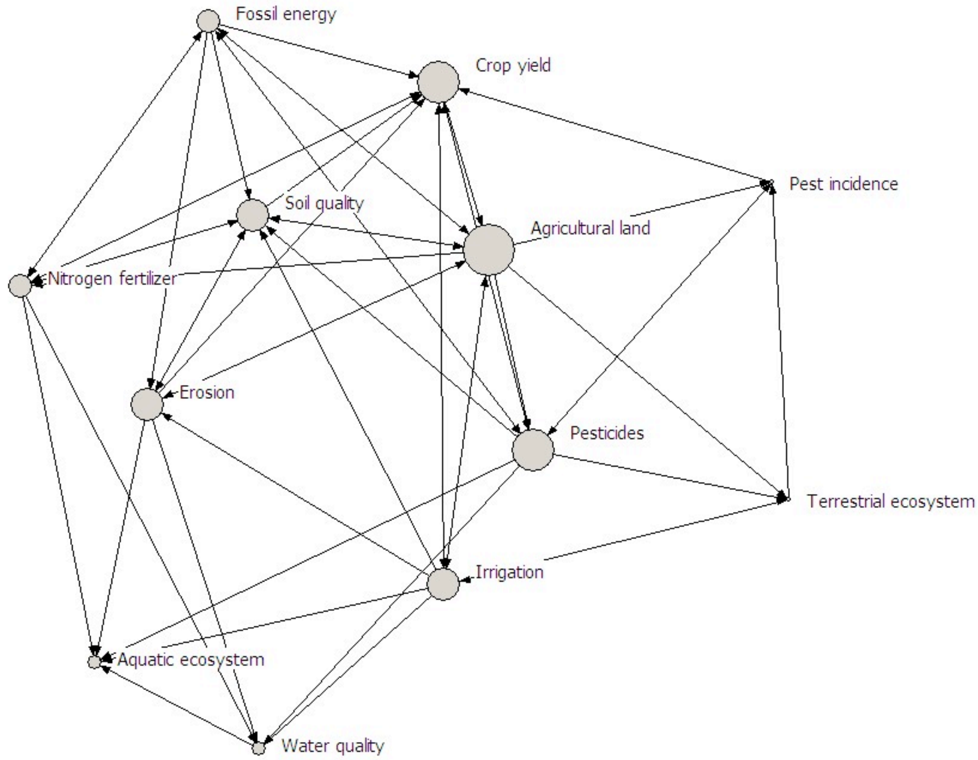

Figure 1. Centrality map of degree influence among agro-environmental sustainability variables for Sinaloa maize production. The size and location of each circle is indicative of centrality or influence, i.e., the larger the circle and closer to the center of the map it is, the more influence it has in the system. Prepared using the software NETDRAW.

Weight Distribution of Agro-Environmental Sustainability Variables

The stakeholders weighted soil quality as the most important variable for the environmental sustainability of maize production. Water-related variables –irrigation and water quality– were weighted second and fourth most important, respectively. In terms of weight distribution, the top three variables (soil quality, irrigation, and nitrogen fertilizer) represent 40% of the total weight. The lowest three variables (terrestrial ecosystems, fossil energy, and yield) represent 12% of the total weight (Table 6).

Table 6

Stakeholder Weights for Agro-Environmental Sustainability Variables, Derived from Questionnaire Ranking. Column 3 displays the weights after they were redistributed to exclude yield.

Variable	Original Weights	Redistributed Weights
Soil quality	0.169	0.175
Irrigation	0.129	0.133
Nitrogen fertilizer	0.105	0.109
Water quality	0.102	0.106
Agricultural land	0.093	0.097
Pesticides	0.084	0.087
Erosion	0.071	0.074
Aquatic ecosystem	0.068	0.071
Pest & disease incidence	0.055	0.057
Terrestrial ecosystem	0.044	0.046
Fossil energy	0.044	0.045
Yield	0.035	N/A
SUM	1.00	1.00

The stakeholders weighted yield so low that it had very little impact on the aggregate sustainability score. It proved difficult to assess (see "Crop yield," p.78) I removed it from the aggregation model and redistributed the weight among the rest of the indicators. Table 6 shows the original weight distribution (column 2) and the redistribution of weights excluding yield (column 3), which I used to generate the aggregate sustainability score.

To gain a better sense of how different stakeholder groups weighted the agro-environmental sustainability variables, I analyzed the questionnaire results according to the following groups: maize growers, agronomists, researchers, government employees, environmentalists, and growers associations. Figure 2 shows how these different stakeholder groups weighted the variables as compared to each other and the total sample. Some stakeholders fall into more than one group, so their results are accounted for more than once in the stakeholder group analysis, but are counted only once in the total sample analysis. The weighting distribution that is the most similar to the total sample is researchers. The weighting distribution that differed most from the aggregate sample is that of the agronomists, who weighted irrigation, pest and disease incidence, and nitrogen fertilizer as most important, and aquatic ecosystems, terrestrial ecosystems, and pesticide use as the least important.

There are some consistencies among the distinct groups. Soil quality was weighted first or second in importance by five of the six stakeholder groups, and irrigation was weighted first or second in importance by four of the six stakeholder groups. Yield and fossil energy were weighted quite low across sectors. The rest of the variables were generally weighted in the mid-range, though their weight by stakeholder group varied.

Considering the network analysis within the system, the most influential variable, land use, was weighted second in importance by researchers, but no higher than sixth by the other stakeholder groups. The stakeholder groups weighted pesticides, the second most influential system component, with moderate importance to sustainability. Irrigation, the third most influential system component, was consistently weighted among the most important variables to environmental sustainability in Sinaloa maize production.

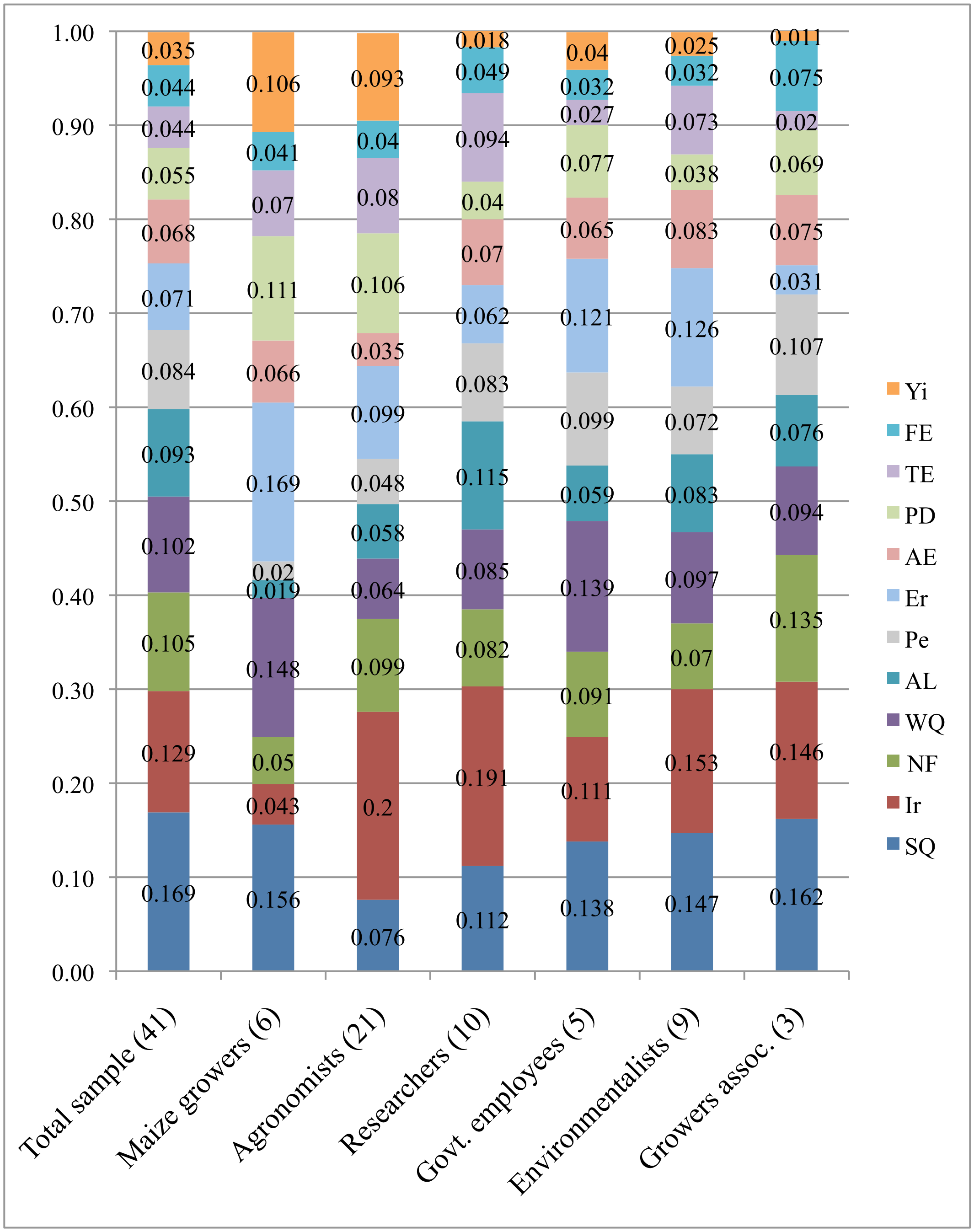

Figure 2. Weight distribution by stakeholder group. SQ = soil quality; Ir = irrigation; NF = N fertilizer; WQ = water quality; AL = agricultural land; Pe = pesticides; Er = erosion; AE = aquatic ecosystem; PD = pest and disease incidence; FE = fossil energy; TE = terrestrial ecosystem; Yi = yield.

Indicators, Current States, Ideal States, Value Functions

Table 7

Indicators, Current States, Ideal States, and Distance to a Sustainable State

Indicator	Variable	Current state	Ideal state	Value in dimens-ionless scale*	Distance to sustainab-le state
% Maize area planted, not harvested	Pest & disease incidence	0.03%[a]	0%	0.99	Very close
% total land in crop production	Terrestrial ecosystem	22%[a]	0-20%	0.98	Very close
Ave. L herbicides/ha/yr	Pesticides	1.15[b]	0	0.90	Very close
Ha. of land in white maize	Agricultural land	471,000[a]	0-347,418	0.71	Close
Ave. kg insecticides/ha/yr	Pesticides	2.5[b]	0	0.69	Close
Net depth cm/ha/yr	Irrigation	72[c]	44[d]	0.59	Close
Ave. L diesel/ha/yr	Fossil energy	130.25[e]	0-65[f]	0.57	Close
T of N/yr in coastal waters from agriculture	Aquatic ecosystem health	53,342[g]	0	0.51	Close
% SOM	Soil quality	0.4%[c]	2%[c]	0.39	Far
% of land affected by hydraulic soil erosion	Erosion	16.2%[h]	0%	0	Far
Ave. E.C. (µS/cm) of field drain water	Water quality	3147×10^{6}[i]	465×10^{6}[j]	0	Far
Ave. Kg N/ha/yr	Nitrogen fertilizer	437[b]	180[c]	0	Far
AGGREGATE SUSTAINABILITY			1	0.45	Far

*See pp. 70-74 for value functions representing the relationship of each indicator to sustainability.

[a] Gobierno del Estado de Sinaloa, 2010
[b] Eakin et al. 2009
[c] Expert opinion
[d] Ojeda-Bustamante, Sifuentes-Ibarra, & Unland-Weiss, 2006
[e] FIRA, 2006
[f] Lal, Eckert, Fausey, & Edwards, 1990
[g] Páez-Osuna et al., 2007
[h] SEMARNAT, 2009
[i] CONAGUA, 2008b
[j] CONAGUA, 2008a

Pest and disease incidence. The indicator for pest and disease incidence is percent of area planted in maize but not harvested. A shortcoming of this indicator is that, while it represents lost productivity due to pests and disease, it may also reflect damage from extreme weather events, such as a frost. A second shortcoming of this indicator is that it does not capture whether pests and disease reduce the yield on the hectares that are harvested. Furthermore, it does not account for whether low pest and disease incidence is a result of high pesticide use, however, this is captured in the indicators for pesticides (below). In 2010, 129 of the 464,692 ha planted in maize were not harvested (Gobierno del Estado de Sinaloa, 2010). The current state is thus 0.03%. The ideal state is 0% area planted and not harvested, in other words, all land planted is harvested. The current state of the indicator is very close to sustainability. The value function for this indicator has a decreasing concave relationship to sustainability because area planted and not harvested represents wasted resources (seeds, energy, water, etc.), lower productivity, and imbalances in the crop management system, which would suggest that a different management approach is needed (Figure 3).

Terrestrial ecosystem health. The primary concern for this variable is how much agricultural land use is permissible in the greater context of the environment, with a focus on the agricultural sustainability principle of long-term enhancement of environmental quality and natural resources. The indicator for terrestrial ecosystem health is percent of total landscape in crop production. The current state is based on the 2010 level of 1,297,586 ha, or 22% of the state's surface area (Gobierno del Estado de Sinaloa, 2010). This represents cropland,

and does not include pasture. A shortcoming of this indicator is that it accounts for all land in the state, including non-arable land. It would be more suitable to compare the current amount of cropland with potentially arable land; however, this information was not available. The ideal state ranges from 0-20%. To identify a tipping point for this indicator, I reviewed biology and ecology literature in Sinaloa in attempt to identify years in which events resulting in ecosystem change or the decline of wildlife occurred as related to agricultural land use changes. The major conversion of land from thorn forest to agriculture in the 1950s through the 1970s is mentioned in academic literature on the region, but not associated with evidence of ecosystem decline or wildlife populations (Sauceda López & Gómez Soto, 2003; Vega Aviña, 2003). Still, land use change is often cited as one of the major threats to Sinaloa's wildlife (Martínez López, 2003; Rubio Rocha & Beltrán Magallanes, 2003; Rubio Rocha & Cupul Magaña, 2006; Sauceda López & Gómez Soto, 2003). In addition, there may be a substantial lag between the time the land is converted and when a decline in ecosystem functioning becomes evident. Because of a lack of evidence that the current state is unsustainable, and because most land use changes associated with agriculture occurred decades ago, it is assumed that the current state of the indicator is very close to sustainability. However, it is not recommended that cropland expand any further. The value function for percent of total landscape in agriculture shows a decreasing sigmoid relationship to sustainability (Figure 4). This reflects that some land in agriculture will not affect ecosystem functioning. However, past a certain threshold of land in agricultural use, sustainability decreases rapidly, but will not completely disrupt ecosystem function until a second threshold is reached.

Pesticides. I assessed two indicators for this variable: average kilograms of insecticides applied per hectare per growing season (kg/ha/yr), and average liters of herbicides applied per hectare per growing season (L/ha/yr). A shortcoming of both indicators is that they do not account for which pesticides farmers are applying, as this data was not available. It is an important consideration for environmental sustainability, however, because some pesticides are more harmful than others. The weight the stakeholders assigned to this variable (0.087) was divided by 2 to accommodate both indicators. Thus, they each have a weight of 0.043. Fungicides were not assessed because, according to Eakin et al. (2009), only 5% of growers apply them to their maize crops. 89% of farmers surveyed reported having used insecticides in the 2009 growing season with an average seasonal insecticide use or current state of 2.5 kg/ha/yr. 70% of respondents reported having used herbicides in the 2009 growing season, with an average application of 1.15 L/ha/yr (Eakin, et al., 2009). Pesticides are beneficial in terms of the agricultural sustainability criteria of provisioning basic human food needs, but harmful for long-term enhancement of environmental quality and natural resources. In other words, pesticides help increase production, but there are diminishing returns to their use, and they have great potential to harm people and the environment. Thus, using zero pesticides is the ideal state for both indicators. Factoring in their positive influence on production, the value functions representing herbicide and insecticide use (Figures 5 and Figure 7, respectively) both have a decreasing convex relationship to sustainability, in which the best management recommendations for Sinaloa are within the range of 0.8 to 1. Best management practices for Sinaloa suggest ~2 L/ha/yr of insecticides and ~1.75 kg/ha/yr of herbicides, though the recommendations vary depending on the chemical (Fundación Produce, 2003). The current state of the indicators for herbicide use and insecticide use are very close to a sustainable state and close to a sustainable state, respectively.

Agricultural land. Devoting land to maize is part of meeting Mexico's food needs, a principle of agricultural sustainability. Yet, some stakeholders questioned whether Sinaloa is overproducing white maize because about 70% of white maize production is used for human consumption, and the rest is used as livestock feed or for industrial use (Gobierno del Estado de Sinaloa, 2010). Sinaloa's high production may also be depressing prices, affecting economic sustainability. In addition, stakeholders expressed concern over the state's maize monoculture and the threat of pests and disease, however, no serious impacts of this kind have occurred thus far. Based on these concerns, I assessed the sustainability of agricultural land use in terms of maize monoculture, and meeting domestic human food demands.

It is complicated to precisely identify what a sustainable land use arrangement would be for a given area. Given the time constraints of this project, I chose instead to assess the number of hectares of agricultural land devoted to white maize in Sinaloa, which addresses the issues of monoculture and production more than the issue of land use arrangement. A weakness of this indicator is that it does not account for land area in yellow maize, which is part of Sinaloa's maize monoculture, but does not necessarily contribute to food production. Some yellow maize is used as livestock feed, in which case it does contribute to food production, but some is used for industrial purposes. Another weakness is that at different scales, such as cities or irrigation districts, land in maize is highly concentrated in some cases. For example, some irrigation districts in Culiacán have up to 80% of their land planted in maize (Eakin, et al., submitted). Assessing land use at the state scale does not capture these concentrations, but is more apt at capturing food production. Another weakness of this indicator is that, while it captures land in maize and ultimately encourages reducing area planted in maize, it does not account for the potential damage of the crops that may replace maize. In other words, the crops that might replace maize may actually be more environmentally damaging than maize, and in these cases, it would be preferable to keep the land in maize, even if it does not mitigate the maize monoculture. An additional shortcoming of the indicator is that it does not account for potential ecosystem services provided by crops, such as carbon sequestration and oxygen production. Much of the land planted in maize is left fallow during the spring and summer. Although this does save water, it also represents an opportunity cost in terms of ecosystem services not provided, as well as lost potential revenue from a spring-summer crop. In addition, fallowing the land leaves the soil vulnerable to erosion.

The indicator for agricultural land is similar to the indicator for terrestrial ecosystem health. However, for agricultural land use the primary concern is monoculture and sufficient food production. For the variable of terrestrial ecosystem health, the primary concern is how much agricultural land use is permissible in the greater context of environmental functioning. In 2010, 1,297,586 ha were devoted to crop production (Gobierno del Estado de Sinaloa, 2010). Of that, 471,000 ha (36.3% of current agricultural land) were devoted to white maize in 2010, which is the current state of the indicator (Gobierno del Estado de Sinaloa, 2010). 3.7 million tons of Sinaloa's white maize are used for human consumption (Gobierno del Estado de Sinaloa, 2010). With an average yield of 10.65 tons/ha (SAGARPA, 2010), 347,418 ha (26.7% of current agricultural land) would be needed to produce that amount of maize. In terms of environmental sustainability, zero land in maize would also be sustainable because ecological function does not depend on maize cultivation, and maize could be produced elsewhere to satisfy Mexico's human food demands. The ideal range of agricultural land devoted to maize in Sinaloa, then, is between 0 and 347,418 ha, or 0-20% of agricultural land. The current state of the indicator is close to sustainability. The value function representing agricultural land in maize shows a decreasing sigmoid relationship, reflecting that 0-347,418 ha is sustainable in terms of environmental quality and provisioning basic human food needs, while also showing that increasing the land in maize would diminish sustainability because of problems associated with overproduction and monoculture (Figure 6).

Irrigation. Sinaloa's irrigation water is derived from eleven river dams throughout the state, and distributed via extensive irrigation infrastructure that was largely constructed before the 1950s (Ortega Noriega, 1999). These rivers are mainly fed from snowmelt in the Sierra Madre Occidental Mountains in the east of the state (Schmidt Jr., 1976). Dams that help store water from surface sources such as rivers can have significant social and ecological costs (e.g. siltation, cutting off water sources used by human communities, disrupting habitat for wildlife, etc.), presenting sustainability tradeoffs for water use. Also, water supplies from surface water sources depend on annual precipitation. If there is a drought, there may not be enough water to meet agricultural demand. In Sinaloa, the dams and irrigation infrastructure were established decades ago. Drought does not appear to have affected maize production in Sinaloa since its adoption in the early 1990s (Comisión Nacional del Agua, 2008; Corporación OSSO - Colombia, 2010; SIAP, 2010) –though climate change may increase future risks. Thus, I did not assess the source or availability of irrigation water. Stakeholders did inform, however, that water availability affects agricultural land use.

The indicator for the variable of irrigation is water use efficiency. Irrigation efficiency reflects on sustainability in that irrigation water in Sinaloa is a finite resource; using it for one crop, or using it inefficiently, means that the water is not being used for another crop or purpose. For example, when Sinaloa farmers transitioned to maize production in the early 1990s, they went from planting two crops per year (such as a wheat/soy rotation) to planting only one crop per year –maize– because of the limited water supply and the higher water demands of maize. This has implications for lost production opportunities and soil preservation, as bare soils are more inclined to erode (Pimentel, et al., 1995). In addition, over-irrigation can increase runoff, transport agrochemicals, and lead to groundwater contamination, increased water turbidity, and nutrient loading in waterways (Páez-Osuna, et al., 2007).

The unit of analysis for irrigation is net centimeters of water per hectare per growing season (cm/ha/yr). The actual amount of water applied per hectare is not currently measured in Sinaloa. Local experts estimate that the current state of irrigation use in maize production is a net irrigation depth of 72 cm/ha/yr, with an average of four irrigations per season. Based on a study of water conservation in irrigated maize production in Sinaloa, a net irrigation depth of 44 cm/ha/year is the ideal state (Ojeda-Bustamante, et al., 2006). The current state of the indicator is close to sustainability. Irrigation water use has a positive relationship with Sinaloa maize production in that evapotranspiration exceeds annual precipitation, making irrigation necessary for achieving commercial yields (Ojeda-Bustamante, et al., 2006). So, at the farm scale, the value function for the sustainability of irrigation use is an increasing convex curve (Overman & Sholtz III, 2002). However, at the regional scale there are tradeoffs and opportunity costs for water use, meaning sustainability decreases past the threshold of 44 cm/ha. The value function representing irrigation use for maize production at the regional scale is thus bell shaped, reflecting the diminishing returns and diminishing sustainability of excess irrigation use (Figure 8).

Fossil energy. The indicator for fossil energy is average liters of diesel fuel consumed per hectare per season (L/ha/yr). This primarily represents machinery use and fuel use efficiency. It also has implications for emissions of

CO_2, a greenhouse gas released in the burning of fossil fuel. According to Eakin et al. (2009), every farmer in the sample reported that they mechanically prepare their land and plant their maize crop. All but one farmer in the sample harvest mechanically. Annual diesel fuel use for Sinaloa maize production ranges from a minimum of 71 L/ha to a maximum of 189.5 L/ha (FIRA, 2006). I averaged these for the current state: 130.25 L/ha. Some fossil fuel use is expected given Sinaloa's mode of production (mechanized monoculture). However, significantly reducing consumption is possible. Interviewees mentioned that many Sinaloa farmers needlessly till during the summer fallow season. Over-tilling not only wastes fuel and increases CO_2 emissions, but can also lead to erosion and other negative outcomes (Pimentel, et al., 1995).

The ideal state of the indicator is the range of 0-65 L/ha. This is based on diesel use for reduced-tillage (in this case, chisel plowing, however, there are many forms of reduced-tillage): 65 L/ha/year (Lal, et al., 1990). While zero fossil fuel use is currently an unrealistic expectation for Sinaloa maize production, the range suggests that the less fossil fuel is used, the better. Conservation or reduced tillage is not widely practiced in Sinaloa, however, experts believe it is a viable option for Sinaloan maize growers. One consideration is that some conservation tillage practices require farmers to purchase or rent specialized machinery, which has implications for economic sustainability. However, many reduced tillage practices have the added benefit of increasing soil organic matter. The current state of the indicator is close to sustainability. The value function representing this indicator shows a decreasing convex relationship to sustainability, reflecting that some fossil fuel use is sustainable, but that sustainability decreases as more fossil fuel is consumed (Figure 9).

Aquatic ecosystem health. The indicator for aquatic ecosystem health is tons of nitrogen from agricultural sources in coastal waters. There is no data specific to maize for this indicator. Nitrogen loading in aquatic systems can lead to significant changes in the aquatic environment, including eutrophic and/or hypoxic conditions that result in fish kills, which do occasionally occur in Sinaloa's estuaries (Páez-Osuna, et al., 2007). A weakness of this indicator is that it does not account for the presence or impacts of other agrochemicals in Sinaloa's aquatic ecosystems (see Carvalho, et al., 1996; Green-Ruiz & Páez-Osuna, 2001, 2003; F. Páez-Osuna, Bojórquez-Leyva, & Green-Ruiz, 1998).

According to Páez-Osuna and colleagues (2007), agriculture is the principle anthropogenic source of nitrogen in Sinaloa's coastal waters, contributing 53,342 tons per year (the current state), or 29.9% of the total annual nitrogen flows into the coast. Because this indicator reflects the sustainability principle of long-term enhancement of environmental quality and natural resources to show the impacts of agriculture on the aquatic ecosystem, the ideal state is zero. The current state of the indicator was determined to be close to sustainability. The value function representing this indicator shows a decreasing convex relationship to sustainability (Figure 10). It is difficult to establish precisely what amount of anthropogenic nitrogen flow would be permissible or unsustainable in a system, especially as eutrophic and hypoxic conditions depend on additional factors such as temperature and season (Rabalais, et al., 2002).

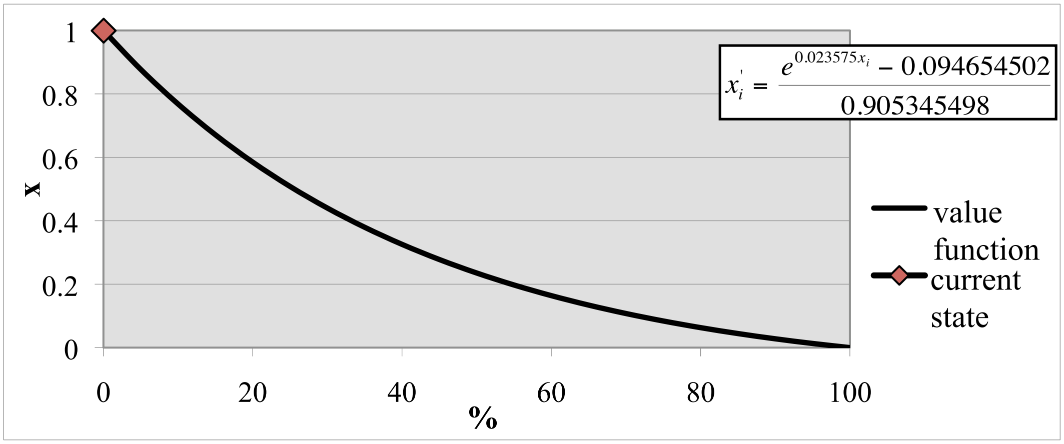

Figure 3. Value function for the indicator for pest and disease incidence (% area planted in maize but not harvested).

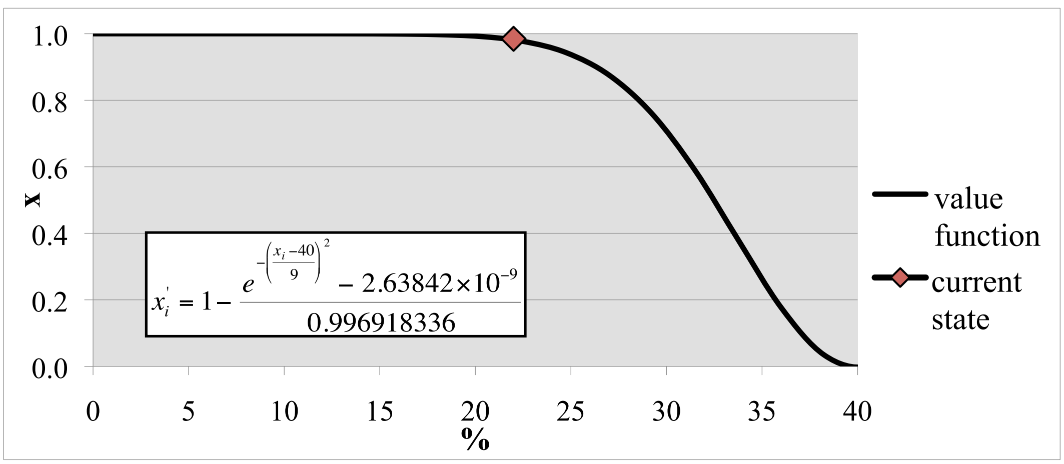

Figure 4. Value function for the indicator for terrestrial ecosystem health (% of total landscape in agriculture).

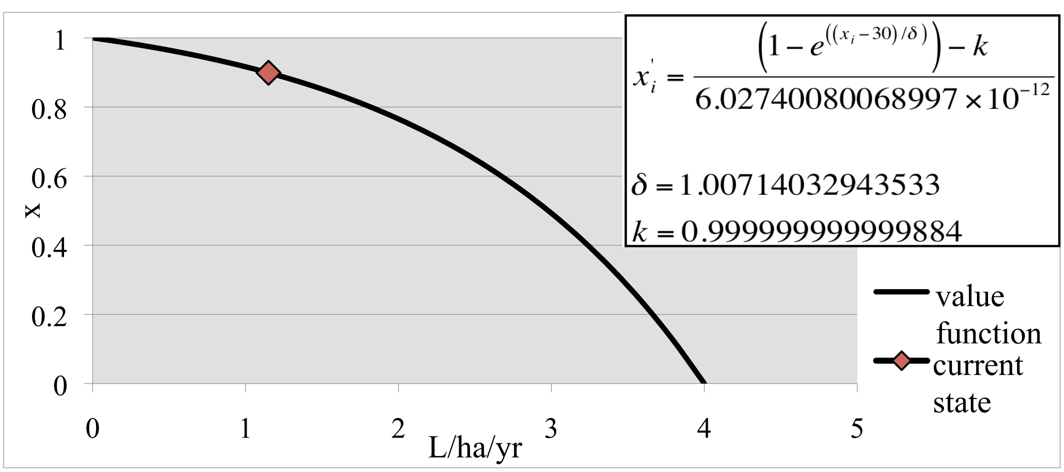

Figure 5. Value function for the first of two indicators for pesticides (annual herbicide use).

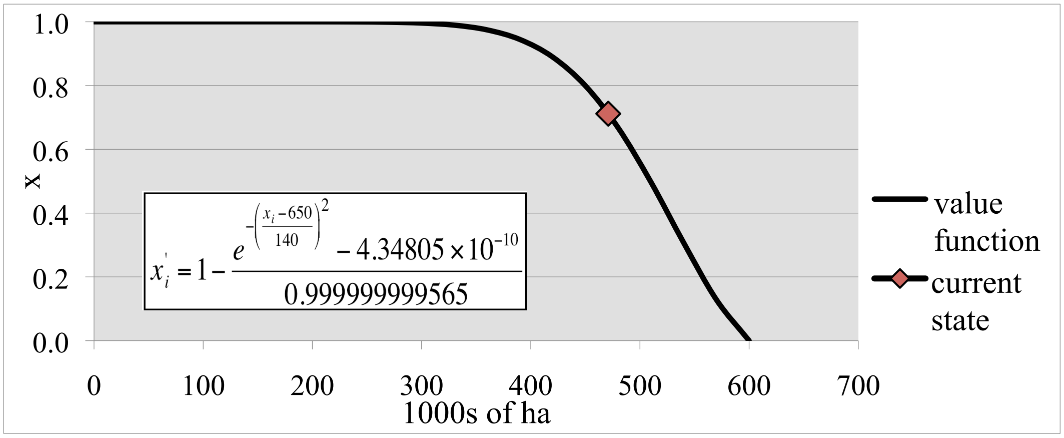

Figure 6. Value function for the indicator for agricultural land (ha of agricultural land in maize).

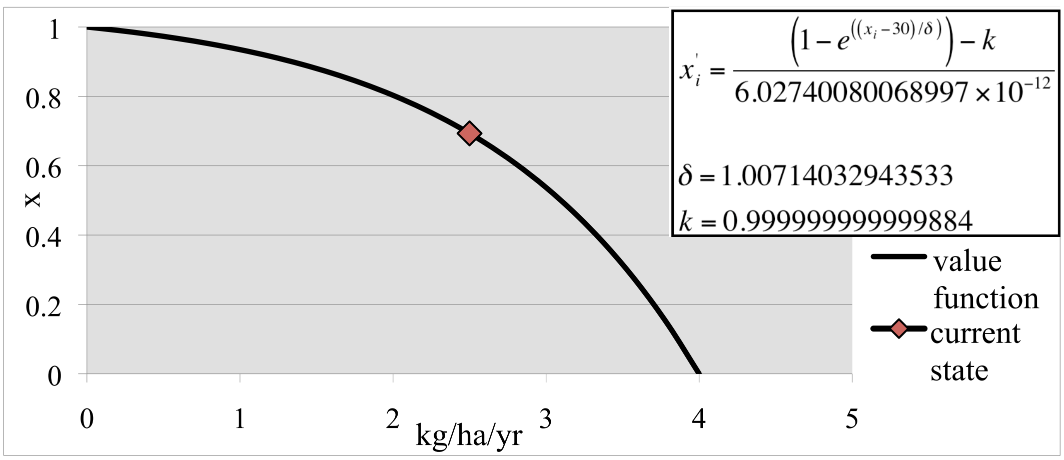

Figure 7. Value function for the second of two indicators for pesticides (annual insecticide use) to sustainability.

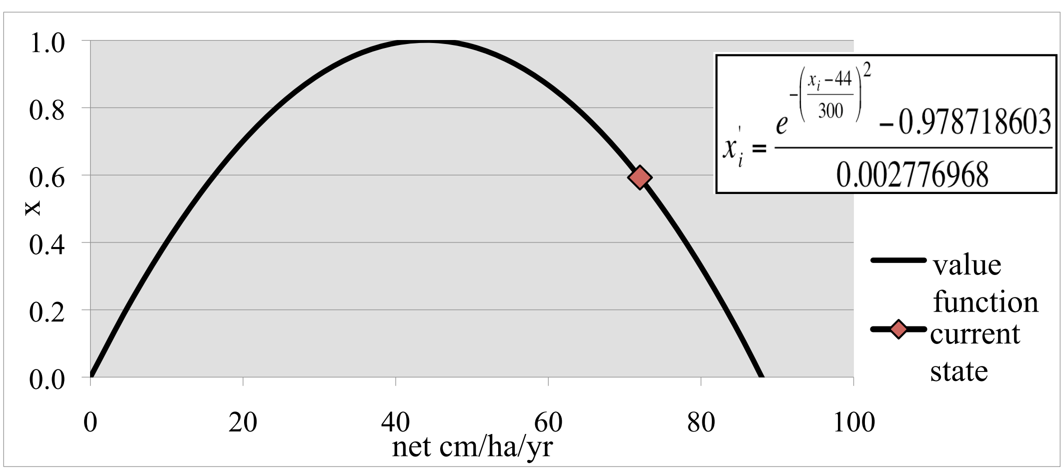

Figure 8. Value function for the indicator for irrigation (annual irrigation water use).

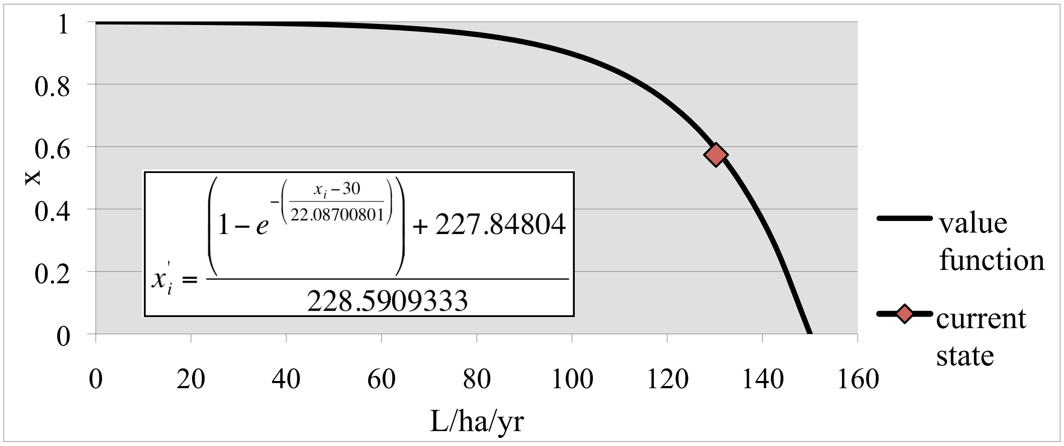

Figure 9. Value function for the indicator for fossil energy (annual diesel consumption).

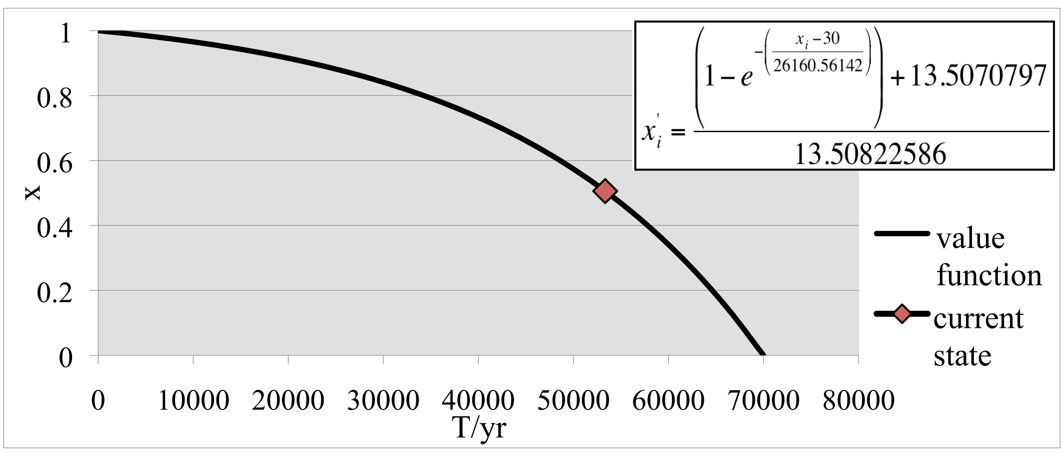

Figure 10. Value function for the indicator for aquatic ecosystem health (tons/year of nitrogen from agricultural sources in coastal waters).

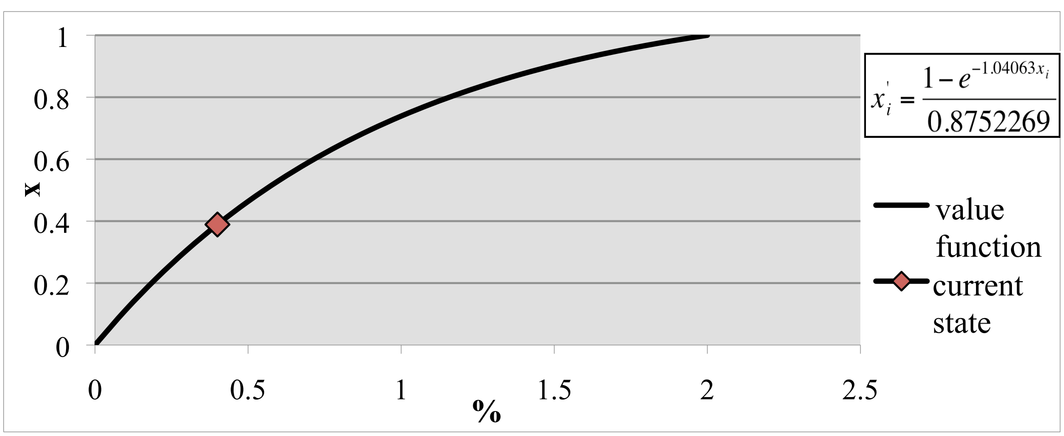

Figure 11. Value function for the indicator for soil quality (% Soil Organic Matter (SOM)).

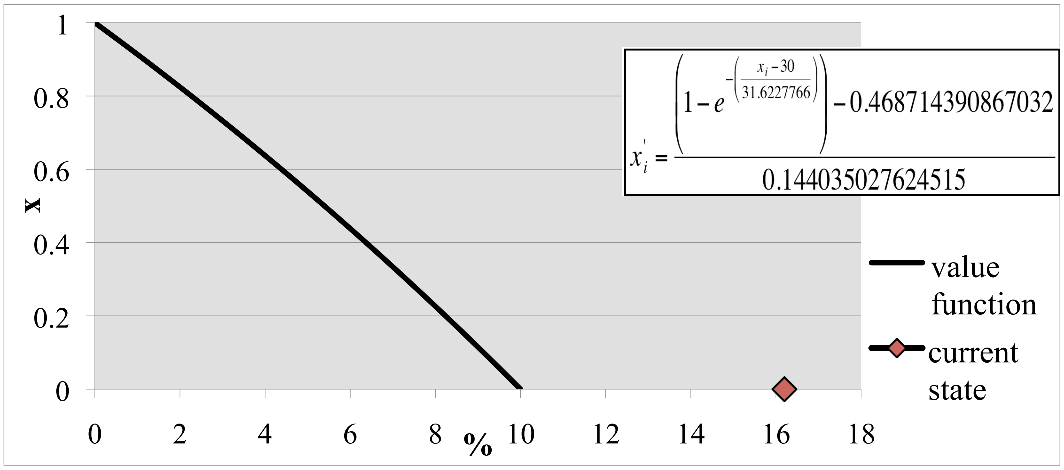

Figure 12. Value function for the indicator for erosion (% land affected by hydraulic erosion).

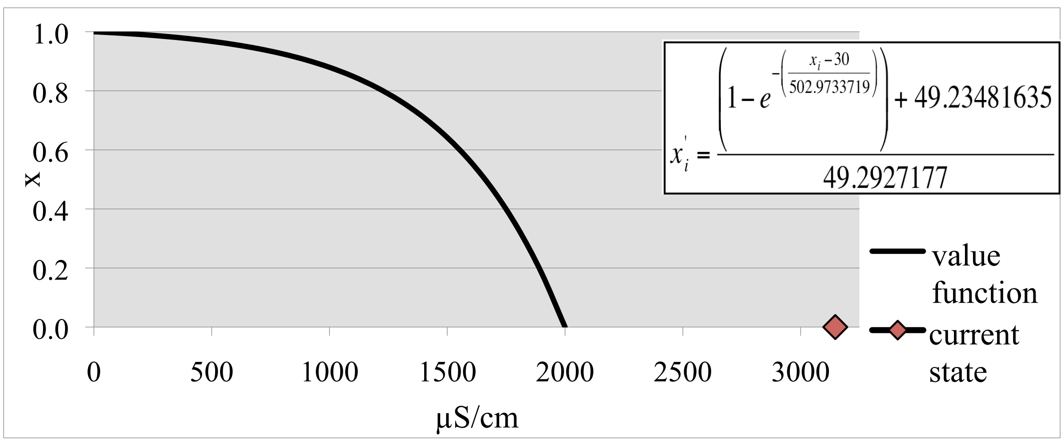

Figure 13. Value function for the indicator for water quality (electrical conductivity of water in field drains).

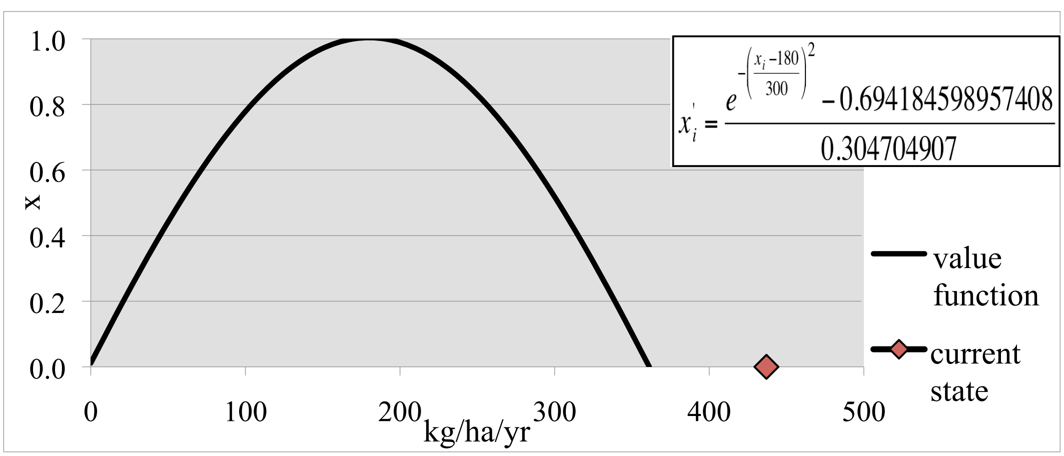

Figure 14. Value function for the indicator for nitrogen fertilizer (annual N fertilizer use).

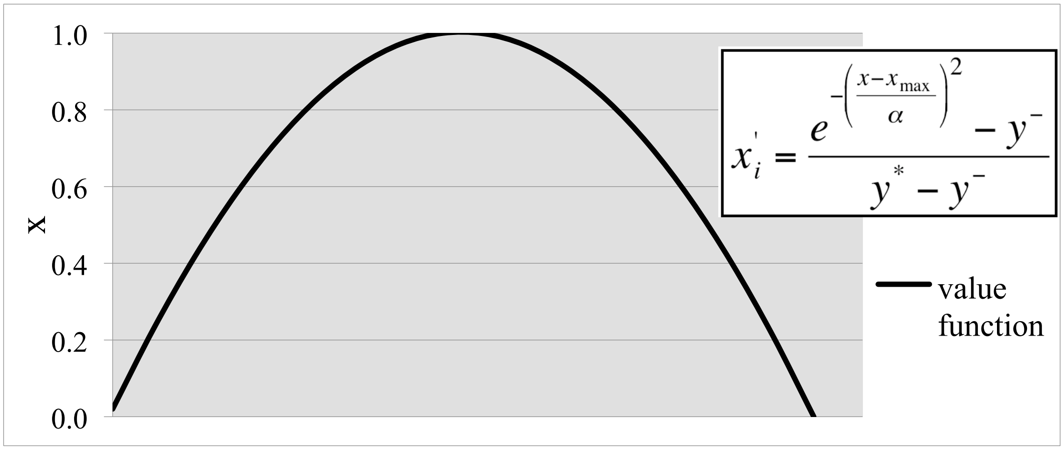

Figure 15. Value function for crop yield.

The fact that fish kills do occur under current conditions indicates that nitrogen levels are, at least at times, too high. However, Sinaloa's fisheries and shrimp farms continue to operate, and the coast is still host to a great deal of biodiversity, which implies that the coastal ecosystem is resilient. Still, ecosystems do not operate in a linear fashion, and a threshold may have already been crossed that could result in a state change at any time.

Soil quality. The indicator for soil quality is percent of soil organic matter (SOM). According to estimates by local experts, the current SOM level in Sinaloa soils is between .01% and .8%. I averaged these values for a result of 0.4% as the current state. These experts suggested that the ideal state of SOM in Sinaloa soils is 2%. The current state of the indicator is far from sustainability. SOM level has a positive relationship to agricultural sustainability because it supports more plant growth with less dependence on external inputs, meaning that as SOM increases, so does sustainability. However, there are diminishing returns in terms of plant growth as higher SOM levels are attained (Lal, 2009). Thus the value function representing SOM shows an increasing convex relationship to sustainability (Figure 11).

Erosion. The indicator for erosion is percent of land impacted by hydraulic erosion in 2002, the most recent data available. I focus on hydraulic erosion because wind erosion affects only 0.5% of land in Sinaloa (SEMARNAT, 2009), meaning it is not a significant concern for the state. A shortcoming of this indicator is that, while it informs to what extent the state is affected by hydraulic erosion, it does not inform how severe the erosion is, or the spatial distribution of eroded land; those data were not available. This indicator thus includes erosion throughout the state, including the mountains, where erosion is likely to be greater than in the flat valleys where maize is produced. Thus, this interpretation of the current state should be taken with a grain of salt. Another difficulty of this indicator is that in the literature, erosion is not generally discussed in terms of surface area affected, making it difficult to establish the value function. The current state of the indicator for erosion is 16.2% of total state land area (SEMARNAT, 2009). The ideal state for this indicator is zero. The current state of the indicator is far from sustainability. While this assessment of the indicator for erosion is not a precise measurement of the current state, stakeholders did confirm that the occurrence of erosion is a concern for the agricultural sector. The ideal state is somewhat unrealistic because erosion is a natural process that occurs regardless of agricultural management. The value function for erosion shows a decreasing linear relationship, in which low erosion is considered to be within a 0.8-1 sustainability range (Figure 12).

Water quality. The indicator for water quality is average electrical conductivity (E.C.) of water in agricultural drainage canals. E.C. informs the degree of impurity of the water (American Water Works Association, 2003). Conductivity measures the ability of a solution to convey an electrical current. In water, electricity is conveyed by dissolved ions, thus, "conductivity increases in direct proportion to dissolved ion concentrations" (Boyd, 2000, p. 14). In other words, pure water has poor conductivity, and high dissolved ion concentration has high conductivity. A shortcoming of this indicator is that, while it tells us there are dissolved substances in the water, it does not inform *what* is in the water. In addition, this indicator suggests that to improve water quality, the electrical conductivity must be reduced. This would require an increase in water use, which would decrease the sustainability of irrigation. Thus, while it does inform on the current state of water quality, reducing this indicator should not be seen as a strategy for increasing sustainability.

The drainage canals are a strategic place to measure conductivity because the water there accumulates agricultural runoff (excess water, fertilizer, pesticides, eroded soil, salts, etc.) that will eventually go downstream to coastal wetlands, lagoons, and may percolate into groundwater aquifers. The current state of the indicator is 3147×10^6 micro-Siemens per centimeter (μS/cm), based on samples taken mid-growing season (February) from field drains in irrigation district 010 near Culiacán, one of the most productive in the state in terms of maize (CONAGUA, 2008b). This data represents samples from throughout the irrigation district; it is not specific to maize fields. I determined the ideal state to be $465x10^6$ μS/cm, based on average conductivity of water in irrigation canals in irrigation district 010 prior to field application ($365x10^6$ μS/cm), plus 100 to account for further evaporation after field application (CONAGUA, 2008a). This ideal state is somewhat high for conductivity; however, higher conductivity is to be expected in semi-arid regions where irrigation water travels long distances in open canals, such as in Sinaloa. Evaporation during this journey leads to more concentrated ions, and thus higher conductivity. The current state of the indicator is far from sustainability. The value function representing electrical conductivity levels shows a decreasing convex relationship to sustainability, because the higher the conductivity, the less pure the water is, suggesting lower quality, and lower sustainability (Figure 13).

Nitrogen fertilizer. The indicator for nitrogen (N) fertilizer is average kilograms of N applied per hectare per season (kg/ha/yr). According to Eakin et al. (2009), 99.5% of respondents said they use N fertilizer. The average application of N fertilizer, or the current state, is 437 kg/ha/yr (Eakin, et al., 2009). Local experts suggested that a sustainable state would be 180 kg/ha/yr, which is sufficient to achieve a good yield. However, yield goals must be realistic and achievable, and it is not likely that N fertilizer application is the factor that prevents growers from achieving their yield goals (Karlen & Sharpley, 1994). The current state of the indicator is far from sustainability. In terms of plant growth, N fertilizer has an increasing convex relationship because it increases yields, but only to a certain point, because plants have a limit to how much N they can absorb (Soule & Piper, 1992). In terms of environmental sustainability, when applied in greater quantities than recommended, N fertilizer is negative because it can lead to leaching and eutrophication of waterways, it can alter the N cycle, it emits the greenhouse gases CO_2 (at the manufacturing point) and N_2O (at the field level and in downstream wetland and aquatic ecosystems), and wastes the energy (natural gas) needed to manufacture the fertilizer. The value function representing average kg/ha/yr of N fertilizer shows a bell-shaped relationship to sustainability, reflecting that N fertilizer increases yields to a point, but has diminishing returns and negative outcomes beyond that point (Figure 14). While beyond the scope of this assessment, it is worth mentioning that because there are diminishing returns to N fertilizer use, applying fertilizer beyond the recommended level also diminishes economic sustainability, because farmers are purchasing more inputs than necessary, thereby reducing their profit margin (Trewavas, 2002).

Crop yield. The variable of yield proved too complex to assess at the regional level, so I did not include it in the assessment. As mentioned in Chapter II, to assess yield only in terms of a single crop is to justify any management practice based on yield gains, reflecting economic investment rather than ecological yield capacity. Agriculture cannot stay on this path and be sustainable. Past a certain threshold, yield gains come at an environmental and economic cost that diminishes systemic sustainability. The value function representing the relationship of yield to sustainability is thus bell shaped, reflecting this tradeoff (Figure 15). However, to assess yield's systemic nature as a proxy for the relationship among environmental resources, socio-economic conditions and productivity (Bindraban, et al., 2000) would be extremely complex at the regional level, and not very informative. In some ways, the aggregate assessment is a holistic interpretation of yield, as yield is an outcome of management practices and ecological conditions. Yield is especially reflected in the indicator for agricultural land use. Still, ecological yield capacity is a field level indicator: the sum of soil quality, water availability and use, farm management, and other field level components that may vary greatly across the region. Rather than assigning a sustainable level for yield, Sinaloa's maize farmers should assess their fields' ecological yield capacity by having the soil tested and adjusting their input use to context-appropriate levels.

Summary. The current state of the indicators for the variables of pest and disease incidence, terrestrial ecosystem, and pesticides (herbicides) are very close to a sustainable state (0.76-1). The current state of the indicators for the variables of agricultural land, pesticides (insecticides), irrigation, fossil energy, and aquatic ecosystem are close to a sustainable state (0.5-0.75). The current state of the indicators for the variables of soil quality, erosion, water quality, and nitrogen fertilizer were found to be far from a sustainable state (0-0.49).

As revealed in the value functions, a slight change in the current state of many of the indicators would change their sustainability status. For example, the current states of the indicators for irrigation and fossil energy are close to a sustainable state, but they rest on a steep decline in their respective value functions. A subtle increase in the current state would push these variables into the far-from-a-sustainable-state range. The indicators for pest incidence, agricultural land, and pesticides likewise sit on steeply declining value functions, such that a slight increase would move them down to the close-to-a-sustainable-state range in the cases pest incidence and herbicides, and far-from-a-sustainable-state range in the cases of agricultural land and insecticides. Likewise, a subtle decrease in irrigation and fossil energy would push these indicators closer to a sustainable state.

Systemic Sustainability

The aggregate system is far from an environmentally sustainable state. Though the variables were assessed individually, the three analyses of the system (system influence, stakeholder weight, and current state analysis) may be considered together for a more complete understanding of the Sinaloa maize system (Figure 16). Comparing the stakeholder weights and current state results, variables that stakeholders weighted low in importance –pest incidence, terrestrial ecosystem, and fossil energy– tend to be closer to a sustainable state, while variables the stakeholders weighted higher in importance –soil quality, irrigation, and nitrogen fertilizer– are far from, or, in the case of irrigation, technically close to a sustainable state but bordering on far from sustainability in their current state.

Comparing system influence and the current state results, the most influential or active variables –agricultural land and pesticides– are close to sustainability. They have the capacity to detract from sustainability, but in their current state they do not do so significantly. The least influential, or passive indicators – aquatic ecosystem and water quality– are close to a sustainable state but bordering on being in the far range, and far from a sustainable state,

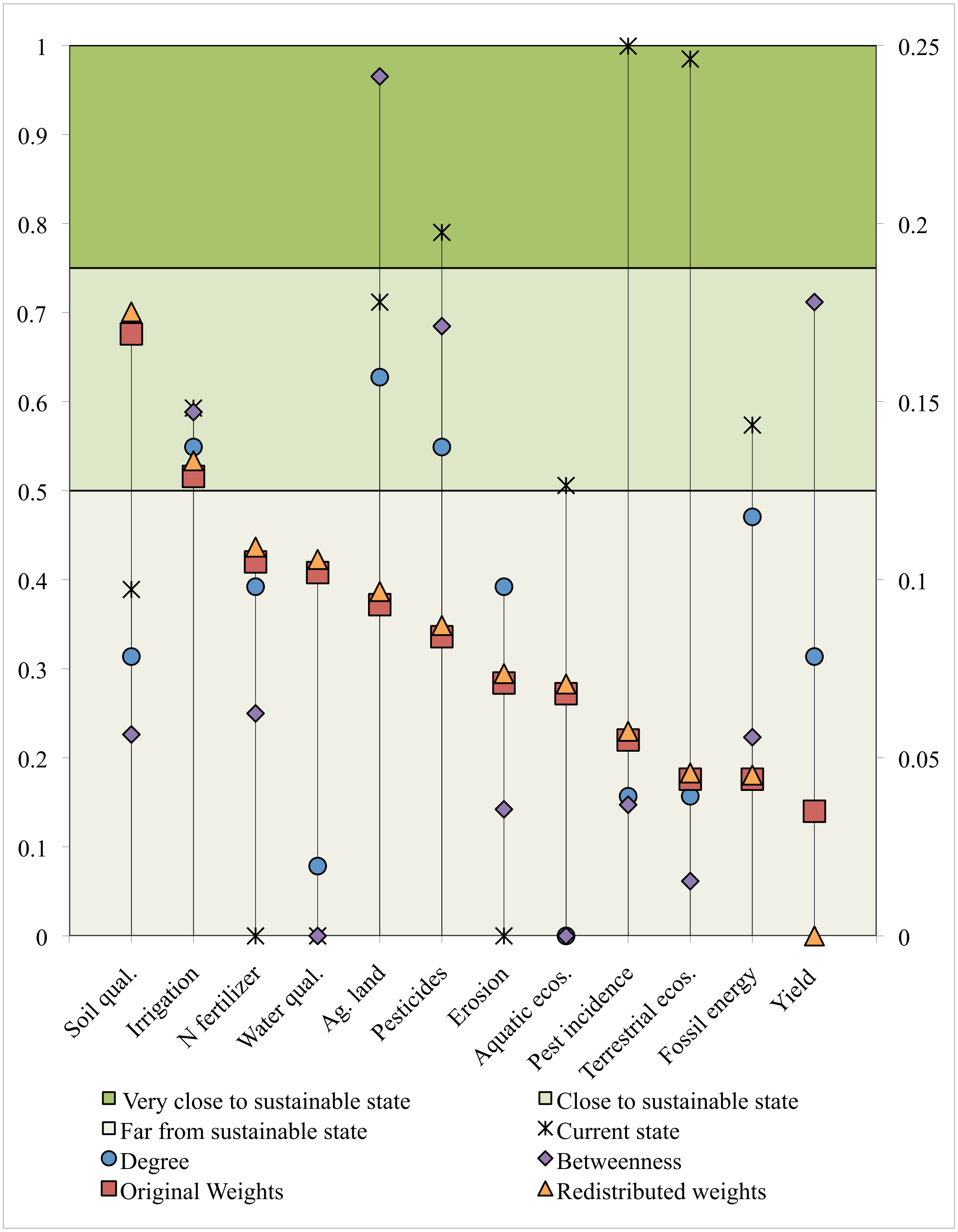

Figure 16. Summary of Results. The current state results are plotted to the primary vertical axis. The original weights, redistributed weights, and influence results (degree and betweenness, normalized between 0 and 1) are plotted to the secondary vertical axis.

respectively. Water quality and aquatic ecosystem are influenced by the moderately influential variables of nitrogen fertilizer and erosion, both of which are far from a sustainable state. Nitrogen fertilizer and erosion are influenced by soil quality (far from a sustainable state) and fossil fuel use (close to a sustainable state), both variables with moderate influence.

There does not appear to be a correlation between the results of the stakeholder weights and system influence. Soil quality, with the highest weight, has average influence. Yield, with the lowest weight, has high influence. The variables with the greatest influence (agricultural land) and least influence (aquatic ecosystem) were both weighted in the midrange.

It is important to relate the results of the systemic assessment to the criteria on which I assessed it: the long-term enhancement of environmental quality and natural resources, and the provisioning of basic human food needs (American Society of Agronomy (ASA), 1989). As revealed by the analysis of the indicator for agricultural land, Sinaloa's maize growers are significantly contributing to the national food supply, thus satisfying the criteria of provisioning basic human food needs. The variables of terrestrial ecosystem, aquatic ecosystem, water quality, irrigation, soil quality, and erosion reflect on the criterion of enhancing environmental quality and natural resources. The results of the assessment of the indicators for these variables reveal that Sinaloa's maize system is not meeting this criterion. Only the indicator for terrestrial ecosystem is very close to a sustainable state, but there is such little information on this indicator that this is not a confident conclusion. The indicators for water quality, soil quality, and erosion are far from a sustainable state. The indicators for irrigation and aquatic ecosystem are close to a sustainable state, but are bordering on far from a sustainable state. Efforts to improve the environmental sustainability of maize production in Sinaloa should focus on meeting the agricultural sustainability criteria of enhancing environmental quality and natural resources.

Intervention points. The most effectual intervention point for improving the environmental sustainability of the Sinaloa maize system is irrigation. Even a subtle decrease in the current state would greatly increase the sustainability of the indicator. For example, decreasing the current state of 72 cm to 65 cm –a change of only 7 cm– would push the indicator into the very-close-to-a-sustainable-state range. The high weight of irrigation means that a change in irrigation has a greater impact on the aggregate sustainability score than variables with lower weights. Because irrigation also has high influence, an improvement in irrigation also means an improvement in the variables that it affects: soil quality, water quality, agricultural land, erosion, aquatic ecosystem, terrestrial ecosystem, and yield. This will further improve the aggregate sustainability. This is especially true of the variables of soil quality and water quality, which both have high weights and are both far from sustainability. In addition, improving soil quality, erosion, water quality, the aquatic ecosystem, and the terrestrial ecosystem would enhance environmental quality and the natural resource base, helping the Sinaloa maize system meet this criterion of agro-environmental sustainability. Even a small change in irrigation could mean a significant change in the sustainability of the system.

Other potent intervention points are soil quality and nitrogen fertilizer. Both variables have a high weight but are far from a sustainable state, thus any improvement would have a significant impact on the aggregate sustainability score. While soil quality itself has average influence, the variables it does influence include agricultural land and yield, both of which are highly influential in the system. Thus, improvements in soil quality would indirectly lead to improvements throughout the system. Like soil quality, the variable of nitrogen fertilizer has average influence in the system. However, the variables it does influence include soil quality and water quality, both of which are far from a sustainable state, have a high weight, and reflect on environmental quality and the natural resource base. By targeting nitrogen fertilizer, three variables with high weights would move toward sustainability, improving the aggregate sustainability score. In addition, targeting nitrogen fertilizer would indirectly help meet the agro-environmental sustainability criteria of the enhancement of environmental quality and the natural resource base. Improvements in soil quality and nitrogen fertilizer would result in direct and indirect improvements in the sustainability of the system.

Barriers to change. Anecdotally, stakeholders identified various barriers to change in the direction of sustainability in Sinaloa. Many mentioned a lack of political will and public policy in support of sustainability for the state. These stakeholders acknowledged that the theme of sustainability has been talked about in Sinaloa for some time, but there has been little to no action as a result. Another barrier that stakeholders frequently mentioned was the ignorance of farmers about the impacts of their management decisions, both on their farm and downstream. This was attributed partially to the independent nature of farmers, but also to the fact that most farmers get their management advice from private agribusiness interests such as seed companies, fertilizer companies, or credit distributers. There has been a fall in public extension support that leaves farmers without anyone to turn to for management advice except fellow farmers and private interests looking to push a product on the farmer. The high rate of land rental among maize farmers was identified as an obstacle as well, as farmers have little incentive to invest in improving the quality of a parcel that they may not be farming next year. Two stakeholders pointed to federal farm subsidies as a barrier because they dilute the cost of production, thus mitigating the disincentive that input costs should be providing to reduce input use. In other words, subsidies encourage input use both directly and indirectly.

Stakeholder Recommended Variables

Of the forty-one responses, fourteen (34%) gave recommendations on additional variables to assess (Appendix E). Five recommendations were related to economic sustainability: efficiency in labor use, input use as related to lowering the cost of production, efficiency in the production chain, financing options, and harvest contracts as potential indicators. Another five recommendations were related to specific management practices associated with sustainable production: conservation tillage, biological pest management, integrated pest management, planting date, and composting green waste. Five recommendations were related to seed genetics: monitoring for contamination from transgenic maize varieties, monitoring for high yielding seed varieties, and germplasm repositories for the preservation of genetic diversity. Another topic that two stakeholders recommended is the presence of local fauna. Four recommendations are related to agrochemical monitoring or contamination. Finally, two recommendations are related to improving public politics and laws related to the environment.

Chapter 5

DISCUSSION AND CONCLUSION

I was able to answer my research questions with a few caveats. My literature review revealed that water, soil, inputs, ecosystem, atmosphere, yields, land, and pests and disease were the most common themes addressed in agro-environmental assessments. I adapted these themes according to their relevance for conventional maize production in Sinaloa as outlined in chapter II, with a focus on the variables of soil quality, erosion, water quality, irrigation, nitrogen fertilizer, pesticides, fossil energy, agricultural land, pests and disease, ecosystems, greenhouse gases, and crop yields. To incorporate stakeholder values into the sustainability assessment, I used MCDA, engaging local stakeholders through interviews and a simple questionnaire. My analysis shows that the current state of maize production in Sinaloa is far from an environmentally sustainable state.

Methods

In my thesis, I applied existing knowledge about agro-environmental sustainability to the new case study of Sinaloa maize production, and assessed the current state according to the values of stakeholders. Compared to other agro-environmental assessments, there are some similarities and some differences. One similarity is the initial approach: Walter and Stützel (2009) also reviewed the literature for indicators and categorized them by theme. The variables I addressed for the case of Sinaloa maize closely align with those in the OECD (1997) framework for environmental assessment of agriculture. Like many of the assessments I reviewed, my assessment is indicator-based.

A difference among my assessment and those I reviewed is the objective. Some assessments seek to compare two or more production systems (e.g. Perales Rivas, et al., 2000; Rasul & Thapa, 2003), others explore sustainability theoretically (e.g. Rigby, et al., 2001), and still others focus on one component of the environmental system (e.g. soil quality, input use; Carter, 2002; Vilas-Ghiso & Liverman, 2007). In contrast, my objective was to apply agro-environmental sustainability principles to an existing management system and establish achievable goals, or ideal points, toward sustainability given the current economic, technological, cultural, and political conditions of the system. In other words, my approach to sustainability assessment is designed to be useful to and applied by stakeholders, or use-inspired. As a result, the sustainable states identified in this assessment are not as rigorous as those assessments looking to establish what type of management is most sustainable, or more closely corresponds to the ideals of sustainable agriculture. As the goals I established are met, however, new goals must be established that will help the system continue on the path toward sustainability.

Another important difference in my assessment is the key function of stakeholder values in the assessment. While some assessments emphasize stakeholder involvement (e.g. Van Cauwenbergh, et al., 2007), the MCDA approach allowed me to account for both the current state of the variables assessed, and their importance to the stakeholders. For example, the low sustainability of soil quality, a variable with average systemic influence, has high weight in the analysis because stakeholders value it most. To demonstrate this point, if the indicator for soil quality, SOM, were to go from the current state of 0.4% to the ideal state of 2%, the aggregate sustainability score would increase from 0.44 to 0.55. If the SOM level were to decrease to 0% (very far from a sustainable state), the aggregate sustainability would decrease to 0.37. The SOM level accounts for 17% of the aggregate sustainability score, which is the weight that stakeholders gave the variable of soil quality. In contrast, the variable with the lowest weight in the assessment, fossil energy (because yield was not assessed), represents only 4.5% of the aggregate sustainability score.

MCDA provides a method for incorporating stakeholder values into the assessment, describing an indicator's relationship to sustainability, and translating the current state into a common scale to facilitate comparison with indicators of various units. However, MCDA does not link the indicators as a system, i.e. show how the system components relate to each other. Network analysis filled this gap. The combination of MCDA and network analysis was thus key for a systemic analysis of maize production in Sinaloa.

Stakeholder Weights

Looking at the results for the weights, the variables that stakeholders weighted high in importance tend to be far from sustainability. This implies that stakeholders have a good understanding of current concerns in the system. Given that the stakeholders weighted yield lowest, it appears the stakeholders are more concerned with Sinaloa's natural resources and their management than maize production. However, the low ranking of aquatic and terrestrial ecosystems, suggests that natural ecosystems are not a priority to stakeholders, either. Nitrogen fertilizer use was weighted third most important, suggesting that stakeholders are concerned about the current level of use, perhaps because of the cost of fertilizer, the dependence on fertilizer for high yields, the associated ecological impacts, or a combination of these factors.

A surprising result given that my analysis focuses on environmental sustainability of agriculture is that all but one group weighted aquatic ecosystems and terrestrial ecosystems quite low in importance; the outlier is the group of researchers, who weighted terrestrial ecosystems fourth in importance. This may mean that the other stakeholder groups see maize and/or agriculture as an integral part of Sinaloa that provides important functions for society and the economy. Perhaps because agricultural production depends on natural resources, these have a higher weight than natural ecosystems. It may also mean that these stakeholders are more focused on active or influential system components rather than the more passive, less influential variables such as terrestrial and aquatic ecosystems. However, it may also mean that stakeholders do not perceive that Sinaloa's natural ecosystems are threatened, whether or not they are.

Systemic Environmental Sustainability

The aggregate system is far from a sustainable state. Yet, the most influential variables are close to a sustainable state, and the least influential variables are far from a sustainable state. There appears to be a mistake: the influence analysis could be incorrect, or the sustainable levels identified for the most influential variables are not rigorous enough. However, the aggregate analysis reflects stakeholder priorities and the distance of the current state from the ideal state. The fact that stakeholders weighted soil quality, nitrogen fertilizer use, and water quality, all of which are far from sustainability, as highly important gives them greater weight in the aggregate system, despite being moderately active or passive in the system. These variables thus weigh down the aggregate sustainability of the system.

An interesting result is that water quality is far from sustainability, while the aquatic ecosystem is close to sustainability. Yet, water quality influences aquatic ecosystems. This suggests that there is something buffering the coast from agricultural runoff. Two local experts believe that Sinaloa's coastal wetlands are absorbing a significant portion of agricultural runoff, preventing it from reaching the coast. Another stakeholder suggested that the vegetative growth in the canal drains is absorbing excess nutrients, acting as a buffer. If this is the case, the tradeoff is that the canals will be less efficient at moving water. The analysis reflects the cascading effects and linkages of farm management practices (or lack of maintenance, as with the canal drains) and how they shape agro-environmental sustainability.

The next question is: what influences farm management? Crop yield was revealed to have high betweenness. Though beyond the scope of this analysis, I believe the importance of yield to the Sinaloa maize system is in the realm of economic sustainability: growers need high yields to stay competitive in the current technological, political, and economic climate. Thus, the pursuit of high yields is motivating the management decisions associated with irrigation, nitrogen fertilizer, agricultural land use, and pesticide use, and indirectly influencing pest incidence, erosion, soil quality, and fossil fuel use. This contrasts with the stakeholder ranking of yield as the least important variable in the system in terms of environmental sustainability.

Intervention Points

I identified reducing irrigation and nitrogen fertilizer, and increasing soil quality as the most effectual intervention points for increasing the sustainability of the Sinaloa maize system. All of these interventions are actionable within the next growing season, but it is important to consider how realistic these suggestions are, and identify what the potential strategies for intervention may be, who the relevant actors are, the barriers to change, and the incentives for change. The key actors are growers and public (CONAGUA) and private water institutions (irrigation districts, irrigation modules). To reduce irrigation use without impacting yield, growers should plan their irrigation events according to optimal water absorption times for their crop. The most critical stages for irrigating maize are during the flowering and silking periods (Ojeda-Bustamante, et al., 2006). Reducing irrigation use could be achieved within the next growing season, though it may take a few growing seasons for growers to work out their new irrigation regimen. Reducing irrigation is a feasible intervention, however, change is not likely to occur unless the government begins to regulate water use. Farmers have little reason to reduce their water use because the cost of water is low, and their use is not regulated. Irrigation modules currently do not measure the actual volume of water that is applied to a field; the irrigation operators estimate the proper amount. Thus, lack of measurement and regulation are the primary barriers to reducing irrigation. Measuring water use and charging for use by volume would encourage growers to reduce water consumption, as well as aid the fair distribution of water allocations. The incentives for growers to reduce irrigation are increased efficiency and the possibility of using the water saved during the winter-maize season to plant a crop during the spring-summer season. A spring-summer crop could increase farm revenue and has the added benefit of protecting the soil against erosion. Planting a legume crop would improve soil nitrogen, which would reduce dependence on nitrogen fertilizer, lowering production costs.

The key actors for increasing soil quality are maize growers. The strategies for implementing this intervention involve changes in farm management, such as adopting reduced tillage or no-tillage regimens, working with composts, and/or rotating crops. Growers could adopt these management changes within the next growing season; however, at least a few years must pass before growers will experience the benefits of their efforts to increase soil quality. Though increasing soil quality is a feasible intervention, the time lag may be a barrier to change. Another potential barrier is that growers may resist adopting management changes, especially those practices that may be cost-prohibitive (e.g. the renting or purchase of specialized machinery). The fact that much of the maize area planted is rented (de Ita Rubio, 2003) is a disincentive for this intervention, as increasing soil quality requires capital investment, and growers do not have a long term commitment to their rented parcels. The potential lack of cooperation from neighboring ranchers is another potential obstacle. An agronomist explained that part of the challenge of adopting no-till in Sinaloa is that neighboring cattle sometimes roam into fallow maize fields, which may compact the soil, necessitating tillage. Overcoming this challenge will involve better communication among neighbors and potentially fence installation. However, maize growers facing this challenge could also adopt a form of reduced tillage that increases soil quality but still loosens the soil, such as chisel plowing, or rotating crops. Given that the stakeholders weighted soil quality as the most important variable to environmental sustainability, it appears they understand that there are incentives for improving soil quality. These include healthier crops and less dependence on external fertilizers, which may decrease the cost of production.

The key actors for reducing nitrogen fertilizer are maize growers. To reduce nitrogen use without reducing yield or profits, growers should plan their fertilizer applications according to the optimal nutrient absorption times of their crop. Maize generally has low nutrient uptake at the beginning of the season, high uptake during plant growth, and low uptake as the crop matures (Millar, et al., 2010). Other potential strategies for reducing nitrogen fertilizer use include improving soil quality and irrigation management, and rotating maize with a leguminous crop (Díaz Valdés, 2006; Pretty, 2008). Reducing nitrogen fertilizer use could be achieved within the next growing season, though it may take a few growing seasons for growers to work out their new fertilizer regimen. This is a feasible and realistic intervention, the benefits of which would be experienced immediately. The primary incentives for reducing nitrogen use are lowering the cost of production, and reducing the downstream environmental impacts associated with over-fertilization (e.g. eutrophication of water bodies). The barriers to reducing nitrogen fertilizer use include the habits and traditions of growers, who may resist management changes. Part of this barrier is the common practice of calculating nitrogen use on the basis of desired yield. In other words, growers may be loosing profits trying to achieve a high yield rather than basing their fertilizer use on the best economic return for investment ("maximum return to nitrogen"), part of which is having a realistic expectation for the ecological yield capacity of their fields (Millar, et al., 2010). Growers will need to measure their success not by yield (tons/hectare), but by the best economic returns for production costs. Strategies such as improving soil quality and irrigation and incorporating crop rotations will also require changes in farm management, which may be cost-prohibitive. However, as mentioned above, these changes would have multiple benefits for growers and sustainability.

Agricultural land is another possible intervention point, however, it is potentially problematic. The variable of agricultural land is a reflection of the scale of agricultural management decisions and production. It is so influential because it directly impacts the variables of soil quality, irrigation, nitrogen fertilizer, pesticides, erosion, pest incidence, terrestrial ecosystem, and fossil energy. Any changes in agricultural land would change all these variables. One way to increase sustainability by intervening through agricultural land is reducing the current state of the indicator for this variable: area planted in maize. One way to reduce the maize area in Sinaloa is to rotate the maize crop with a different crop for the winter season. This would reduce the maize monoculture, which would be good for sustainability. However, it would also result in management changes on that land. The new crop that replaces maize will have its own management requirements, including irrigation, pesticide, and fertilizer applications, which may or may not be more environmentally damaging than maize. In other words, an intervention to increase the sustainability of the indicator for agricultural land (reducing maize area planted) could have the appearance of improving sustainability because it reduced the maize monoculture, when in actuality it may result in greater environmental damage than if the land had continued to be planted in maize. Another potential intervention related to agricultural land would be to fallow land planted in maize. This would also reduce the maize monoculture, however, if no cover crop is planted, it may expose the land to erosion, reducing soil quality, and overall sustainability. Thus, interventions in agricultural land must be carefully planned, and take input use, erosion, and potential downstream impacts into account.

If done well, an intervention in agricultural land could potentially have a dramatic positive impact on environmental sustainability in Sinaloa. However, this is not a realistic expectation. Maize is among the most profitable crops for Sinaloan growers, which is why so many plant it. Part of the reason that it is profitable is government support, which institutionalizes maize production. Agriculture is a major economic activity in the state, and fallowing land is not a financial option for many farmers. Thus, it is unlikely that land will be taken out of agricultural production or maize production.

Stakeholder Recommendations

While the stakeholders' recommendations for additional variables to assess provided insight into their priorities and concerns, I did not assess the variables they recommended for various reasons. Those related to economic, political, and legal concerns were beyond the scope of agro-environmental sustainability. The recommendations related to specific management practices (conservation tillage, biological pest management, etc.) suggest that some stakeholders are aware of alternative management options and consider them viable in Sinaloa. I did not assess these management practices because the positive outcomes associated with them, such as reduced pesticide use, reduced fossil energy use, and increased soil quality, were already captured in the assessment. In addition, there is no existing data on how many growers have adopted these practices. Similarly, agrochemical contamination was captured in the variables of water quality, aquatic ecosystem, pesticide use, and fertilizer use. The recommendation to assess local fauna is highly related to agro-environmental sustainability, and would have been an informative variable to include in this assessment; however, assessing it would require a very specialized local knowledge that was not achievable in the time frame of the study.

The recommendations related to seed genetics represent diverse concerns. Transgenic contamination could impact production capacity, but I believe the concern of the stakeholders is marketability, as some consumers have shown an aversion to transgenic foods (Clay, 2004; Lehrmann, 1999). The concern of high yielding seed varieties is related to yield and production. In contrast, the concern over genetic diversity is related to breeding options for the future, as well as biodiversity preservation.

Though highly relevant to my study, I did not to assess seed genetics because there are no sustainability metrics or standards for this variable. First, the concern of food production is captured in the variables of yield and agricultural land use. The concern over agricultural biodiversity is very important in the alternative agriculture discourse in terms of preserving landraces, promoting soil health, providing wildlife habitat, and as a means of pest control (McNeely & Scherr, 2003; Pretty, 1995), but this is not an appropriate metric for Sinaloa at this point in time because its mode of production is mechanized monoculture: the sole goal is food production, not biodiversity. My analysis shows that maize monoculture is not yet a problem in Sinaloa in terms of pests and disease, but it is a potential concern for the future. According to Eakin et al. (2009), 72% of respondents plant one of three seed varieties: Pioneer 30P49, Bisonte, and Cebu. Under the current mode of production, increasing agricultural biodiversity would mean planting different commercial varieties, or devoting land currently in maize to another crop. Using a greater variety of commercial maize seeds would not meet the agricultural biodiversity goals of alternative agriculture. I addressed converting land currently in maize to another crop in the variable of agricultural land. In a mechanized monoculture system, growers could increase biodiversity in the ecological sense by planting hedgerows, or leaving corridors of native vegetation. However, there is no data on how many growers do this in Sinaloa. Some stakeholders expressed concern over the impacts of transgenic contamination. Concerns over potential risks of transgenic crops are frequently cited in the sustainable agriculture discourse (e.g. Garcia & Altieri, 2005; Pretty, 2001), but there is, as of now, little evidence that it diminishes sustainability beyond negative perceptions (Lehrmann, 1999), making it difficult to assess.

Caveats and Lessons Learned

There are a few weaknesses of the study that could be improved upon. In general, the study could be improved by sampling a larger number of stakeholders, especially more maize growers. The accuracy of the study could be improved by collecting primary data (data observed or collected directly by me, the researcher) at the desired scale. However, this would have been very costly. I relied on secondary data (data collected by others) and/or expert opinion for current state levels for ten of the thirteen indicators. The values for the indicators of soil quality, irrigation, and fossil energy are estimations from local experts or agencies, so they may not be very precise. These are weaknesses in that I cannot attest to the accuracy of this data, and it was not always the most informative for my objectives. For example, a better indicator of water quality would be the average nitrogen level in irrigation drains. Average rate of erosion (T/ha/year) would have been a far more informative indicator for erosion than percent of the state surface area affected by erosion. Changes in fauna populations would have been more indicative of the sustainability of the current state of terrestrial ecosystem than percent of the state's surface area devoted to crop production. While the indicator for aquatic ecosystem – annual tons of nitrogen from agricultural sources deposited in coastal waters – is informative, it is difficult to interpret without data on aquatic life, such as fish kills, rate of reproduction, or other indicators of the well-being of sea life. My use of secondary data is a strength, however, in that half of the data I used for the current state of indicators is collected and made available by government agencies (CONAGUA, FIRA, SAGARPA, SEMARNAT, and SIAP), which means that future data will likely be available and collected using the same methods at the same scale, thus facilitating follow up studies at no additional cost to these agencies or researchers.

The sustainable states of indicators for management variables (e.g. irrigation, nitrogen fertilizer) were selected to be attainable, with the assumption that as those goals are approached and attained, new sustainability goals will be established. While this approach to the ideal state is flexible, the assumption that new goals will be established is a weakness because it depends on follow-up assessments. These assessments must adapt to the new conditions of the system by assessing relevant agro-environmental variables. They must also capture changing stakeholder values by redistributing the questionnaire on which the MCDA weight analysis is based. This approach to ideal states also lacks a vision of where the system could or should be in terms of sustainability. This could be addressed, using the same approach to ideal states, by doing visioning exercises with stakeholders about what kind of agricultural system and environment they would like to see in Sinaloa into the future.

Another weakness was a mistranslation in the questionnaire. For the variable of terrestrial ecosystems, thinking of the importance of native vegetation as wildlife habitat, I translated the variable of terrestrial ecosystems as "presence of native vegetation" (*presencia de vegetación nativa* instead of *ecosistemas terrestres*). As evidenced by their comments (Appendix E), some stakeholders interpreted presence of native vegetation as weeds, which, as my analysis attests, is not a major problem in Sinaloa. Thus, the weight of terrestrial ecosystems may not reflect how all stakeholders actually value terrestrial ecosystems. I translated aquatic ecosystem as "condition of natural water sources" (*condición de fuentes de agua natural*), which some stakeholders interpreted as irrigation source. I assessed this variable in terms of contamination with interest in the protection of the coastal biological community. Irrigation use was weighted high in importance, so this misunderstanding may skew the weight for aquatic ecosystems up. To address these variables, the questionnaire would have to be re-administered with more explicit, clear translations.

I was not able to ascertain the importance of the ecosystems that agriculture has displaced to ecosystem function and ecosystem services in Sinaloa: primarily thorn forest and the floodplain riparian forests of Sinaloa's major rivers. Shreve (1937) describes the vegetation profile of the flood plains and the thorn forest, pointing out the latter as one of the most important of the region, with evidence of relations among thorn forest species and Sonoran desert species. Schmidt Jr. (1976) informs that thorn forest represents 75% of the state's natural vegetative pattern. After irrigation infrastructure was constructed in the 1940s, however, large portions of these ecosystems were rapidly replaced with agriculture. Deforestation of thorn forest has slowed since the 1970s, but thorn forest is one of the least protected ecosystems in Mexico (Vega Aviña, 2003).

While it does not currently seem to be a concern, thorn forest may prove to be an important part of Sinaloa's environment functioning. For example, the prairies of the American Midwest were not thought to be valuable and were destroyed on a tremendous scale; some estimate that as much as 99.9% of these prairies have been altered by human activities, including agriculture. Today that attitude has changed as prairie grasses are now known to play an essential role in maintaining soil structure, preventing erosion, and absorbing atmospheric carbon (Sampson & Knopf, 1994). Studies of Sinaloa's lowland ecosystems are needed to understand the ecosystem functions they provide, and how to sustainably manage them.

As a few stakeholders aptly pointed out in their questionnaire comments, I did not address fauna, part of the variable of ecosystems. Concerns associated with wildlife in Sinaloa include hunting, habitat fragmentation, and habitat loss (Martínez López, 2003). Though not an issue for maize production, another important concern with economic implications is pollination. While I could not verify this claim, two stakeholders said that to pollinate crops, growers now must rent bees, bats, and beetles, but that ten to fifteen years ago they did not need to.

As mentioned, assessing fauna-related variables would require a specialized local knowledge that was not attainable in the time frame of the study; however, including fauna in the assessment would have undoubtedly strengthened the analysis.

My analysis does not cover the positive activities that are helping mitigate environmental impacts and improving sustainability in Sinaloa. These include agricultural solid waste collection, crop diversification efforts, reforestation efforts, and heritage seed conservation programs. The improper disposal of empty agrochemical containers was a considerable problem in Sinaloa. Now, the *Campo Limpio* (Clean Countryside) program promotes the proper cleaning of these containers and collects them for recycling and disposal (Campo Limpio, 2007; Cruz, et al., 2006). According to stakeholders, the program has been successful in Sinaloa. The state government and SAGARPA are both actively promoting diversification out of white maize (Gobierno del Estado de Sinaloa, 2010; López, 2010). This will help reduce the overproduction of white maize, however, diversification is largely toward yellow maize, which will not reduce the maize monoculture. Two stakeholders described farmer-sponsored reforestation efforts in the mountains to help protect the watershed that supplies irrigation water. According to these stakeholders, the species being planted are primarily of economic interest (redwood, cedar) rather than species that reflect the vegetative distribution of the region, however, the effort is a step in the right direction. The *Comisión Nacional de Áreas Naturales Protegidas* (CONANP, National Commission for Protected Natural Areas) has a program for conserving *criollo* (heritage) maize varieties (CONANP, 2010). The program is active in Sinaloa, promoting agro-biodiversity and genetic conservation.

An obvious weakness is that my assessment is limited to one year, one crop, and one realm of sustainability (environment). I did not assess a historical time series of data, which would have given a better sense of management practices, climate factors, crop losses, and resource availability; however, historical data was not available for many indicators. A temporal perspective would have also shed light on the relative sustainability of maize compared to the crops it replaced. According to a few interviewees, maize is less environmentally harmful than the cotton, soy, and wheat that was cultivated before the expansion of maize because those crops required more pesticides, however, they acknowledged that maize cultivation uses more nitrogen fertilizer. Maize requires less water than cotton, but more water than the individual crops of soy and wheat. However, planting a single crop of maize per year requires less water than an annual crop rotation of soy and wheat.

In terms of crop, I assessed only maize. Given the time frame of this project, maize is a logical focus for an environmental sustainability assessment because it represents so much of the agricultural landscape and has become increasingly important for social and economic sustainability. As I began this research, I anticipated that maize would be the most environmentally impactful of Sinaloa's crops. However, my interviews suggested otherwise. According to local experts, vegetable production in Sinaloa consumes high volumes of fertilizer, and significantly more total pesticides than maize, despite representing a much smaller portion of agricultural land. Wright (2005) called attention to this issue in the 1980s, before commercial maize production took off in Sinaloa. Today, vegetables are increasingly grown in greenhouses, which are energy and material intensive. The agroplastics used for vegetable production in Sinaloa are often burned in open fires rather than recycled, adding another layer of concern for environmental sustainability (Cruz, et al., 2006). In addition, many vegetables are water-intensive, and may also contribute to pressure on water stores. To truly understand agro-environmental sustainability in Sinaloa, other crops, especially vegetable crops, need to be assessed and incorporated into the system analysis as well.

While I used a systems approach to agro-environmental sustainability, the assessment is not truly systemic because of my focus on the environmental realm of agricultural sustainability, excluding the other two pillars of sustainability: society and economy. For example, many pesticides are known to cause cancer in humans (Alavanja, et al., 2004). However, because I did not assess the social component of sustainability, I did not account for this in my assessment of the sustainability of pesticide use, or the aggregate Sinaloa maize system. Social and economic issues cannot be separated from environmental issues. Thus, social and economic issues came up in interviews and the literature. Though I did not assess them and was unable to verify the claims of interviewees, I elaborate on economic and social sustainability in the following two sections.

Economic Sustainability

Agriculture is an important part of the Sinaloa economy, representing 14.9% of state GDP (Gobierno del Estado de Sinaloa, 2009a). Maize alone represents 39% of the total value of crop production in the state (Gobierno del Estado de Sinaloa, 2010). However, there are some concerns for the economic sustainability of maize production in Sinaloa. For example, it is unclear whether the income from commercial maize is sufficient for growers to survive on. Profitability is a concern for social sustainability as well, because it impacts employment, working conditions, and workers' wages. An analysis by FIRA (2006) suggests that to break even, Sinaloa growers must obtain a yield of 9.37 T/ha (the average yield is 10.65 t/ha (SAGARPA, 2010)). One interviewee said that a grower needs to plant at least ten ha to make a living, but that living off of an agricultural income is increasingly difficult as consumerism has increased in Mexico in recent decades, and that many Sinaloan growers depend on additional sources of income. Praise for Sinaloa's high yields came up frequently in interviews, however some stakeholders mentioned that growers are over-applying nitrogen fertilizers and over-irrigating in pursuit of these yields, reducing their profits and environmental sustainability, rather than adjusting their expectations to the limits of their land and resources. When asked about the profitability of maize, and why growers are producing more white maize than the market demands, interviewees frequently responded that there are no other economically viable options for Sinaloa growers right now. 75% of Sinaloa growers surveyed said they switched into maize because it was the most profitable or attractive crop

(Eakin, et al., 2009). However, overproduction may be depressing prices and reducing profitability. If this is the case, as growers adopt new technology to stay competitive, they must continually increase production to keep up with their costs. As other growers adopt the new technology, the competitive edge of the technology is lost, overall production increases, and prices fall. This phenomenon is known as the agricultural treadmill (Cochrane, 1959; Levins & Cochrane, 1996; see Eakin, et. al., submitted).

A significant portion of total maize farm earnings in Sinaloa –nearly 30 percent– are from government subsidies (FIRA, 2006). Federal support for Sinaloa maize comes in many forms. The government pays a premium on the price of white maize that other kinds of maize, such as yellow maize, do not receive. Other supports include PROCAMPO (direct payments based on acreage in nine basic grain crops, including maize), fuel supports, and price supports such as *Compras Anticipadas* (Futures Markets), *Cobertura de Precios* (Price Coverage), and *Ingreso Objetivo* (Target Income) programs, among others. Various stakeholders emphasized the importance of the Compras Anticipadas program for Sinaloa maize because Sinaloa is far from the centers of maize consumption (in the center and south of the country). Sinaloa growers thus depend on the government to find contract buyers for their maize, ensure the contract, and to subsidize the cost of transit. In 2008 the program capped support for white maize at 3.85 million tons, leaving over one million tons of Sinaloa maize without commercialization coverage (Juarez, Kuss, & Ford, 2009). Even with this cap, Sinaloa was the primary recipient of commercialization supports for maize (Appendini, 2010b; Scott, 2010). Various interviewees said that commercialization is a big problem because the cost of commercialization is reducing profit margins for maize growers. Some argued that the government should cover commercialization for all of Sinaloa's production, even though Sinaloa was producing more white maize than is demanded for human consumption, and the surplus 1.3 million tons is used as yellow maize for industrial use or as livestock feed. In 2010, the government expanded commercialization support in Sinaloa to 4.8 million tons of white maize (Gobierno del Estado de Sinaloa, 2010). Sinaloa's dependence on government support calls into question the free market ideals of the neoliberal reforms that initially incentivized Sinaloa growers to plant maize, and raises concerns of path dependency (Eakin, et al., submitted). While Sinaloa maize contributes to the national food supply, the question remains whether the government should be subsidizing commercial production while reducing supports for subsistence and smaller-scale production that contributes to local food security in other parts of Mexico (Appendini, 2009; de Janvry, Sadoulet, & Gordillo de Anda, 1995; Scott, 2010).

An indirect subsidy that Sinaloa's growers benefit from is the government funded maintenance of irrigation infrastructure. There are 11 river dams, 9,032 kilometers of canals, and 8,653 kilometers of drains throughout the state (Gobierno del Estado de Sinaloa, 2009a). The cost of irrigation water for growers is low, but maintaining this infrastructure is very costly; one stakeholder estimated that the cost of maintenance is around 300 million U.S.D. a year, an expense that is being absorbed by taxpayers. This high cost of irrigation calls into question what services or projects could be funded that would benefit a greater number of Sinaloans. It could also be argued, however, that this subsidy benefits not only Sinaloan farmers, but consumers of Sinaloa's produce as well.

Another issue of concern is credit access. Credit opportunities for small-scale grain farmers have decreased since the 1990s (de Janvry, et al., 1995; Eakin, 2006), reducing participation in agriculture as smaller scale producers cannot keep up with the technological innovations of the sector, and therefore can no longer compete commercially. This may have contributed to the widespread phenomenon of *rentismo*, or land renting in Sinaloa. This is a form of land concentration (concentration of land-holdings by fewer and fewer actors). It is estimated that over half the agricultural land area in the winter season (dominated by maize) is rented, primarily from smallholders and ejidatarios (de Ita Rubio, 2003).

Land rental represents a major portion of production costs. The estimated average rate for land rental is 8,000 Mexican pesos, or roughly $680 USD per hectare (Centro de Estadística Agropecuaria: Secretaría de Agricultura Ganadería y Desarrollo Rural, 2009), which represents about 27% of the total cost of production (Eakin, et al., submitted). It is estimated that purchased inputs represent about 39% of the total cost of production; labor is 14%; insurance is 10%; and land preparation is 10% (Eakin, et al., submitted). Land rental and purchased inputs (about 66% of total production costs), then, are a serious constraint on profitability. While one stakeholder was concerned about farmer debt, bank representatives explained that their farmer clients rarely default. However, banks appear to be working mainly with larger producers that are deemed more commercially viable, while smaller producers obtain financial support from input suppliers, intermediaries, and other less regulated credit sources (Eakin, et al., submitted), complicating their viability in the commercial sector.

Looking at the larger economy, maize production has the potential to impact other economic sectors. Maize production, and agricultural production in general, have the potential to negatively impact other economic sectors through environmental degradation, such as the fishing industry and growing tourism industry. This reinforces the importance of agro-environmental sustainability.

Considering economic potential in Sinaloa, some stakeholders emphasized the need for the state to develop a food processing industry or ethanol industry that would help absorb Sinaloa's maize surplus. Other stakeholders expressed concern that Sinaloa's agricultural sector is dependent on agricultural inputs (machinery, seeds, nutrients) from international sources, expressing interest in the development of these industries within Mexico. Local scholars are exploring these possibilities and concerns (Aguilar Soto, 2007; Aguilar Soto & Gaxiola Carrasco, 2009).

Social Sustainability

There are many aspects of social sustainability related to maize production in Sinaloa, including national food supply, the aging farmer population, land renting, farm worker wages and working conditions, and agrochemical related health problems, among others. Sinaloa's white maize production plays a major role in satisfying Mexico's food needs, producing 26% of Mexico's total white maize production, approximately 70% of which is used for human consumption (Gobierno del Estado de Sinaloa, 2010). White maize is a culturally appropriate crop for satisfying food demand and maintaining food sovereignty. In Mexico, white maize is preferred over yellow maize for human consumption for its texture and high flour content (Appendini, 2010a; Fitting, 2006). However, the major centers of maize consumption in Mexico are the center and south – not the north, where Sinaloa is located. Thus, Sinaloa's maize must be shipped around the country to reach consumers. As mentioned, high production in Sinaloa may be leading to a decrease in local production in the center and south of Mexico, reducing food security in those regions. Sinaloa also represents a geographic concentration of production that is vulnerable to market, climate, and environmental shocks. For example, the major frost event of February 2011 devastated the maize crop, leaving the country in need of about 3 million tons of white maize (Enciso, 2011; Valdez Cárdenas, 2011). This event raises concerns about Mexico's lack of emergency food stores, and calls into question whether Mexico should rely so much on one region for such a significant portion of its food supply. It is yet to be seen how Sinaloa will recover from the event economically and socially.

A concern for social sustainability in maize production is the future of farming as the farmer population ages and approaches retirement. According to interviewees, the youth have expressed little interest in farming. Related to the concern of aging farmers and with implications for environmental, economic, and social sustainability, is the phenomenon of *rentismo*, or land rental in the maize sector (see section "Economic Sustainability," above). As farmers leave the sector because they are aging or because they cannot compete in the commercial sector, many rent their land to other growers. It is unclear what those who rent out their land do, if anything, to supplement their income, raising concerns about poverty, emigration, and illegal activity. Land rental is a concern for environmental sustainability because growers who rent have less incentive to care for the land (e.g. soil quality) and surrounding natural resources (e.g. water quality, terrestrial and aquatic ecosystems).

Working conditions and farm wages are important social justice issues for agricultural sustainability. Wright (2005) documented agrochemical use in Sinaloa vegetable production in the 1980s, reporting deliberate over-application of pesticides, preventative application (which goes against best management practices), frequent contamination of canals and drinking water supplies, lack of protective clothing for workers, and worker illness and death from pesticide exposure. Sinaloa maize uses far fewer pesticides than vegetables, and requires far less labor, however, this does not mean that labor justice issues are not a concern in maize production.

Agrochemical exposure has been implicated in human health risks, some of which have been falsified, and others verified. For example, nitrate (NO_3^-) has been associated with potable water contamination. Conditions thought to be caused by or related to NO_3^- include blue baby syndrome, stomach cancer, and increased risk of heart attack. Research has largely disproven these claims. It is now thought that NO_3^- is an essential part of the human diet (Hatch, Goulding, & Murphy, 2002). Exposure to pesticides, on the other hand, can lead to serious human health problems, especially cancer and neurological disorders (Alavanja, et al., 2004). Agricultural workers and residents of rural towns that draw groundwater for human consumption may be especially susceptible to these health risks.

In terms of governance and government regulation, legislation exists that legally protects the environment at both the federal and state levels. At the federal level for example, Article 27 of the Constitution calls for the protection of natural resources, and Article 73 establishes basic protections for the environment. At the state level, environmental law focuses on preventing and controlling contamination of air and water, solid waste, and dangerous activities. One important law is *La Ley del Equilibrio Ecológico y la Protección al Ambiente del Estado de Sinaloa* (LEEPAES; Law of Ecological Equilibrium and Environmental Protection in the State of Sinaloa), passed in 1991. While these legal protections for the environment exist, addressing environmental problems has not been a priority for the state government (Karam Quiñones, 2003).

Sinaloa Maize in Perspective

There has been little research on the environmental impacts of agriculture in Sinaloa, making it difficult to specify environmental outcomes of maize production and agriculture's impacts on natural processes. In light of the current lack of information, to gain a better sense of the potential impacts of maize production in Sinaloa, it is useful to consider another case: the United States, with a focus on the state of Nebraska, the third most important maize-producing state in the U.S. in terms of production and area planted (National Corn Growers Association (NCGA), 2010). Nebraska is an apt comparison with Sinaloa because both states grow maize under irrigation, and they have similar yields. Nebraska, however, produces maize on a much larger scale than Sinaloa (Table 8). Nebraska also has a much longer history of commercial maize production, dating to the 1850s (Olson & Naugle, 1997), though irrigated production didn't expand until the 1930s (Hickey, 1992). This long legacy may shed light on the potential outcomes of long-term maize production and maize expansion in Sinaloa.

Maize production in the U.S. is known to have persistent pest problems, requiring elevated pesticide use over time. Erosion in U.S. maize production is estimated to be about 8.6 metric T/ha/yr (Clay, 2004). In terms of management, Sinaloa growers use more nitrogen, insecticides, and irrigation water, but less phosphorus and fewer herbicides than U.S. growers. Sinaloa has a slightly higher average yield (Table 8). Data on the actual rate of erosion in Sinaloa could not be found.

Table 8

Comparison of Sinaloa and Nebraska/U.S. maize production and management

	Sinaloa	Nebraska/U.S.	Difference
Area planted in maize (ha)	559,722[a]	3,716,512[f]	- 85%
Average yield (t/ha)	10.65[b]	10.36[f]	+5.2%
Annual precipitation (cm/yr)	80[c]	58.2[g]	+37.5%
Average irrigation (cm/ha)	72[d]	47.5[h]	+51.6%
Average nitrogen (kg/ha)	437[e]	153[i]	+285%
Average phosphorus (kg/ha)	0	65[i]	-100%
Average insecticides	2.9 L/ha[e]	2.8 kg/ha[i]	+ ~3.6%
Average herbicides	1.15 L/ha[e]	6.2 kg/ha[i]	- ~81.5%

[a] Gobierno del Estado de Sinaloa, 2010
[b] SAGARPA, 2010
[c] Comrie & Glenn, 1998; Liebmann et al., 2008
[d] Local expert estimate
[e] Eakin et al. 2009
[f] NCGA, 2010
[g] U.S. Department of the Interior & U.S. Geological Survey, 2011
[h] Payero et al., 2006
[i] Pimentel & Pimentel, 2008

Environmental impacts associated with agriculture are well documented in Nebraska. These include groundwater overdraft, groundwater pollution, surface hydrology alteration, over-application of inputs, and biodiversity loss. Groundwater overdraft – two-thirds of which is used for irrigation (Olson & Naugle, 1997) – has become a serious problem provoking attention from environmental groups as well as state regulation (Hickey, 1992). Groundwater contamination is another concern. A six-year study by Spalding and colleagues (2003) detected fourteen pesticides and transformation products from agrochemicals in a Nebraska aquifer. Verstraeten, Carr, and Steele (1999) found that municipal water wells and the Platte River are connected to aquifers contaminated with herbicides. Brye, Norman, Bundy, and Gower (2000) demonstrated that agricultural land use, management, and tillage have altered regional hydrology, and reinforced mechanized agriculture's potential for chemical leaching. Kessavalou and others (1996) tested Nebraska's best management practices for center-pivot irrigation and fertilizer application, and found that large amounts of nitrate were still being leached. In southeast Nebraska, of 268 test sites of streams and groundwater, 37% were found to exceed the maximum drinking water limit for nitrogen, and many were found to surpass the advisory levels for livestock (de Walle & Sevenster, 1998). The massive loss of native vegetation in the Midwest is detrimental to maintaining soil structure, and has led to the endangering of a number of animal and plant species, and species extinctions (Sampson & Knopf, 1994).

Beyond these local impacts, agriculture in the U.S. Corn Belt has significant downstream effects. The most notable of these is the infamous dead zone in the Gulf of Mexico caused by the outflow of Mississippi River water contaminated by agricultural runoff from the Midwest. Nitrogen fertilizer and Atrazine, an herbicide commonly used in U.S. maize fields and a major groundwater polluter in the Corn Belt, are thought to be the primary causes of the dead zone (Clay, 2004). Both nitrogen and Atrazine are used in Sinaloa maize production (Fundación Produce, 2003). In addition, pesticide use is dangerous to human health. Aside from the estimated 25 million poisonings per year worldwide, multiple epidemiological studies have linked pesticide exposure to significantly higher rates of many types of cancers among farmers and farm workers (Alavanja, et al., 2004).

The case of Nebraska demonstrates that large-scale commercial maize production is not environmentally benign. It suggests that Sinaloa maize production could lead to groundwater pollution, surface hydrology alteration, biodiversity loss, and harmful eutrophic conditions in water bodies, calling attention to the need for further research on the environmental impacts of agriculture, and strategies and actions to mitigate negative outcomes in Sinaloa. However, the temporal and spatial scales of production play a role in the scale of impacts. As in the Sinaloa system, the area planted in maize in Nebraska influences all associated management practices, and augments the environmental impacts. For example, if all maize growers in Nebraska are using more herbicides than necessary, and there are almost four million hectares in cultivation versus about 500,000 ha in Sinaloa, the impacts will be much more dramatic in Nebraska than in Sinaloa. Growers have been cultivating commercial maize in Nebraska for over 150 years, where Sinaloa growers have been cultivating commercial maize for about twenty years. So, while Sinaloa is a maize monoculture with high input use similar to maize production in the U.S. Corn Belt, the scale of maize production in Sinaloa is small compared to the Corn Belt, and impacts are likely to be on a smaller scale, too.

This does not mean that risks to people's health and the environment's health do not exist, or that conditions are static; impacts can accumulate and get worse over time. Sinaloa growers use far more nitrogen fertilizer than necessary, putting groundwater resources at risk, and loading nutrients in aquatic ecosystems. Over-tilling and not planting cover crops may increase erosion, reduce soil quality and lead to even more nutrient loading in aquatic ecosystems. On a more positive note, herbicide and insecticide use, a major problem in many conventional cropping systems, is quite low in Sinaloa. Pests and disease are not currently a serious concern. However, maize is not the only crop cultivated in Sinaloa. Vegetable production is an important part of the agricultural economy. For many of the vegetables produced in Sinaloa, such as tomatoes, bell peppers, and chiles, growers use significantly more inputs, especially pesticides, than are used in maize. In addition, much of Sinaloa's vegetable produce is exported, meaning that its resources are being consumed and contaminated by agriculture not to increase Mexican food security, but to stock American grocery stores. The social and environmental risks and impacts of agricultural production should be taken into consideration and weighed against the economic benefits of food exports.

Recommendations

To improve the sustainability of maize production in Sinaloa and knowledge of the system, there are things different groups of actors such as maize growers, government agencies, and researchers can do. The following recommendations are derived from my interviews with local experts, the results of my analysis, and from my own observations.

Maize Growers.

- Use irrigation water judiciously to conserve and make more water available for spring crops. An experiment on maize production in Sinaloa shows that, using furrow irrigation, normal yields were achieved with a net irrigation depth of 44 cm/ha under conditions of normal water availability. However, a crop's water requirements are variable, depending on season, climate, management, soil conditions, and seed variety, and therefore must be adjusted to local conditions. The most critical stages for irrigating maize are during the flowering and silking periods (Ojeda-Bustamante, et al., 2006). In an experiment with maize in Sinaloa, Díaz Valdés and colleagues (2008) found drip irrigation to be more sustainable than furrow irrigation in terms of water and soil use. However, drip irrigation requires an initial capital investment, with implications for economic sustainability.
- Use less fertilizer, especially nitrogen (N). Fertilizer type, timing, placement, and rate are all important considerations for reducing fertilizer use without losing profitability. N fertilizer type and placement depend on the context and soil type. In terms of timing, "nitrogen uptake is generally low at the beginning of the growing season, increasing rapidly during vegetative growth, and dropping sharply as the crop nears maturity" (Millar, et al., 2010, p. 189). Early N application, then, is often not absorbed by the crop, but by the atmosphere and downstream water bodies. In addition, as higher levels of N fertilizer are used, more N ends

up in the atmosphere and water bodies, rather than the crop it was intended for (Millar, et al., 2010). In Sinaloa, Díaz Valdés (2006) found that 200 kg N/ha of maize, in conjunction with a drip irrigation system, resulted in more residual soil nitrogen at the end of the experiment, and was more cost effective than applications of 300 and 400 kg/ha of N with a traditional furrow irrigation system. Sinaloa experts suggest that 180 kg/ha of N is sufficient to achieve a good yield in Sinaloa. However, growers should calculate for their land what the appropriate N rate is for the best returns, also known as the "maximum return to nitrogen" (MRTN) approach, rather than using the yield based N rate that is now typical in large scale row crop systems (Millar, et al., 2010).

- Test soil annually. This is inexpensive, and will inform what the parcel is capable of yielding, as well as inform what soil amendments and fertilizers are most suitable for the context of the parcel.
- Increase soil organic matter (SOM) to improve soil quality. There are multiple approaches for this, including reduced tillage, adding green compost and/or animal manure, rotating crops, and planting cover crops, among others (Magdoff & Weil, 2004; Uri, 1999). Growers should bear in mind that increasing SOM could be a slow process that may take years.
- Rotate crops to increase crop diversity, improve soil health, increase yields, and reduce pest infestation, which often occurs when the same crop is cultivated annually in the same place (Magdoff & Weil, 2004; Rosset & Altieri, 1997; Soule & Piper, 1992). This will also reduce the land area in

maize, reduce pests, and reduce problems associated with overproduction (e.g. price depression). Rotating legumes will increase the soil nitrogen content, reducing the need for fertilizers (Pretty, 2008). Crop diversification is being encouraged by the state government (Gobierno del Estado de Sinaloa, 2010) and SAGARPA officials (López, 2010).

- Reduce tillage. This will save money in terms of fossil fuel and labor, improve soil structure, and reduce erosion (Uri, 1999). Aside from reducing cultivations, there are multiple methods for reducing tillage, including minimum tillage, chisel plowing, plow-planting, ridge tillage, and no-tillage (Lal, et al., 1990).
- Plant a cover crop during the spring season to reduce erosion and maintain soil quality (Magdoff & Weil, 2004). Legumes are a good option because they increase soil nitrogen (Pretty, 2008).
- Track budgets for all resource inputs, not just in terms of financial cost, but actual input use as well (e.g. kg/ha fertilizer, cm/ha irrigation, kg/ha pesticides, L/ha diesel, etc.). Calculate the potential savings from reducing cultivations, nitrogen use, diesel, and other inputs.
- Explore alternative farming practices that would be appropriate for the growers' land, and could be adopted in the short and long term.

Government.

- Support and create incentives for sustainable farm management.

- Increase public education of Sinaloa's environment and environmental stewardship.

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- Monitor nitrogen, phosphorus, and pesticide levels, as well as eroded soil in irrigation drains.
- Maintain and update irrigation infrastructure to avoid water losses from leakages and evaporation.
- Test groundwater for agrochemical contamination. Pay special attention to towns that draw groundwater for human consumption.

Irrigation Districts and Modules.

- Monitor the amount of water that is applied to agricultural fields to increase water use efficiency and ensure that each grower receives his or her allocation.

Researchers.

- Monitor the crops that are the most input intensive and environmentally impactful. Identify ways to reduce input use in these crops.
- Test groundwater for agrochemical contamination. Pay special attention to towns that draw groundwater for human consumption.
- In the towns in which groundwater is drawn for human consumption, study medical records for patterns of illnesses associated with agrochemical poisoning.

- Research Sinaloa's wetlands. Knowledge of the wetlands is currently very limited, and the impacts of agriculture on the wetlands are unknown. Wetlands are proven to be effective filters of agricultural wastewater (Benyamine, Bäckström, & Sandén, 2004). Their maintenance in Sinaloa may thus be critical to sustainability in Sinaloa.
- Monitor local fauna populations as indicators of overall ecosystem health. Local experts believe that crustaceans, birds, and microbes are likely the species most impacted by anthropogenic activities.
- Do a follow up study to the work of Angus Wright (2005). Are working conditions safe today? Are laborers healthy? Do they earn a just wage? Is pesticide use in accordance with regulations?
- Research and/or assess the sustainability of vegetable production and aquaculture, including shrimp farming, in Sinaloa. Weigh the benefits of these activities against negative outcomes. For example, are these products exported internationally, and therefore are Sinaloa's resources being exported? How much revenue do they procure? How many people do they gainfully employ? Are the working conditions safe? What are the environmental impacts of these activities?
- Do research that responds to the needs of farmers.

Conclusion

The study uses the MCDA method for incorporating stakeholder values into sustainability assessment. It emphasizes the decision process of assessment as part of the results, and illustrates the relationship of each indicator to sustainability with value functions that convert the current state of each indicator in a natural scale to a common scale to facilitate their comparison. Agricultural sustainability is framed not as a theoretical end goal, but as a perpetual journey in which stakeholders navigate current environmental, economic, social, and political conditions for the continual betterment of the system. The approach to sustainability is practical, emphasizing achievable goals and effective, realistic interventions in an established system. The analysis highlights sustainability from three perspectives: stakeholder values (MCDA), current state analysis (MCDA), and system influence (network analysis). An advantage of the study is that it synthesizes existing knowledge about the system, calling attention to the current state of knowledge, and what data need to be collected.

The results of the agro-environmental sustainability assessment of commercial maize production in Sinaloa show that maize production has significant implications for overall sustainability. Stakeholders are most concerned with soil and water resources, and least concerned with natural ecosystems and maize yields. The current state of the system is far from an environmentally sustainable state. While it currently meets the agro-environmental sustainability criteria of the provisioning of basic human food needs, the system is far from meeting the criteria of enhancing environmental quality and the natural resource base. The most effectual interventions for improving environmental sustainability in Sinaloa are reducing irrigation and nitrogen fertilizer use, and increasing soil quality. Once the sustainability goals identified in this assessment are achieved, new goals should be identified to keep Sinaloa on a trajectory toward increasing sustainability. Considering the legacy of environmental damage associated with maize production in the American Midwest, Sinaloa stakeholders should consider what they want the future of their environment, economy, and society to be, and how or if maize production can be part of building that future.

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APPENDIX A

INSTITUTIONAL REVIEW BOARD REQUIREMENTS

ARIZONA STATE UNIVERSITY
RESEARCH AND ECONOMIC AFFAIRS

Office of Research Integrity and Assurance

To:	Hallie Eakin GIOS Build
From:	Mark Roosa, Chair Soc Beh IRB
Date:	04/02/2009
Committee Action:	**Exemption Granted**
IRB Action Date:	04/02/2009
IRB Protocol #:	0903003836
Study Title:	Market Integration and Climate as Drivers of Change in the Mexican Maize System: Multi-Scale Interactions in Livelihood and Land Use Change

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2) .

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.

APPENDIX B

INFORMATION LETTER FOR INTERVIEW PARTICIPANTS

Proyecto: La integración del mercado y factores climáticos como motores de cambio en el sistema maicero mexicano

5 Julio 2010

Estimado Participante,

Esta carta tiene como propósito solicitarle nos conceda usted una entrevista para aprovechar su conocimiento y recabar información sobre el sector maicero de México.

Estamos desarrollando un proyecto que estudia los cambios que han sucedido en la producción de maíz de México en los últimos diez años. Con base en nuestros estudios, hemos observado que a nivel nacional se han dado cambios importantes en las regiones donde se produce maíz, lo que ha dado como resultando una nueva geografía del maíz. Nos interesa profundizar en los factores que han influido en estos cambios a través una comparación de tres estudios de caso . Estos estudios se harán en Chiapas, Estado de México y Sinaloa. Nos interesa tanto comprender las diferencias regionales en los patrones de producción, como entender las implicaciones de tales cambios en la seguridad alimentaria y el uso de suelo a nivel regional.

Quisiéramos iniciar el proyecto entrevistando a funcionarios, técnicos, investigadores, científicos, líderes de asociaciones agrícolas, comerciantes y expertos del sector maicero, como usted, para comprender las distintas perspectivas sobre los cambios que se han observado en el sector maicero.

Con su participación en la entrevista, esperamos adquirir un mejor entendimiento de los efectos del auge del cultivo de maíz en Sinaloa. Aunque el estudio no pretende ofrecerle un beneficio directo, agradecemos muchísimo su participación.

El proyecto tiene financiamiento de la Fundación Nacional de Ciencias de los Estados Unidos. Participan investigadores de la Universidad de California en Santa Barbara (UCSB), la Universidad Estatal de Arizona (ASU), el Colegio de México (COLMEX) en México, D.F., y El Colegio de la Frontera Sur (ECOSUR) en San Cristóbal, Chiapas.

Cabe señalar que este estudio tiene fines estrictamente académicos, por lo cual las entrevistas son de carácter confidencial. No compartiremos o publicaremos el contenido de las mismas, ni los nombres de los entrevistados. Sin embargo, nos interesa estudiar las opiniones y conocimiento de los entrevistados en relación con su profesión y cargo, por lo que usaremos títulos descriptivos a la hora de reportar nuestros resultados (por ejemplo, “un comerciante de grano de maíz de

Hermosillo reportó que…”). Aunque no esperamos que el contenido de la entrevista tenga información confidencial, consideramos importante informarle la forma en que se utilizará la información que nos proporcione.

La entrevista que quisiéramos hacer no nos tomará más de una hora de su valioso tiempo. Estaremos en Sinaloa entre las fechas del 30 de junio hasta el 9 de julio para juntarnos a su conveniencia. Si está usted de acuerdo, nos gustaría grabar la entrevista para facilitar la recuperación precisa de la información, pero si esto le parece inadecuado nos bastará con tomar notas. Si grabamos su entrevista podemos proporcionarle una copia en formato digital si así lo deseara.

Para cualquier aclaración, puede comunicarse directamente conmigo a los teléfonos que aparecen abajo. Además, puede comunicarse a la Chair of the Human Subjects Institutional Review Board (Responsable Institucional del Grupo de Revisión de Sujetos Humanos), a través de la Oficina de Integridad y Seguridad de la Investigación de la Universidad Estatal de Arizona, en el teléfono 001 480-9656788 para cualquier aclaración sobre los derechos de los entrevistados y las implicaciones de participar en esta investigación. Agradecemos de antemano su disponibilidad para el éxito de nuestro estudio.

Atentamente,

Hallie Eakin

APPENDIX C

AGRO-ENVIRONMENTAL SUSTAINABILITY INDICATORS FROM

LITERATURE REVIEW

WATER

Runoff, Leaching

1. Chemical loss rates (runoff) (Sands & Podmore, 1993)
2. Increasing/high rates of nitrate leaching beyond root zone (Stockle et al., 1994)
3. Increasing/high rates of pesticide leaching beyond root zone (Stockle et al., 1994)
4. Nitrate leaching (Hansen et al., 2001)
5. Phosphorous leaching (Hansen et al., 2001)
6. Sediment loss rates (runoff) (Sands & Podmore, 1993)
7. Water flow buffering function (flooding & runoff) (Van Cauwenbergh et al., 2007)

Nitrogen

1. Increasing/high rates of nitrate leaching beyond root zone (Stockle et al., 1994)
2. Increasing/high rates of nitrates and toxic organics in drinking waters (Stockle et al., 1994)
3. Increasing/high rates of nitrates of chemical loading into surface streams (Stockle et al., 1994)
4. Nitrate in surface waters (Flores Martinez et al., 2005)
5. Nitrate leaching (Hansen et al., 2001)
6. Nitrate levels ((Doran & Zeiss, 2000)
7. NO3 leaching (Kim et al., 2009)

Water Quality

1. Acidification of lakes and rivers (Vaughan, 2004)
2. Degradation of coastal waters (Vaughan, 2004)
3. Groundwater pollution (Vaughan, 2004)
4. Supply (flow) of quality water function (adequate quality) (Van Cauwenbergh et al., 2007)
5. Water quality risk (OECD, 2001)
6. Water quality state (OECD, 2001)

Water Use

1. Depletion of groundwater from increased crop irrigation (Vaughan, 2003)
2. Water consumption (ecological water scarcity index) (Walter & Stützel, 2009)
3. Water reuse (Flores Martinez et al., 2005)
4. Water use efficiency (OECD, 2001)
5. Water use intensity (OECD, 2001)

Irrigation Infrastructure

1. Canal maintenance (de Ita Rubio, 2003)
2. Efficient management in irrigation districts (Flores Martinez et al., 2005)
3. Irrigation technology (OECD, 2001)
4. Storage capacity of principal dams (Flores Martinez et al., 2005)

Groundwater Extraction

1. Depletion of groundwater from increased crop irrigation (Vaughan, 2003)
2. Freshwater consumption (Vaughan, 2004)
3. Groundwater extraction (Flores Martinez et al., 2005)
4. Total extraction for consumption (Flores Martinez et al., 2005)

Phosphorus

1. Groundwater pollution (Vaughan, 2004)
2. Phosphorous leaching (Hansen et al., 2001)
3. Total phosphorus in surface waters (Flores Martinez et al., 2005)

Biochemical Oxygen

1. Biochemical demand of oxygen (DBO5) (SEMARNAT, n.d.)
2. Biochemical oxygen in surface waters (Flores Martinez et al., 2005)
3. Chemical demand of oxygen (DQO) (SEMARNAT, n.d.)

Water Availability

1. Supply (flow) of water function (adequate amount) (Van Cauwenbergh et al. 2007)
2. Water scarcity (de Ita Rubio, 2003)
3. Water stress (OECD, 2001)

Eutrophication

1. Algal blooms (Vaughan, 2004)
2. Eutrophication (Kim et al., 2009)
3. Increasing eutrophication of water bodies (Stockle et al., 1994)

Salinization

1. Salinization of groundwater (Flores Martinez et al., 2005)

Other

1. Guidelines of river basin and technical committees on groundwater (Flores Martinez et al., 2005)
2. Increasing BOD in surface streams (Stockle et al., 1994)
3. Increasing coliform counts in surface streams (Stockle et al., 1994)
4. Increasing lake or pond sedimentation (Stockle et al., 1994)
5. Median annual precipitation (de Ita Rubio, 2003)
6. Total suspended solids (SEMARNAT, n.d.)

SOIL

Erosion

1. Eolic erosion (de Ita Rubio, 2003)
2. Erosion (Carter, 202; Perez-Grovas, 2000; Flores Martinez et al., 2005)
3. Erosion levels (Lopez-Ridaura et al., 2002)
4. Erosion rates (Sands & Podmore, 1993)
5. Hydraulic erosion (de Ita Rubio, 2003)
6. Increasing or steadily high erosion rates (Stockle et al., 1994)
7. Risk of erosion by water (OECD, 2001)
8. Risk of erosion by wind (OECD, 2001)
9. Soil erosion control (Taylor et al., 1993)

10. Soil flow buffering function (mudflows, landslides buffered) (Van Cauwenbergh et al., 2007)
11. Soil loss (input/output ratio (mass balance) (Walter & Stützel, 2009)
12. Soil loss (Perales Rivas et al., 2000)

Soil Organic Matter (SOM)

1. Biophysical characteristics of soils (compaction, % organic matter) (Lopez-Ridaura et al., 2002)
2. Change in organic matter (Sands & Podmore, 1993)
3. Decreasing organic matter content (Stockle et al., 1994)
4. Depletion of SOM (input/output ratio (mass balance) (Walter & Stützel, 2009)
5. Organic material content (Hansen et al., 2001; Paetz & Wilke, 2005; Perales Rivas et al., 2000; Pimentel et al., 1995)
6. Organic matter content/texture (Doran & Zeiss, 2000)
7. Organic matter incorporated in soil (López-Ridaura et al., 2005)
8. SOM - (subattributes: macro-organic matter C & N (particulate C & N), Light fraction C & N, microbial biomass C & N, mineralizable C & N) (Carter, 2002)

Carbon

9. Carbonate concentration (Carter, 2002)
10. Organic Carbon (Gomez et al., 1996)

Nutrients

1. Mineral deficiency/sufficiency (plant tissue nutrient levels) (Krishna, 2002)
2. Nutrient availability (Carter, 2002)
3. Nutrient balance (Lopez-Ridaura et al., 2002; Perez-Grovas, 2000)
4. Nutrient depletion (input/output ratio (mass balance) (Walter & Stützel, 2009)
5. Nutrients (Pimentel et al., 1995)
6. Plant nutrient status (Doran & Zeiss, 2000)
7. Soil nutrient balances (kg/ha) (López-Ridaura et al., 2005)
8. Trace element concentrations (Paetz & Wilke, 2005)

Nitrogen

9. Nitrate levels (Doran & Zeiss, 2000)
10. Soil surface nitrogen balance (OECD, 2001)

Soil Physical Attributes

1. Biophysical characteristics of soils (compaction, % organic matter) (Lopez-Ridaura et al., 2002)
2. Change in bulk density (Sands & Podmore, 1993)
3. Compaction (Carter, 2002; Perales Rivas et al., 2000)
4. Damage to soil structure (soil pressure/resistance ratio) (Walter & Stützel, 2009)
5. Leachable salts (esp. NO3) (soil electrical conductivity at time of fertilization and after harvest (Doran & Zeiss, 2000)
6. Physical properties and variations (Paetz & Wilke, 2005)

7. Soil compaction/physical condition (Doran & Zeiss, 2000)
8. Soil structure (Carter, 2002)
9. Soil texture (Kim, 2t al., 2009; Pimentel et al., 1995)
10. Structure (Hansen et al., 2001)
11. Structure development (Pimentel et al., 1995)

Soil and Moisture

1. Change in water holding capacity (Sands & Podmore, 1993 (Bindraban, Stoorvogel, Jansen, Vlaming, & Groot, 2000)
2. Decreasing infiltration (Stockle et al., 1994)
3. Decreasing water holding capacity (Stockle et al., 1994)
4. Infiltration rates (Pimentel et al., 1995)
5. Ponding (Doran & Zeiss, 2000)
6. Soil humidity (Perales Rivas et al., 2000)
7. Soil water storage (Doran & Zeiss, 2000)
8. Water retention (Carter, 2002)
9. Water-holding capacity (Pimentel et al., 1995)

Soil Fertility

1. Fertility (de Ita Rubio, 2003)
2. Maintenance of soil fertility (Rigby et al., 2001)
3. Soil fertility (Perales Rivas et al., 2000)
4. Soil fertility maintenance (Taylor et al., 1993)
5. Soil fertility management (Rasul & Thapa, 2003)
6. Soil fertility status (chemical analysis of soil samples from farms) (Rasul & Thapa, 2003)
7. Net soil nutrient supply (Bindraban, et al., 2000)

Contamination

1. Degradative potential of leached pollutants (persistence, mobility) (Sands & Podmore, 1993)
2. Depth of leached pollutants (Sands & Podmore, 1993)
3. Ecotoxicological questions (verification of effects of chemicals added to soil on life-forms) (Paetz & Wilke, 2005)
4. Heavy metals (de Vries et al., 2002)
5. Nature, concentrations, and distribution of contaminants (Paetz & Wilke, 2005)
6. Soil contamination (input/output ratio (mass balance) (Walter & Stützel, 2009)

Soil Salinity

1. Increasing salinization of soils (Stockle et al., 1994)
2. Salinity (Carter, 2002; Vaughan, 2004)
3. Salinization of soil (Flores Martinez et al., 2005)
4. Sodicity (Carter, 2002)
5. Desertification (de Ita Rubio, 2003)

Soil Depth

1. Soil depth (Gomez et al. 1996; Pimentel et al., 1995)
2. Soil thickness (Sands & Podmore, 1993)

3. Topsoil depth (Doran & Zeiss, 2000)

Soil Acidification

1. Acidification (Carter, 2002)
2. Acidification/alkalinisation (input/output ratio (mass balance) (Walter & Stützel, 2009)
3. Increasing alkalization (Stockle et al., 1994)
4. Soil acidification/leaching losses (Doran & Zeiss, 2000)

Soil biota

1. Biology (Hansen et al., 2001)
2. Presence and distribution of biological species of interest (Paetz & Wilke, 2005)
3. Soil biota (Pimentel et al., 1995)

Protective Cover

1. Soil cover (OECD, 2001)
2. Soil protective cover % (Doran & Zeiss, 2000)

Runoff

1. Runoff (Doran & Zeiss, 2000)
2. Surface runoff (Perales Rivas et al., 2000)

Soil Use

1. Change in use of soil (Flores Martinez et al., 2005)
2. Land/soil use (Paetz & Wilke, 2005)

Tillage

1. Tillage systems (Carter, 2002)
2. Tillage practices (Kim, et al., 2009)

pH

1. Soil pH (Carter, 2002; Paetz & Wilke, 2005)

Other

2. Aggregate stability (Carter, 2002)
3. Decreasing cation exchange capacity (Stockle et al., 1994)
4. Decreasing earthworm activity (Stockle et al., 1994)
5. Nature, concentrations, and distribution of naturally occurring substances (Paetz & Wilke, 2005)
6. Supply (stock) of quality soil function (Van Cauwenbergh et al., 2007)
7. Supply (stock) of soil function (loss minimized) (Van Cauwenbergh et al., 2007)
8. Surface area affected by soil degradation (Flores Martinez et al., 2005)
9. Water stable aggregates (Carter, 2002)

INPUTS

Fertilizers

1. Amount of fertilizer applied per unit of land (Rasul & Thapa, 2003)
2. Consumption rates of minerals (P_2O_5, K_2O, CaO) (Walter & Stützel, 2009)
3. Eutrophying substances - marine (aquatic eutrophication potential) (Walter & Stützel, 2009)

4. Eutrophying substances - terrestrial (terrestrial eutrophication potential) (Walter & Stützel, 2009)
5. Fertilizer application (Vaughan, 2004)
6. Fertilizer per capita (Vilas-Ghiso & Liverman, 2007)
7. Fertilizer consumption (Vilas-Ghiso & Liverman, 2007)
8. Proportion of area covered by each type of fertilizer (Rasul & Thapa, 2003)
9. Proportion of farmers using inorganic & organic fertilizers (Rasul & Thapa, 2003)

Nitrogen

10. N fertilizer (kg N ha) (Kim et al., 2009)
11. Nitrogen efficiency (OECD, 2001)
12. Rise of over-application of nitrogen (Vaughan, 2003)

Phosphorus

13. Phosphorus fertilizer kg P_2O_5 ha) (Kim et al., 2009)
14. Rise of over-application of phosphorus (Vaughan, 2003)

Potassium

15. K fertilizer (kg K_2O ha) (Kim et al., 2009)

Energy

16. Electricity (MJ ha) (Kim et al., 2009)
17. Energy source (on farm, local, distant) (Sands & Podmore, 1993)
18. Energy type ratio (fossil/human/organic) (Sands & Podmore, 1993)
19. Energy: non-human in/useable out (Sands & Podmore, 1993)
20. LPG (MJ ha) (Kim et al., 2009)
21. Natural gas (MJ ha) (Kim et al., 2009)
22. Organic energy in/useable out (Sands & Podmore, 1993)

Pesticides

1. Amount pesticides used (Doran & Zeiss, 2000)
2. Insecticides (kg a.i. ha) (Kim et al., 2009)
3. Pesticide risk (OECD, 2001)
4. Pesticide use (OECD, 2001)
5. Pesticides (normalized treatment index) (Walter & Stützel, 2009)
6. Toxicity of pesticides used (Doran & Zeiss, 2000)

Chemicals

1. Agronomic inputs (Kim et al., 2009)
2. Chemical inputs (de Ita Rubio, 2003)
3. Chemical soil parameters/effects of direct inputs to soil (Paetz & Wilke, 2005)
4. Rise of over-application of agrochemical inputs (Vaughan, 2003)

Herbicides

1. Herbicide application (Carter, 2002)
2. Herbicides (kg a.i. ha) (Kim et al., 2009)

Other

1. Equipment (de Ita Rubio, 2003)
2. External inputs/total inputs (López-Ridaura et al., 2005)

3. Lime (kg a.i. ha) (Kim et al., 2009)
4. Machinery (de Ita Rubio, 2003)
5. Organic matter inputs (Carter, 2002)
6. Seed source (Rigby et al., 2001)

FOSSIL FUEL

1. Consumption of combustible fossil fuels (Flores Martinez et al., 2005)
2. Diesel (MJ ha) (Kim et al., 2009)
3. Fossil energy in/useable out (Sands & Podmore, 1993)
4. Fossil fuel consumption (rates) (Walter & Stützel, 2009)
5. Gasoline (MJ ha) (Kim et al., 2009)
6. Total fossil energy use (Kim et al., 2009)

ECOSYSTEM

Biodiversity

1. Biodiversity (SEMARNAT, n.d.)
2. Biological diversity (Vaughan, 2004)
3. Decreasing wildlife populations (Stockle et al., 1994)
4. Earnings from other species (Perez-Grovas, 2000)
5. Genetic diversity (OECD, 2001)
6. Number of species (Perales Rivas et al., 2000)
7. Species diversity (wild life; non-native species) (OECD, 2001)
8. Supply (stock) of biotic resources function (maintain biodiversity, spontaneous biodiversity, flow of biotic resources buffered) (Van Cauwenbergh et al., 2007)

Crop(s)

1. Crop management (Rigby et al., 2001)
2. Crop rotation (Carter, 2002; Hansen et al., 2001)
3. Nitrogen fixed by leguminous species (kg) (López-Ridaura et al., 2005)
4. Number of managed species (Perez-Grovas, 2000)
5. Number of species grown (Lopez-Ridaura et al., 2002)
6. Permanent ground cover (Gomez et al., 1996)

Habitat

1. Decreasing adequacy of wildlife habitat (Stockle et al., 1994)
2. Habitat matrix (OECD, 2001)
3. Intensify farmed agricultural habitats (OECD, 2001)
4. Semi-cultivated areas (Hansen et al., 2001)
5. Semi-natural habitats (OECD, 2001)
6. Uncultivated natural habitats (OECD, 2001)

Aquatic habitats

7. Acidification of lakes and rivers (Vaughan, 2004)
8. Algal blooms (Vaughan, 2004)
9. Degradation of coastal waters (Vaughan, 2004)
10. Increasing lake or pond sedimentation (Stockle et al., 1994)

Forests

1. Deforestation (Vaughan, 2004)
2. Forest resources (SEMARNAT, n.d.)
3. Rates of deforestation (Vaughan, 2003)

Other

1. Environmental risk (SEMARNAT, n.d.)
2. Small biotopes (Hansen et al., 2001)

ATMOSPHERE

Greenhouse gasses

1. Average annual concentrations of Ozone (Flores Martinez et al., 2005)
2. CH_4 (Hansen et al., 2001)
3. CO_2 (Hansen et al., 2001)
4. Gross agricultural GHG emissions (OECD, 2001)
5. N_2O emissions from soil (Kim et al., 2009)
6. NO_x emissions for soil (Kim et al., 2009)
7. Number of days ozone exceeded norm (Flores Martinez et al., 2005)
8. Ozone (INE, 2009; Vaughan, 2004)
9. Soil organic carbon accumulation or depletion (Kim et al., 2009)

Particulate Matter

1. Average annual concentrations of particulate matter less than 10microns (Flores Martinez et al., 2005)
2. Dust (Fraser, personal communication April 20, 2010)
3. Increasing fine particulates (<10; PM 10 dust index) (Stockle et al., 1994)
4. Number of days particulate matter less than 10 microns exceeded norm (Flores Martinez et al., 2005)
5. Suspended particles with diameter less than 10 microns (INE, 2009)
6. Suspended particles with diameter less than 2.5 microns (INE, 2009)

Nitrogen

1. Ammonia (NH_3) (Hansen et al., 2001)
2. Average annual concentrations (Flores Martinez et al., 2005)
3. Nitrogen dioxide (NO_2) (INE, 2009)
4. Nitrous oxide (N_2O) (Hansen et al., 2001)
5. Number of days NO_2 concentrations exceeded norm (Flores Martinez et al., 2005)

Ozone (O_3)

1. Average annual concentrations of Ozone (Flores Martinez et al., 2005)
2. Number of days ozone exceeded norm (Flores Martinez et al., 2005)
3. Ozone (INE, 2009; Vaughan, 2004)

Sulfur dioxide ($S0_2$)

1. Average annual concentrations of SO_2 (Flores Martinez et al., 2005)
2. Number of days SO_2 concentrations exceeded norm (Flores Martinez et al., 2005)
3. Sulfur dioxide (SO_2) (INE, 2009)

Carbon Monoxide (CO)

1. Average annual concentrations of CO (Flores Martinez et al., 2005)
2. CO (INE, 2009)
3. Number of days CO concentrations exceeded norm (Flores Martinez et al., 2005)

Other

1. Air acidification (Kim et al., 2009)
2. Airflow buffering function (Van Cauwenbergh et al., 2007)
3. Field burning (Fraser, personal communication April 20, 2010)
4. Increasing odor intensity (Stockle et al., 1994)
5. Increasing/steadily high soil erosion rates by wind (Stockle et al., 1994)
6. Pesticides (Fraser, personal communication April 20, 2010)
7. Supply (flow) of quality air function (Van Cauwenbergh et al., 2007)

LAND

Land Management

1. Cropping pattern (cropping intensity, crop diversification, mixed cropping) (Rasul & Thapa, 2003)
2. Environmental features and land use patterns (OECD, 2001)
3. Land occupancy (naturalness, degradation potential) (Walter & Stützel, 2009)
4. Land use pattern (proportion of land under field crops, homestead, orchard) (Rasul & Thapa, 2003)
5. Landscape management (OECD, 2001)

Land Use

1. Agricultural land use (OECD, 2001)
2. Change in land use (Vaughan, 2003)
3. Land use (Vilas-Ghiso & Liverman, 2007)

Surface Area

1. Change in agricultural land (OECD, 2001)
2. Stock of agricultural land (OECD, 2001)
3. Surface area in agriculture (Flores Martinez et al., 2005)

Other

1. Contaminated sites (SEMARNAT, n.d.)
2. Landscape costs and benefits (OECD, 2001)
3. Surface area affected by edafic degradation (Flores Martinez et al., 2005)

CROP YIELDS

Yield Trends

1. Decreasing yields (Stockle et al., 1994)
2. Variability of production (Perales Rivas et al., 2000)
3. Yield trends (Lopez-Ridaura et al., 2002)

Yield

1. Yield (kg/ha) (López-Ridaura et al., 2005)
2. Crop yields (Perales Rivas et al., 2000)

3. Yield gap (actual yield to potential yield) Bindraban, et al., 2000)(Bindraban, et al., 2000)
4. Dry yield (Kim et al., 2009)

Production/Consumption

1. Maize production/consumption (López-Ridaura et al., 2005)
2. Yield gap (kg/ha) (López-Ridaura et al., 2005)

Other

1. Frequency of crop failure (Gomez et al., 1996)
2. Minimum yield in driest years (kg/ha) (López-Ridaura et al., 2005)
3. Number of grains produced per plant (Perez-Grovas, 2000)
4. Quality of product (Perez-Grovas, 2000)
5. Relationship between yield and SOM (Carter, 2002)
6. Weight of grains of one plant (Perez-Grovas, 2000)
7. Yield standard deviation (kg/ha) (López-Ridaura et al., 2005)
8. Yield variation with rainfall variation (kg/mm) (López-Ridaura et al., 2005)
9. Yield variation with temperature variation (kg/C) (López-Ridaura et al., 2005)

PESTS AND DISEASE

Management

1. Disease control (Taylor et al., 1993)
2. Insect control (Taylor et al., 1993)
3. Pest & disease management (proportion of farmers using biological, mechanical, & chemical methods) (Rasul & Thapa, 2003)
4. Pest/disease control (Rigby et al., 2001)
5. Weed control (Taylor et al., 1993)

Incidence

1. Incidence of pest, disease, weeds (Lopez-Ridaura et al., 2002)
2. Pest incidence (Perez-Grovas, 2000)

APPENDIX D

STAKEHOLDER QUESTIONNAIRE

Proyecto de maíz en México: caso de Sinaloa
Asuntos ambientales

1) Considerando la sustentabilidad del cultivo de maíz en Sinaloa en relación al medio ambiente, por favor alinee los siguientes asuntos ambientales según su importancia, con el #1 como el más importante y el #12 como el menos importante. Si se le ocurre un buen indicador para el asunto, por favor escríbalo en la ultima columna.

Asuntos Ambientales	**Orden**	**Indicador?**
Erosión		
Calidad del suelo *(ej: materia orgánica, salinidad, etc.)*		
Calidad del agua *(ej: polución, escorrentía agrícola, etc.)*		
Incidencia de plagas, maleza, y enfermedades		
Rendimiento/perdida de maíz *(ej: T/ha, superficie siniestrada, etc.)*		
Presencia de vegetación nativa		
Condición de fuentes de agua natural *(ríos, lagos, mar, etc. Ej: Condición biológica, etc.)*		
Uso de fertilizante de nitrógeno *(ej: eficiencia de aplicación, volumen aplicada, etc.)*		
Uso de agua de riego *(ej: abastamiento de agua, eficiencia, etc.)*		
Uso de combustibles fósiles *(ej: total consumo de energía fósil por año agrícola, etc.)*		
Uso de plaguicidas *(ej: toxicidad de plaguicidas, volumen de plaguicidas aplicada por año, etc.)*		
Uso de terreno *(ej: diversidad de cultivos, superficie en agricultura, cambios al uso de terreno, etc.)*		

2) Hay algo que no está en la lista que deba de ser considerado? Que es, que sería un buen indicador, y donde estaría en la alineación de importancia?

APPENDIX E

STAKEHOLDER RECOMMENDATIONS FOR ASSESSMENT

These comments were handwritten on the stakeholder questionnaires. This table shows my translation of my best guess of what was written in Spanish. In some cases more than one stakeholder made the same comment. If this was the case, the number of times a comment was made is indicated in parentheses next to the comment. Some comments were not legible; these are not included. I coded the comments according to whether they are an indicator, ideal state, intervention, and/or a comment on the current state.

Comment	Indicator	Ideal state	Intervention	Comment
Erosion				
Quantify influence of air and water management	x			
Physical chemical content	x			
Plant with irrigation, lowers organic material				x
Topsoil loss (3)	x			
Increase organic matter			x	
Add soil organic matter; they are doing this	x			x
Dissolved solids in estuaries	x			
Soil analysis	x			
Build soil dams			x	
Soil quality				
Measure soil organic matter (2)	x			
Identify nutrient availability	x			
Sinaloa has good soil quality				x
Indicators of affectation				x
Soil with a minimum of high content of 40		x		
Stop using agrochemicals			x	
Direct planting			x	
Soil analysis				x
Tillage			x	
Measure structure	x			
Analyze fertility (2)	x			
Soils are saline because of fertilizer use				x
Salinity	x			
Apply compost			x	
.4% now, ideal would be 2%	x	x		x
Water quality				
Analysis of fertilizer and pesticide residues	x			
Sinaloa is a good region with dams, need improvement				x
% of irrigation water in drains	x			

Comment	Indicator	Ideal state	Intervention	Comment
Water free of salts and agrochemicals		x		
Analyze carbonates	x			
Free of heavy metals and pathogens		x		
Water analysis (3)	x			
Nitrogen	x			
SO_4 in groundwater and ocean	x			
NO_3 in groundwater and ocean	x			
Availability	x			
Salinity	x			
Productivity of coastal bays	x			
Pollution	x			
Pest and disease incidence				
Monoculture	x			
With monoculture this is increasing				x
Index of increase	x			
Seek the best planting technique			x	
Monitor urban economy	x			
Stop using agrochemicals, use rock powders			x	
By knowledge and comparison				x
Identify new pests	x			
Availability of control	x			
Monitor (2)			x	
Not serious				x
Yield/crop loss				
Lack of knowledge of the needs of soil, water impacts yield				x
% Affectation of P & E, productivity	x			
Compare the statistics from 30 years ago and analyze	x			
Review cost/benefit	x			
Bioorganic with chemical zoton/ha			x	
Organic Mexican hybrid/2 tons/ha				x
Total tons/ha produced (2)	x			
Yield	x			
Only when there are rains or cyclones				x
Calibration of harvesting equipment				x
Seed genetics	x			
Not relevant				x
Terrestrial ecosystem (*presencia de vegetación nativa*)				
Alteration of vegetative communities	x			

Comment	Indicator	Ideal state	Intervention	Comment
It’s controllable				x
Index of diversity	x			
Does not represent a problem. Avoid with tilling			x	x
Evaluate				
Informs soil problems				x
Herbicide application	x		x	
It is controllable with consistent practices				x
Examine the biology of the soil	x			
No problem				x
Aquatic ecosystem				
Climate change influences the patterns of rains and the amount of water captured in dams				x
Generally adequate but there are years where quantity is a problem				x
Indicators to increase capture	x			
Try not to use groundwater			x	
Evaluate the hydrological area	x			
Free of heavy metals and microbiological pathogens		x		
Not contaminated		x		
If there is no water, there is no production				x
Water quality	x			
Not a problem				x
Nitrogen fertilizer				
Residual nitrogen in groundwater, drains, estuaries	x			
They apply without studies of prices and they generalize				x
% Diversification of fertilizer sources	x			
Attempt to get fertilizer from natural sources			x	
Analyze soil fertility	x			
With green compost, humification, and micro-organisms that fix nitrogen from the air			x	
Fertilizers	x			
Transport and accumulation in groundwater	x			
Availability in the market	x			
Survey growers				x
They are technifying everyday				x
Monitor nitrogen to be more efficient	x			
Volume	x			
Analyze soil quality each cycle				

Comment	Indicator	Ideal state	Intervention	Comment
Irrigation				
Measure the irrigation applied/ha and associate with yield	x			
In years with little water growers should plant less maize			x	
Index to measure volume/surface area	x			
In Sinaloa's conditions we should us 300 c/ha and make topographical curves				x
With organic material and microbiological flora we require less water and genetic resistance				x
Natural condition of the plant		x		
Water use	x			
Volume/ha	x			
Infrastructure			x	
Flow and use	x			
Measure in the field	x			
They are technifying				x
Better use			x	
Efficiency	x			
Fossil energy				
Production systems associated with energy use	x			
Contamination	x			
Lack of efficiency; % efficiency in its agricultural use	x			
Organize and use of machinery	x			
Try to avoid for motivations of contamination			x	
Financial cost of investment and costs in the development of production unit	x			
Eliminate machinery and chemical fertilizers			x	
Diesel use in agricultural machinery	x			
Minimum tillage	x			
Total consumption				
Pesticides				
Associate the maize monoculture with major presence of pests, resistance of pests to pesticides	x			
Some exaggerate the amount without determining the specific cases by field				x
% decrease of chemical insecticides vs. biological insecticides	x			
Use pesticides of organic origin to reduce the parts per million			x	

Comment	Indicator	Ideal state	Intervention	Comment
Evaluate % of toxins accumulated in produce	x			
Biopesticides, beneficial insects, etc.	x			
According to the presence of beneficial and harmful insects	x			
Measure in drain water	x			
Availability of products	x			
Survey growers				x
It’s necessary to lower this				x
If they are efficient	x			
Volume	x			
Agricultural land				
Rotate crops associated with soil quality, yield, costs			x	
# hectares in maize as compared to the diversity of other crops	x			
Monoculture	x			
Planting a monoculture of maize is the most dangerous practice if we want to continue planting in Sinaloa. This aspect would be #1				x
Monoculture is #1 problem, other problems derive from this				x
It is very important to use crop rotation to avoid soil degradation				
Analyze the increase in geodiversity of soil and if organic material goes up or not, so we can invent another model of soil use	x			x
Incorporate green compost in rotation with crops, and fixing nitrogen from the air and assimilation of phosphorus			x	
Agricultural surface area	x			
Availability of quality surface area	x			
Its necessary to establish rotation based on restructuring productivity				x
Adaptability of each crop	x			
Surface area	x			
Other suggestions				
Financial/economic:				
% hours/labor agricultural management	x			
Efficient costs production/ha				
Efficient use of inputs, origin and availability	x			

Comment	Indicator	Ideal state	Intervention	Comment
Efficiency in the supply chain and added value (grower and efficiency) – capitalization of the producer				x
Financing: attractive and competitive rates that allow continued activity, measure in interest rates	x	x		
Financing				x
Harvest contracts	x			
Seed genetics				
The use of transgenic varieties (1-3) – can be measured by continually observing the crop by a number of representative years to be able to evaluate with statistics	x			
Transgenic contamination	x			
Seed varieties (yield varies)	x			
Germplasm banks (seeds)			x	
Use of varieties and transgenic materials	x			
Farm management				
Organic agriculture			x	
Rate of incorporating crop waste during fallow periods	x			
Rate of biological pesticide use	x			
Using integrated pest management programs	x			
Planting date (autumn)	x			
Agrochemical contamination				
Use of Faena, which increases the relation of c/n and sterilizes humans	x			x
How NO_3 accumulates in soil and water	x			
Measure contaminate levels in topsoil	x			
Stop using agrochemicals, use organics, biologics and a great diversity of minerals with a base in rock powders (rehabilitate soils, whose origin is from rocks)			x	
Politics & law				
Pass environmental legislation to harmonize with federal law			x	
Design environmental public politics, which currently don't exist			x	
Wildlife				
Presence of native fauna (insects, birds, reptiles, etc.)	x			
Presence of regional fauna (insects, reptiles, birds, and mammals)	x			

APPENDIX F

VALUE FUNCTIONS FOR SUSTAINABILITY

A value function is a mathematical expression that is used to normalize values of a variable in a common scale (Beinat, 1997). They involve a transformation from a natural scale to a scale of 0 (anti-ideal) to 1 (ideal). In general, there are two types of value functions: nominal and continuous. Nominal value functions are used to represent the level of satisfaction provided by different states denoted by names, such as soil type. Continuous value functions are used to represent the grade of satisfaction provided by the states of continuous variables, such as percent, or hectares. Because they are continuous, the functions form a family of continuous curves.

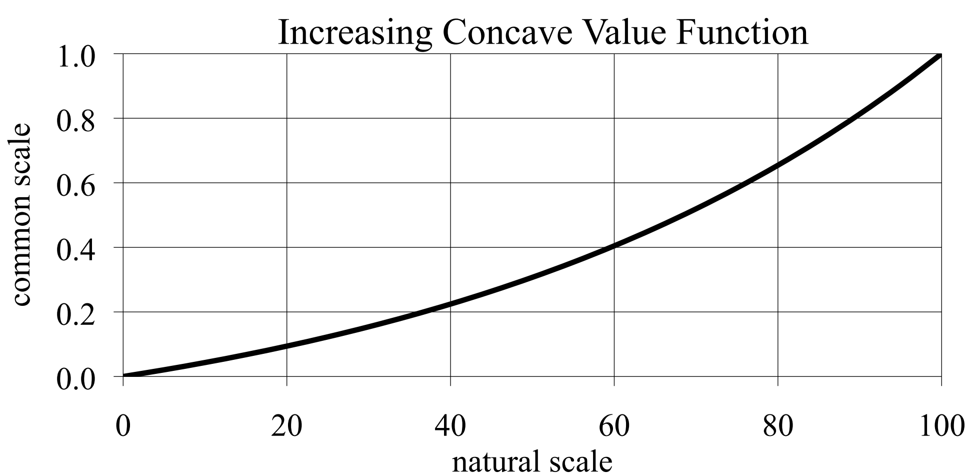
Increasing. The value for stakeholders increases as the value of the variable increases, reaching its ideal value at the highest point of the range. There are two types of increasing functions:

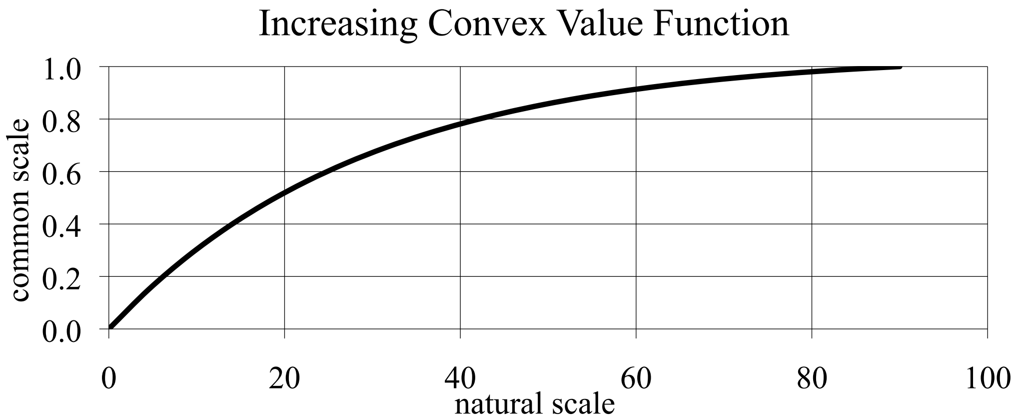
$$\textbf{\textit{Concave:}}\ v = \frac{e^{-\gamma x} - y^{-}}{y^{*} - y^{-}} \quad (3)$$

$$\textbf{\textit{Convex:}}\ v = \frac{1 - e^{-\gamma x} - y^{-}}{y^{*} - y^{-}} \quad (4)$$

When $\gamma = -\log\left(\frac{\log(1.1 + 0.88(10-\beta))}{\log(x_{\max})}\right)^{2}$ (5)

where γ is the modulator of the exponential function ($1/\gamma$ estimates the interval when the function doubles in value), β is the saturation factor that determines the depth of the curve, y^{-} and y^{*} are the minimum and minimum that can be obtained in the value function, and $x_{\max}$ is the maximum value of the variable in its natural scale.





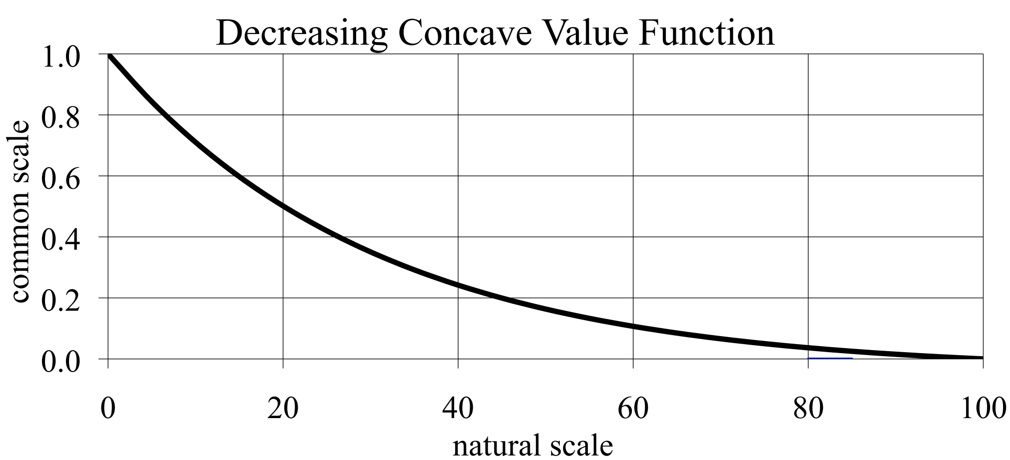
Decreasing. the value for the sector decreases as the variable increases, reaching the ideal value at the lowest point of the range. There are two types of decreasing functions:

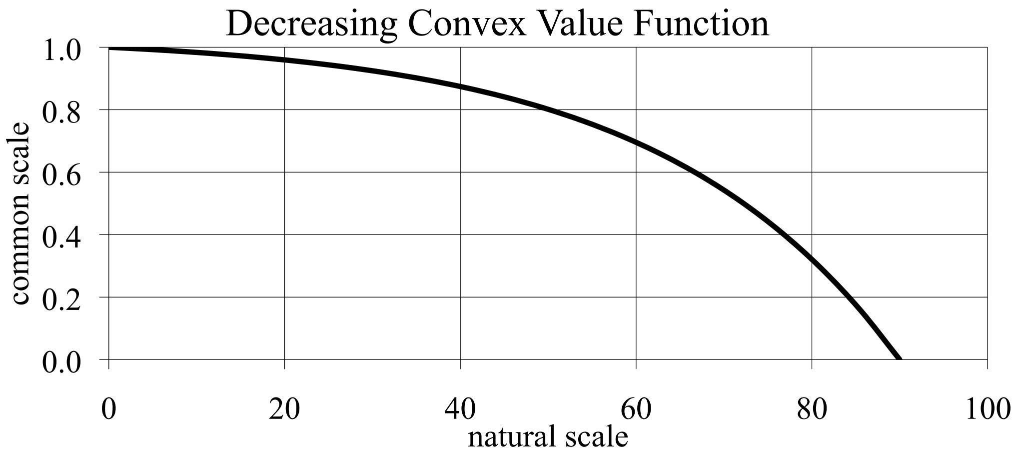
$$\textbf{\textit{Concave:}}\ v = \frac{e^{-\gamma x} - y^{-}}{y^{*} - y^{-}} \tag{6}$$

$$\textbf{\textit{Convex:}}\ v = \frac{1 - e^{\left(\frac{x-30}{\delta}\right)} - y^{-}}{y^{*} - y^{-}} \tag{7}$$

When $\delta = 10^{\left(\frac{3}{10(\log(x_{\max} - \beta))}\right)}$

Where δ is the modulator of the exponential function.



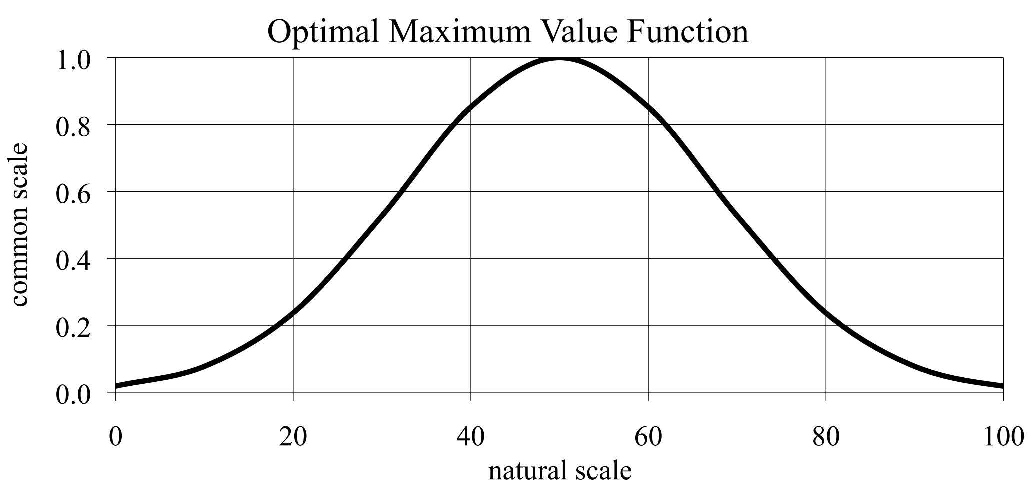


Optimum. This family of curves includes the bell function, in which the value for the sector growers as the variable increases to a point in the middle of its range where it reaches its ideal point, after which the value for the stakeholders decreases as the variable continues to increase until reaching the highest point in its range. Besides the bell curve, it also includes sigmoid relationships.

$$\textbf{\textit{Bell:}}\ v = \frac{e^{-\left(\frac{x - x_{\max}}{\alpha}\right)^2} - y^-}{y^* - y^-} \tag{8}$$

when $x_{\min} < x^* < x_{\max}$

where α is the extent of the bell, $x_{\min}$ is the minimum value of the variable in its natural scale, and x^* is the value of the ideal point of the variable in its natural scale.



Increasing sigmoid:

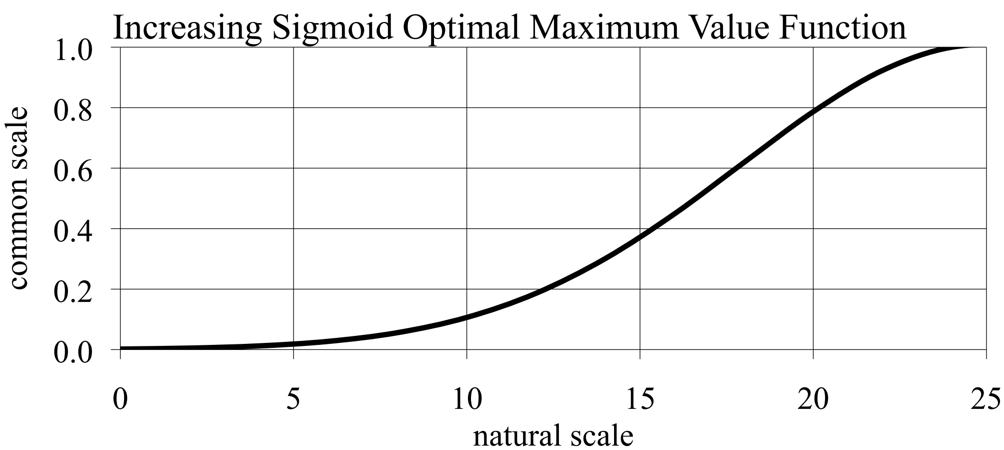
$$\textit{Optimal maximum:}\ v = \frac{e^{\left(\frac{x-x_{\max}}{\alpha}\right)^2} - y^-}{y^* - y^-} \tag{9}$$

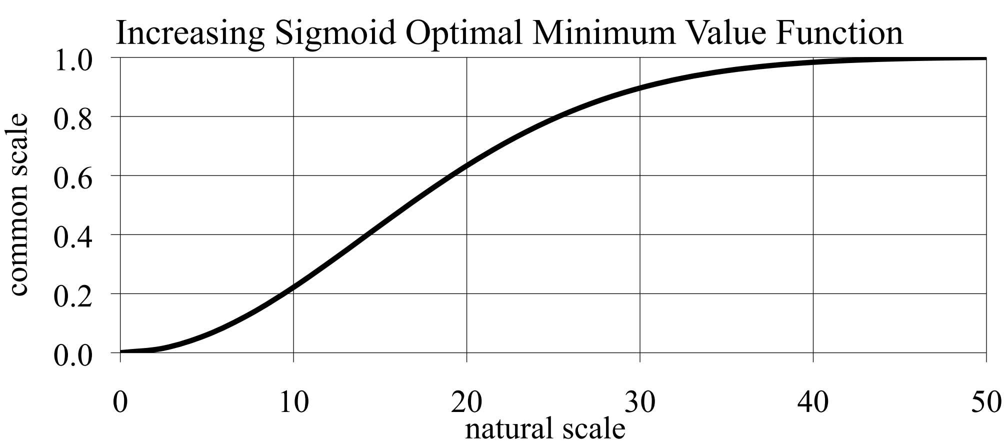
when $x^* = x_{\max}$

$$\textit{Optimal minium:}\ v = 1 - \frac{e^{\left(\frac{x-x_{\min}}{\alpha}\right)^2} - y^-}{y^* - y^-} \tag{10}$$

when $x^- = x_{\min}$

Where x^- is the value of the anti-ideal of the variable in its natural scale.





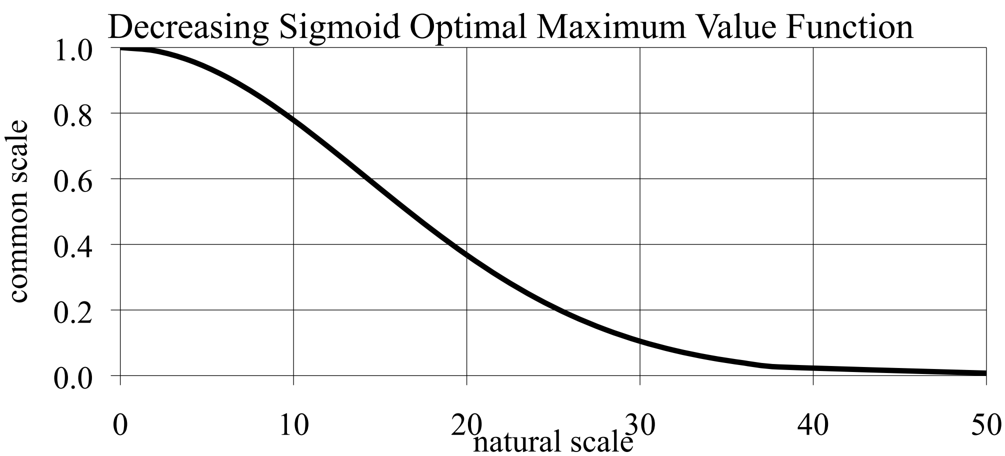
Decreasing Sigmoid:

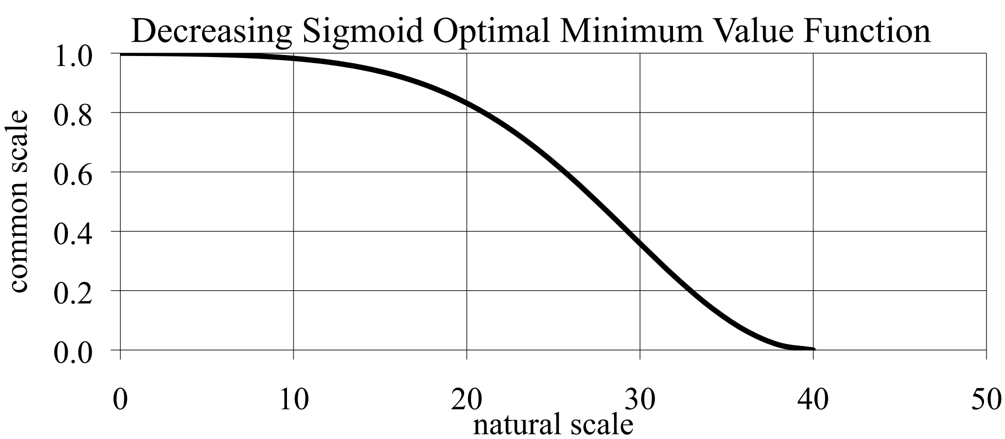
$$\textit{Optimal maximum: } v = \frac{e^{-\left(\frac{x - x_{\max}}{\alpha}\right)^2} - y^-}{y^* - y^-} \tag{11}$$

when $x^* = x_{\min}$

$$\textit{Optimal minimum: } v = 1 - \frac{e^{\left(\frac{x - x_{\min}}{\alpha}\right)^2} - y^-}{y^* - y^-} \tag{12}$$

when $x^- = x_{\max}$





(L. Bojórquez-Tapia, personal communication, July 11, 2011)

APPENDIX G

WEBER-FECHNER LAW OF PSYCHOPHYSICS

The Weber-Fechner Law of Psychophysics describes the relationship between physical magnitudes of stimuli and the perceived intensity of the stimuli. It states that perception is proportional to increases of a stimulus, which can be noticed only after it increases by a constant percentage, known as the "just noticeable difference" or JND. The JND can be interpreted as the smallest increment needed to be able to discriminate among degrees of a stimulus. The relationship between JND and perception is logarithmic: While the JND increases following a geometric progression (i.e., multiplied by a fixed factor, for example, 2), the corresponding perception varies as an arithmetic progression (i.e., in additive constant amounts). In other words, the level of a sustainability attribute has to double in value (i.e., 2^1) in order to be perceived as twice as strong (i.e., 1 + 1), and has to quadruple in value (i.e., 2^2) in order to be perceived as three times as strong (i.e., 1 + 1 + 1).

In formal terms, the category cuts, s_h, are computed with respect to the best state of a stimulus or value of a sustainability factor, s^*:

$$s_h = s^* - s_{h-1} + \frac{\Delta s_{h-1}}{s_{h-1}} s_{h-1} \tag{13}$$

where Δs_{h-1} is the JND.

Since the ratio between the JND and the stimulus is constant, then:

$$s_h = s^* - \left(1 + \frac{\Delta s_{h-1}}{s_{h-1}}\right) s_{h-1} \tag{14}$$

$$r = \frac{\Delta s_{h-1}}{s_{h-1}} \tag{15}$$

and Equation 13 can be rewritten as:

$$s_h = s^* - (1 + r) s_{h-1} \tag{16}$$

and in general,

$$s_h = s^* - (1 + r)^h s_0 \tag{17}$$

where the initial stimulus, ($s_{0,}$) represents the absolute threshold or the smallest detectable level of a stimulus.

The value of s_0 is determined by leaving out s^* from Equation 17 using the upper intensity level, *u*:

$$s_0 = \frac{s_u}{(1 + r)^u} \tag{18}$$

(L. Bojórquez-Tapia, personal communication, July 11, 2011; Lootsma, 1999).