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DYNAMICS OF LIVELIHOOD AND LAND USE/COVER CHANGE IN A TROPICAL SOCIAL-ECOLOGICAL SYSTEM IN THE HUASTECA POTOSINA REGION.

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ABSTRACT

In tropical regions, the dynamics of social-ecological systems (SESs) associated with small producers is characterized by the close interrelation between land use, which is influenced by global, national and local drivers and livelihood development. Understanding the causes of land use dynamics is important, as it may reflect internal and/or external drivers that induce change and thus may be a critical process in achieving sustainable development. Furthermore, it is critical to understand the linkages and dependency between land use change and livelihood development. Smallholder livelihoods change and adapt continuously with land-use change.

Insight into the dynamics of rural SESs is fundamental and requires a complex system's approach, as changes occur unpredictably, non-linearly and system responses are self-organizing and go through different phases of adaptive cycles. In this study, the *ejido* Laguna del Mante (LM), Valles, San Luis Potosi, Mexico is analyzed as a SES considering livelihoods and land use change. In particular, I addressed the underlying question as to "what were the causes of the spatio-temporal dynamics of land use and livelihoods?" and to "which degree were livelihoods adaptive to external disturbances such as climate change, land tenure change or fluctuations in soft commodity markets?". With diverse social-ecological methodologies including semi-structured interviews applied to key stakeholders, life history analysis applied to *ejidatarios*, and observational studies land use and livelihood dynamics were examined.

The historical analysis of the LM-SES demonstrates that the original tropical forest system transformed into a high input livestock enterprise with the arrival of a politically and economically highly influential person. His unexpected death triggered the immediate full collapse of the SES ultimately leading to the foundation of the ejido LM. A cascade of economic (establishment of a local sugar factory, high price of sugarcane, subsidies) and social-political (privatization of ejido land facilitated by the agrarian reform, NAFTA) factors soon converted this smallholder subsistence farming landscape into a sugarcane monoculture, where four distinct livelihood groups developed, yet all principally based on the production of sugarcane. A near-by foreign citrus company introduced wage labor opportunities for the farmers thereby securing their income.

The adaptive cycle as a tool helped to identify the dynamics of this complex SES in LM. In particular, the inclusion of a detailed analysis of the spatio-temporal dynamics of the system serves to demonstrate the influence of important historical political, social, environmental events and the capacity of the system to resist, recover or adapt to external abrupt or gradual disturbances or changes. The current LM-SES, appears to be approaching a biophysical threshold and consequently may lose its ecological and hence social resilience, since the large-scale intensification of sugarcane production is depriving this formerly multifunctional landscape of potential biophysical buffers to resist the effects of soil degradation, drought, pest outbreaks, to name a few and ultimately impoverish the life-support system as a source for livelihood diversification.

RESUMEN

En las regiones tropicales, la dinámica de los sistemas socioecológicos (SSE) asociados con los pequeños productores se caracteriza por la estrecha interrelación entre el uso de la tierra que está influenciado por los factores globales, nacionales y locales y el desarrollo del modo de vida. Es importante comprender las causas de la dinámica del uso de la tierra, ya que puede reflejar factores internos y/o externos que inducen el cambio y, por lo tanto, puede ser un proceso crítico para lograr el desarrollo sostenible. Además, es fundamental entender los vínculos y la dependencia entre el cambio en el uso de la tierra y el desarrollo del modo de vida. El modo de vida de los pequeños agricultores cambia y se adapta continuamente con el cambio en el uso del suelo.

La comprensión de la dinámica de los SES rurales es fundamental y requiere un enfoque de sistema complejo, ya que los cambios ocurren de manera impredecible, no lineal y las respuestas del sistema son autoorganizadas y atraviesan diferentes fases de ciclo adaptativo. En este estudio, se analiza el ejido Laguna del Mante (LM), Valles, San Luis Potosí, México como un SSE, teniendo en cuenta los medios de subsistencia y el cambio en el uso del suelo. En particular, abordé la pregunta subyacente sobre ¿cuáles eran las causas de la dinámica espacio-temporal del uso del suelo y el modo de vida? y ¿en qué medida el modo de vida era adaptable a perturbaciones externas como el cambio climático, el cambio de tenencia del suelo o las fluctuaciones en mercados de productos básicos?. Con diversas metodologías

socioecológicas que incluyen entrevistas semiestructuradas aplicadas a actores claves, análisis del ciclo de vida aplicado a los ejidatarios y estudios observacionales, se examinaron el uso del suelo y las dinámicas de los medios de subsistencia.

El análisis histórico del LM-SSE demuestra que el sistema original de bosques tropicales se transformó en una empresa ganadera de alto ingreso con la llegada de un latifundista de gran influencia política y económica. Su muerte inesperada desencadenó el colapso total inmediato del SSE que finalmente condujo a la fundación del ejido LM. Una cascada económica (establecimiento de una fábrica azucarera local, alto precio de la caña de azúcar, subsidios) y sociopolítico (privatización de la tierra ejidal facilitada por la reforma agraria, TLCAN) pronto convirtió este paisaje agrícola de subsistencia de pequeños agricultores en un monocultivo de caña de azúcar, donde se desarrollaron cuatro grupos distintos de medios de subsistencia, aunque todos basados principalmente en la producción de caña de azúcar. Una empresa extranjea cercana de cítricos introdujo oportunidades de trabajo asalariado para los agricultores, asegurando así sus ingresos.

El ciclos adaptativo ayudó a identificar la dinámica de este complejo SSE en LM. En particular, la inclusión de un análisis detallado de la dinámica espacio-temporal del sistema sirve para demostrar la influencia de importantes eventos históricos políticos, sociales, ambientales y la capacidad del sistema para resistir, recuperar o adaptarse a perturbaciones externas abruptas o graduales o cambios. El LM-SSE actual parece acercarse a un umbral biofísico y, en consecuencia, puede perder su resiliencia ecológica y social, ya que la intensificación a gran escala de la producción de caña de azúcar está privando a este paisaje, anteriormente multifuncional, de posibles amortiguadores biofísicos para resistir los efectos como la degradación del suelo, la sequía, los brotes de plagas, para nombrar unos pocos y, en última instancia, empobrecer el sistema de soporte vital como una fuente de diversificación de modo de vida.

THESIS STRUCTURE

In Chapter I, I introduce the context of the thesis, the justification, objectives and investigation area.

In Chapter II, I introduce the concept of social-ecological systems, including social-ecological resilience, the adaptive cycle metaphor and livelihood development and how they can be used as a conceptual framework to analyze local SES dynamics. An integrated analysis of SESs considers i) the interplay of internal and external factors and their role, ii) potential thresholds, whose crossing may shift the system into an undesirable state, and iii) cross-scale spatial and temporal interactions. Ultimately, an SES approach is the basis to achieve ecosystem or landscape stewardship in that it enhances the sustainable use of natural resources and ecosystem services, and simultaneously aims at maintaining resilient livelihoods.

In the Chapter III, I apply the adaptive cycle as a tool to examine the historical spatiotemporal changes. I demonstrate how integral knowledge on the historical development of a 60-year old social-ecological system (SES) helps to build fundamental understanding of the resilience, and adaptability, of land and people (livelihoods).

In Chapter IV, I identify and characterize livelihood groups associated with the change of a traditional agricultural landscape to a monocropping system. In particular, I examined how socioeconomic, political, institutional, and biophysical drivers contributed to differentiation in livelihood development. I found, that each of the four livelihood groups depends on wage-labor in nearby factories, which reduces the resilience of all identified groups to unpredictable external drivers such as pest outbreaks, shifting markets, climate change, among others.

In Chapter V, I draw general conclusions of the analysis of spatiotemporal dynamic. I could demonstrate, that with the adaptive cycle we could understand and identify the short- or long-term impacts of socio-political-economic drivers in LM and how the system developed four different drivers.

Chapter I

INTRODUCTION

Global effects of environmental and social change, including climate change, land use change, urbanization, migration and globalization, etc., in the last six decades have drastically influenced the condition, distribution and availability of natural resources (Steffen et al., 2007; Steffen et al., 2015) and people's lifestyles (Ribeiro Palacios et al., 2012). Over the past 60 years, the growing interlinkage between the social and ecological dimensions of a multipurpose, multifunctional landscape have become increasingly apparent. Humans have benefited from the goods and services ecosystems provide, however this has often caused severe changes in ecosystem structure and function, with controlling feedbacks on human activity and livelihood development (Foley et al., 2005; Steffen et al., 2007).

When the human (social, economic, cultural, political) and biophysical (climate, biodiversity, ecosystem function) dimensions of a system are strongly interrelated, it has been proposed to take a social-ecological systems (SES) approach, as the dynamics of these SES are highly complex, and adaptive to shocks or unexpected events (Berkers et al., 1998). The SES framework was proposed in 2007 (Ostrom, 2007) to explain the interrelation and dynamics between ecological services and human well-being and balancing resource use and ecosystems maintenance in a constantly changing world (Foley et al., 2005; MEA, 2005). The SES framework seeks to understand the human being as an independent variable, that can take decisions consciously, as an individual or in a group, and thereby influence the outcome of SES processes (Ostrom, 2007; McGinnis et al., 2014).

An SES consists of the ecological and social subsystems, each with its own structures, functions, and variables, but with a strong interaction between them, causing SES to be highly dynamic (Berkers et al., 1998). Each component may react to external changes, hence it is said the whole system reacts in an adapting way. Based on this behavior, the system is considered to be a complex adaptive system (Chapin et al., 2009), which passes through the adaptive cycle (Holling, 1986) by the influence of disturbances (e.g., climate change, market forces), thus causing changes in controlling variables of a SES (Walker et al., 2004a; Armitage et al., 2012). The original intent of the adaptive cycle framework was to explain changes of a dynamic ecosystem considering the phase of growth and exploitation of resources followed by the phase of conservation of accumulated capital (Holling, 1986). Later the adaptive cycle also was applied in social structures, institutional settings, and ecological systems (Gunderson et al., 2002) to understand abrupt and nonlinear changes of a system (Walker et al., 2006).

The adaptive cycle considers different phases of the dynamic of a system: the generation, the conservation, the collapse, and the reorganization. After the impact of an external driver, a well-developed mature system with clear rules and regulations (conservation phase, *K*) may collapse (release phase, Ω) and liberate resources and energy from previously accumulated capital (natural, social, economic). Depending on the environmental, social, political, and institutional conditions and contexts, once the system re-establishes (reorganization phase, *α*) it may adopt a new system state or return in a slightly modified fashion to the previous state, in both cases with similar system structure and function (Gunderson et al., 2002; Huber-Sannwald et al., 2012). Growth, development (regeneration phase, *r*) and accumulation of resources will then lead the system to the stage, where social and/or natural capital build up and become conserved (conservation phase, *K*) (Gunderson et al., 2002; Holling, 1986; Alliance, 2002). With the adaptive cycle also the change of the resilience of a system can be described. Typically, the resilience of a system is high at the *r* phase, it declines in the advanced *K* phase, and increases in the transition from the *Ω* to *α* phase (Walker et al., 2012).

The adaptive cycle of Holling (1986) has been applied for historical analysis of system changes (Huber-Sannwald et al., 2012; Abel et al., 2006; Salvia et al., 2015). Understanding the history of a locality can support in decision-making processes and thus potentially prevent, adapt to and/or mitigate potential future disturbances (Costanza et al., 2007). Different temporal and spatial processes at the scale of the SES may interact with exogenous drivers (i.e. external factors influencing the system) (Walker et al., 2012) and contribute to current system dynamics (Rockström et al., 2009). An important factor in the context of spatiotemporal changes and land use type is land tenure and property rights. They may change over time for various political, institutional or other reasons (FAO, 2002) influencing the use, management, and hence the productivity of the land (Bonilla-Moheno, 2013). Understanding past land tenure and land management practices are essential for current land system use (Dearing et al., 2010).

Almost 40 % of the world population depends on agriculture for their livelihoods (FAO, 2014). Often, small-scale farming has to be supplemented by income from non-farm activities (Ellies, 2016). Predominantly in developing countries, smallholder agriculture is the principal source of income (Cornish, 1998). Due to the small size of those farms, they can't adapt risks easily (Lal, 2000) associated with drought, flooding, crop and animal disease, and market shocks (FAO, 2016). To compensate risk, farmers may consider income diversification (Wan et al., 2016) and participate in off-farm and/or nonfarm[1] activities (Ellis, 2000; Barrett et al., 2001). Neoliberal markets have forced many small-farmers to become proletarians or semi-proletarians (Kay, 1997; Huber-Sannwald et al., 2012; Ribeiro Palacios et al., 2012) such that in many rural areas non-farm activities have become increasingly important (Rigg, 2005; Davis et al., 2010), which however has caused a decline in agricultural areas (Davis et al., 2010).

When neoliberal currents emerged in the national and global economy between 1977 and 1992, tropical Mexico experienced massive deforestation with annual rates of 559,000 ha / year (Cairns et al., 2000). In northeast Mexico, in the geographical region of the Huasteca, by 2011, approximately 80% of the total tropical forest had been deforested to obtain arable land for agriculture and livestock (Peralta-Rivero et al., 2014a; Peralta-Rivero et al., 2014b)

Huasteca Potosina is an ecologically and socially highly diverse region (Miranda-Aragón et al., 2012; Reyes-Pérez et al., 2012; Soriano et al., 2011), approximately 90% of rural households are involved in farming activities, this reflects about the worldwide percentage of farming households [2] (Davis et al., 2010). This region has been affected by climate change with frequent droughts, fires, torrential rains, and high temperatures, which together increases the vulnerability of its inhabitants

[1] Off farm income refers to labor on other farms; Non-farm income refers to non-farm income (Ellis, 1998).

[2] A household can be defined as human groups which share the same roof and resources. Categories of a household include: • People—that is, the individuals and their livelihood capabilities. • Activities—which encompass what they do. • Assets or possessions—this is what they own be it food, property, clothing, houses, livestock, stocks and all things that provide material and social income. • Gains and outputs—These are the resources derived from what they do that allows them to earn a living. (Ellies, 2016)

(Newsham et al., 2012) and agricultural production systems on which their livelihoods depend on.

The ejido Laguna del Mante transformed from a tropical forest system to vast sugarcane monocultures and lemon tree plantations; the area is divided in two longitudinal sections: the protected area Sierra del Abra Tanchipa Biosphere Reserve in the east and intensive agriculture and pasture land in the west.

JUSTIFICATION

Understanding social-ecological system dynamics requires an interdisciplinary approach considering subdisciplines of the social and natural sciences. For instance, the development of agriculture-based livelihoods depends on land cover/use change. Farmers do not only cause but also respond to ecological changes, especially when their livelihoods are affected (Moerlein et al., 2012). Livelihood refers to the means of living considering food and income (Chambers et al., 1991). Furthermore, it includes the people's strategies to adapt to changes triggered by internal or external influences and local knowledge on natural resources, on which local human well-being is depending on (Ashley, 2000; MEA, 2005).

Maintaining long-term multifunctional landscapes requires the adoption of an integrative sustainability framework with the focus on human-environmental interactions; however this framework specifically designed for local conditions is still lacking. Also, social innovation research, a key component of the proposed sustainability framework does not seem to fully consider the social-ecological dynamics (Olsson et al., 2017). Olsson et al. (2017) point out the urgent need for innovation research and practice to elucidate the complex underlying mechanisms in the social-ecological systems dynamics, otherwise we will not be able to improve social inequality and/or generate multifunctional landscapes. With this SES case study, we hope to contribute fundamental understanding of social-ecological system dynamics and thereby provide clear insight for innovative stewardship of multifunctional landscapes.

With the growing need of managing natural resources at the landscape scale (Ager et al., 2015), understanding the interaction between humans and landscapes is paramount (Kline et al., 2017). Changes in international or regional economic markets trigger changes in the use of natural resources which ultimately feedback on livelihood types. The integration of social and ecological approaches is essential to understand these feedbacks and cross-scale drivers (Hoque et al., 2017),however their influence on the well-being of social actors and interest groups has not been sufficiently studied (Tucker et al., 2015). In this context, interest in understanding system resilience is increasing as well as the definition of desirable states of regimes for whom (Carpenter et al., 2001; Hoque et al., 2017). With this case study, we identify resilient production systems and their social-ecological contexts.

RESEARCH QUESTION

How resilient has a young social-ecological agriculture based system been to external biophysical and socio-economic drivers and to which degree have monocropping systems contributed to the homogenization of livelihood groups and to the loss of the multifunctionality of this tropical landscape in the social-ecological system Laguna del Mante?

GENERAL OBJECTIVE

To analyse spatiotemporal dynamics of livelihood development and land use/cover change of Laguna del Mante social-ecological System (LM-SES) considering external and internal factors associated with environmental and social changes and to characterize the main local livelihoods.

INDIVIDUAL OBJECTIVES

1. To identify key concepts and theoretical frameworks that permit an integral analysis of a tropical landscape transformation during the time of the Great Acceleration.
2. To analyse the historical effects of political, economic, social, institutional and biophysical drivers at local, regional, national and global scales on the structure, function and resilience of the developing LM-SES.
3. To identify the main livelihood types, and it´s relationship with land cover/ use change.
4. To examine the current state of LM-SES and its resilience to current and potential future external drivers.

RESEARCH AREA

The *ejido* Laguna del Mante is located in the Northeast of Mexico, in the tropical region called Huasteca Potosina (22° 12' 0" LN, 98° 53' 0" LW) in San Luis Potosi state, at an elevation of 296 m. a. s. l. (CONANP-GIZ, 2012) (Figure 1). The study area is located between the Sierra de Abra Tanchipa in the East, and the Sierra Tigre in the West. The climate is warm sub-humid with the main rainy season between July and September and sporadic precipitation events falling between November and March. Mean annual precipitation is 965 mm (± 209 mm S.E.) (INEGI, 2009; CONANP, 2013a). The topography is characterized by plains and gentle rolling hills and karstic relief (Newsham et al., 2012). Soil types are mainly Phaeozems and in the western part Histosols; near the La Lajilla dam, Gleysols and Rendzina can be found. In the Sierra de Abra Tanchipa,Phaeozom, Lithosols and Rendzinas are present (CONANP, 2013a; CONABIO, 2012).

This area was originally covered by tropical deciduous forest (Peralta-Rivero et al., 2014a) with *Bursera simaruba, Lysiloma divaricata,* and *Phoebe tampicensis.* The landscape is currently characterized by fragments of secondary forest (predominantly by *Sabal mexicana* and *Guazuma ulmifolia* (Rzedowski, 2006)) embedded in a matrix of sugarcane plantations, abandoned agricultural fields, citrus plantations, pastures, *milpa* (traditional polyculture system mainly used for corn production at subsistence level).

Sixty percent of the biosphere reserve “Sierra Abra Tanchipa” (21,464 ha) is located within the limits of the *ejido* LM at the eastern part of the municipality. The La Lajilla dam (28,000 m^3) is located in the northern region of LM. The Biosphere Reserve Sierra del Abra Tanchipa is in the communal land of the LM *ejido*, however as protected area it has certain restrictions regarding its use; e.g. hunting, logging, land use change and the use of fire (CONANP, 2013a).

In 2017, agricultural production of the LM-SES included 55% sugarcane, 16% livestock, 21% pure corn, and 8% mixed corn and beans. In the north, land use is dedicated to livestock farming, in the centre and west it is dedicated to sugarcane, corn and bean production. Corn and bean are used for personal consumption, while sugarcane and livestock are mostly used for commercial purposes.

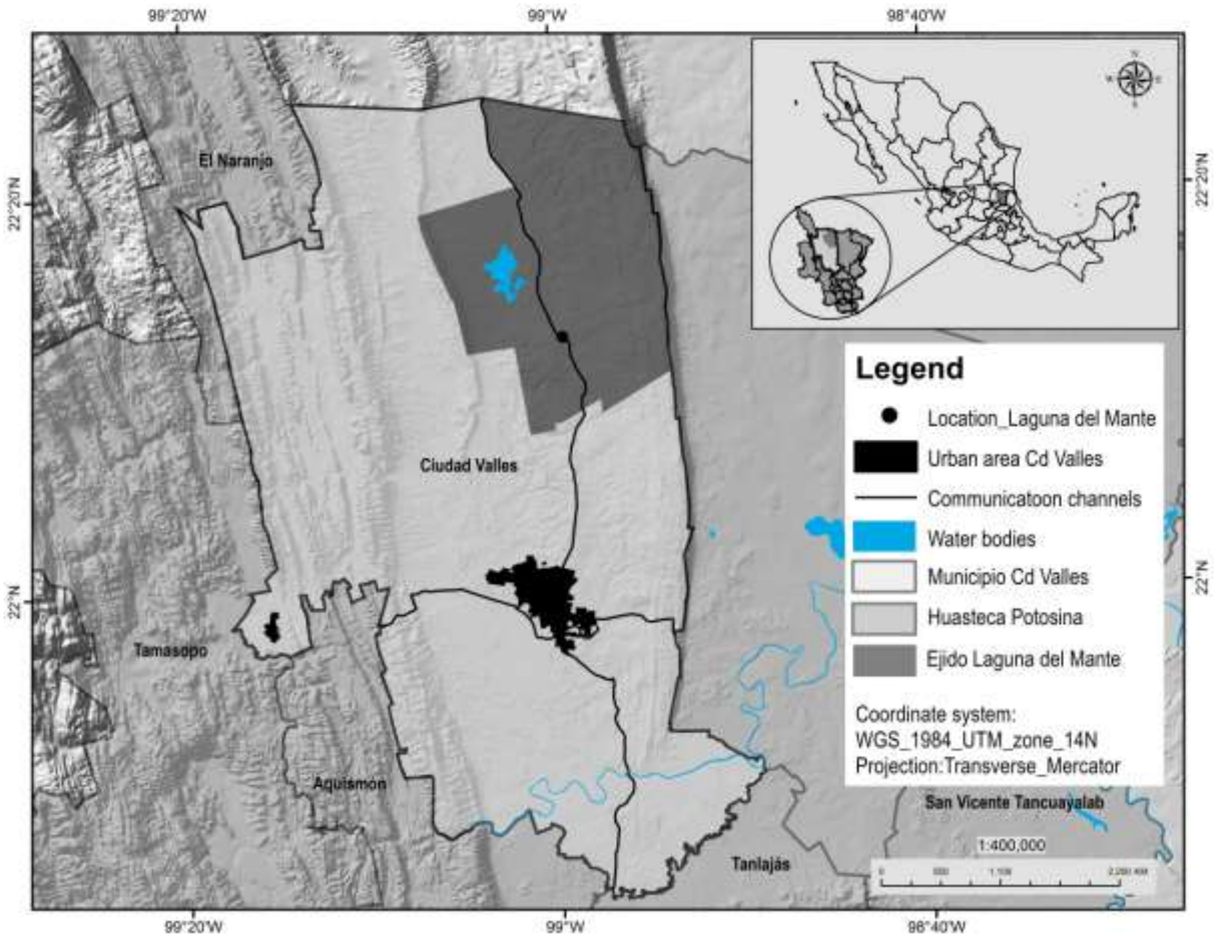

Figure 1: Study area

In 2010, LM had 2,036 inhabitants (SEDESOL, 2013), most of whom are mestizo and 13% indigenous (Teenek and Nahuatl); only 41% of the population was economically active (INEGI, 2010). Of the total population, 23% are *ejidatarios,* which means they are men or women holding special rights and tenure yet no private possession over the common land (Ley Agrario, 1993). Before 1992, the land was governed communally. Since 1992, part of the *ejido* went over into private possession. The majority of *ejidatarios* (62%) possess up to 60 ha, but only 13% of them cultivate all of their land, as access to remote land may be difficult (being up to 30 km from the village) or due to high investments being required in order to start agricultural activities.

Predominant economic activities are the cultivation of sugarcane for a nearby sugar factory, wage-labour in lemon plantations of a local citrus fruit company, wage-labour opportunities in the nearby town of Ciudad Valles, fishing and livestock breeding for local markets, and participation in government programs such as guards of the

Biosphere Reserve Sierra de Abra Tanchipa or fire fighters. By 2005, 5% of the population had migrated (INEGI, 2010), mostly to North America.

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Review article

Condition, Tendency, and Dynamic Interactions in a Resilience Context of a Social-Ecological System

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Abstract

In this paper we will analyze the dynamics of a social-ecological system (SES), which requires an integrated understanding of both the interrelatedness of biophysical and socioeconomic components and the adaptive capacity of these system's components to external drivers. Social-ecological resilience, the adaptive cycle metaphor and livelihood development are presented as the guiding conceptual framework to analyze local strategies, aiming towards the sustainable use of natural resources and to encourage the participation of the community in the management of ecosystem services, thereby improving human well-being. Furthermore, in the light of recurring unpredictable changes, adaptive capacity building and a high responsiveness to these changes may serve as fundamental assets to increase both ecological resilience, including the protection of biodiversity, and social resilience, including social and human capital and institutional capacity. An integrated analysis of SESs considers i) the interplay of internal and external factors and their role in SES dynamics, ii) potential thresholds whose crossing may shift the system into an undesirable state, and iii) cross-scale spatial and temporal interactions. Ultimately, an SES approach favors ecosystem stewardship in that it enhances the sustainable use of natural resources and ecosystem services, and simultaneously resilient livelihood development.

1. Introduction

Over the past six decades, the effects of global environmental change (climate change, land use change, loss of biodiversity, invasion of exotic species) and social change (urbanization, migration, globalization) have had a drastic impact on the distribution, availability and condition of natural resources and ecosystem goods and services **[1]**, **[2]**. In particular, human appropriation of land and continuous land use change are currently the leading global change drivers due to pressing needs to support more than seven billion people with food, fiber, forage, water, and shelter. Without changes in land use policies, deforestation, land conversion, intensification of agriculture, exploitative water use, and air pollution may continue and likely negatively influence ecosystem functioning and will in the long-term jeopardize the provision of ecosystem goods and services **[3]** with direct impacts on human wellbeing **[4]**.

These complex conditions emerge from continuous interrelations and feedback among the socio-economic and biophysical components of these land use systems and thus require a conceptual framework that fully integrates both human and ecological dimensions. The concept of a complex social-ecological system (SES) was first introduced by Berkes and Folkert in 1998 to address human's dependency on ecosystem goods and services and the reciprocal influence of ecosystem dynamics on human decision-making, including terrestrial and aquatic systems. A SES consists of the subsystems of nature and humans, with all their biophysical and social-cultural-political-economic characteristics, respectively. Each subsystem has its own inherent elements, structures, functions and interconnections, which are changing over time. The subsystems are coupled, in that they are interrelated and interacting, while the nature, dynamics, and strength of interaction(s) may change over time in a non-linear fashion [5, 6]. These ecological and human subsystems are also self-organizing and highly adaptive in response to internal or external biophysical and socioeconomic drivers of change **[5]**.

Hence, when considering production systems as SES, natural resource management requires not only fundamental understanding of the context in which the ecosystem functions but also its link to the cultural, political, social, economic, and technological aspects of system dynamics, as well as their feedbacks and impacts on human well-being **[6]**. Non-linear changes, unpredictable events, cross-scale interactions, and approaching thresholds of key variables are some of the underlying sources of system dynamics and inherent features of SES. For this reason, the management of an SES needs to consider multiple sources of dynamics and potential disturbances. It should also take into account a system's capacity to absorb the effects of a disturbance event without losing its structure and function, i.e. its resilience. Since SES are constantly changing at different rates and scales, management decisions need to be flexible and adaptive and not necessarily maximize production but rather enhance a system's capacity to maintain itself **[6]**. To reach this goal, the whole SES must be analyzed and fully understood, especially key interactions and relationships among social and environmental factors, including social vulnerability to unpredictable change. Novel sustainable management of SES needs to include the maintenance of resilience of favorable system states; this integrative approach has been termed ecosystem stewardship **[7]**, an inclusive framework addressing the capacity of the system to cope with and adapt to change and simultaneously consider options for innovation and renewal **[8]**.

This review identifies, characterizes and links the fundamental concepts that need to be considered, monitored and evaluated to understand the condition, tendency, and interaction dynamics of SES. In the following sections, we will explain the characteristics of an SES system and present the necessary conceptual and operational framework to analyze and manage these systems. We will highlight the importance of ecosystem services, livelihood development, adaptive capacity, capacity building and how they are necessarily linked.

2. Characteristics of the social - ecological system

The dynamics in an SES originate from two major sources **[9]**. On the one hand both the biophysical and socioeconomic subsystems consist of a series of slow and fast variables and processes **[10]**. The difference between the two resides in the rate of change: the dynamics of fast variables are detectable on a monthly to yearly basis, while those of slow variables act at a decadal to century scale. Each SES is in a sense idiosyncratic in that it has its own set of key slow variables that are responsible for system change. Examples of slow biophysical variables are perennial vegetation cover, plant species composition, soil organic matter content, and soil depth, while fast biophysical variables are annual precipitation, soil water content, inorganic nitrogen concentration in soil, or primary production. In the socioeconomic dimension, examples of slow variables are quality education, social networks, local environmental knowledge, while examples of fast socioeconomic variables are annual income, subsidy programs, commodity prices or annual crop yield **[11]**. It is important to identify the key slow variables that directly control the dynamics of SES and thereby, in turn, influence the rate of change of many fast variables **[6]** Conventional natural resource management focuses on the dynamics of fast variables, such as forage, crop or livestock production, as they are typically of primary interest. However, by managing fast variables, the slow variables of a system are also affected directly or indirectly **[12]**. The second source of system dynamics is the exogenous drivers that do not form part of the SES of interest, though they exert change on the dynamics of the system **[9]**. Examples of exogenous biophysical and socioeconomic drivers are climate change, invasion of exotic species, globalization, and change in legislation or policies. They may be stable for long periods of time.

It is important to distinguish between variable types and understand system dynamics and stability. Within a stable state of a system, one or more controlling variables of that system state may be changing beyond a certain range; here the system is said to be nearing or crossing a threshold of a certain system state and may enter an alternative state. An alternative state of an SES may be equally stable with different elements but similar functions and structure as the previous stage, but an alternative state of an SES may also be less favorable to a land user or other interest groups **[13]**. An SES can adopt several different states within what is termed a certain regime **[14]**; this depends on the biophysical and socio-economic buffer of a system **[15]**. Buffers may decline, e.g. through the loss of genetic or species diversity or the loss of human capital. In this case a certain SES has lost the response and/or adaptive capacity to external drivers, and a drastic change in one or several key slow variables may push the whole system across a "critical threshold" into a new regime **[16]**-**[18]**. This transition of the system is called "regime shift" **[19]**, **[20]**. A regime shift causes dramatic functional and structural changes in the system, such as the shift from clear to turbid water in a lake or the conversion of a natural grassland into shrubland **[19]**.

3. Resilience

A key characteristic of an SES in relation to its sustainability is the "resilience" **[21]** of a system **[22]**, **[12]**. Resilience refers to the magnitude of change or disturbance a system can absorb without losing its structure, function and feedback processes; for instance, without losing the potential to providing ecosystem goods and services for the well-being of humans **[23]** including the livelihoods of smallholders.

When addressing the resilience concept in relation to SES it is necessary to always specify 1) what type of resilience one is referring to, e.g. ecological, social or social-ecological resilience; and 2) in what potential context of change. In other words, it is necessary to explicitly define "resilience of what and to what" in the light of potential changes, considering temporal, spatial and/or organizational scales **[21]**. When addressing the resilience of a system, it is necessary to focus on slow variables. It is also important to consider that the resilience of a certain state of SES may be desirable or undesirable (for instance, once a regime shift has occurred) for humans, depending on the social-ecological context.

In an SES, social and ecological resilience must be considered simultaneously because of the strong interconnectedness among subsystems. Social groups such as smallholders or communities directly depend on natural resources for their livelihoods. However, resilient ecosystems do not guarantee resilient societies and vice versa. Social resilience including the adaptation of individuals or social groups to environmental, socio-political, and/or socio-economic changes is crucial for the maintenance of rural livelihoods **[24]**. Resilience of livelihoods implies a high degree of adaptability in organization, management and iterative learning **[22]**. Livelihoods remain resilient to disturbances as long as key aspects including food security, reliable income, employment, and health are secured without affecting the reproduction and well-being of people.

4. Social-ecological system dynamics and the adaptive cycle metaphor

The notion of a system being adaptive was originally coined to recognize the highly unpredictable nature of ecological systems **[25]**. Its application has been extended and applied when considering the management of complex systems such as SES **[6]**. Complex systems are self-organizing, change non-linearly, have emerging properties and are unpredictable **[16]**. Hence, the breakdown of a system after a severe or extreme disturbance event may generate new possibilities for continuous development **[26]** in that the system recovers and self-organizes by passing through a series of adaptive (renewal) cycles **[27]**. Holling's (1986) adaptive cycle consists of four phases: exploitation phase (r phase), conservation phase (K phase), collapse/release phase (omega; Ω – phase, corresponding to the end) and reorganization phase (alpha; α - phase, corresponding to the beginning) **[16]** (**Figure 1**).

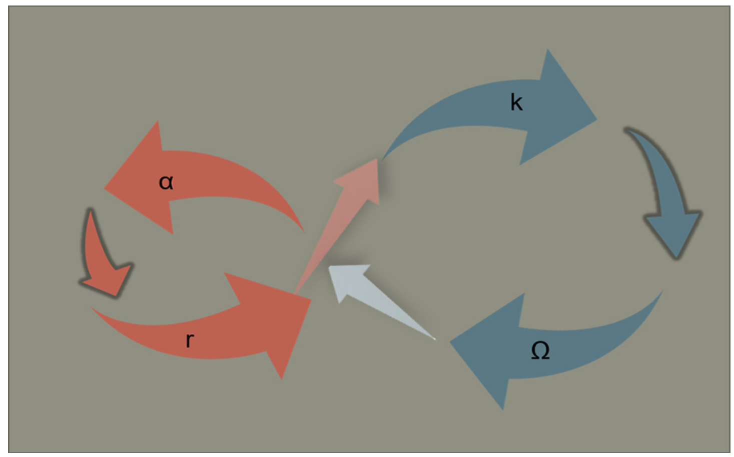

Figure 1: The adaptive cycle modified after (Holling, 1986): The figure shows the four phases of the adaptive cycle: exploitation phase (r phase), conservation phase (K phase), collapse/release phase (omega; Ω – phase, corresponding to the end) and reorganization phase (alfa; α - phase, corresponding to the beginning).

After a disturbance event a system can recover its previous state or adopt a new state depending on its accumulated resources **[13]**. Usually system recovery follows phase changes in the order of r, K, α and Ω. During the exploitation phase (r), the system grows (people, animals, and plant species) given a relatively high availability of resources and new opportunities. In this phase, system elements are weakly connected and/or regulated. When reaching the conservation phase (K), energy becomes increasingly conserved and material accumulates following certain rules. Targeting stabilization and efficiency of the system comes at the cost of losing system flexibility and resilience. However, by removing redundancies and maximizing outcome the system becomes increasingly vulnerable to unpredictable destabilizing extreme events, which may cause the system to collapse (Ω phase). This phase releases all resources and energies that were previously rigidly locked in the system and transitions to the phase of reorganization (α phase), with undefined open results. This means the system reorganizes to the previous state or develops to an alternative (new) state **[14]**.

Adaptive management provides a framework that recognizes and considers the changing phases of a system **[28]**. Huber-Sannwald *et* *al.* **[15]** mention that short-sighted management practices often interfere with the adaptive cycle in a way that disregards system dynamics. Moreover, recognizing that the transition from the K to Ω phase is inevitable opens opportunities to guide the system into renewal at an early K stage to avoid the collapse of a highly rigid system. The renewal of a system can also offer opportunities for alternative, new management strategies **[29]**. Systems considering adaptive management as a strategy require systematic monitoring of key (slow and fast) variables and iterative evaluation of the impacts of disturbance and management on these variables and system performance. That way it is possible to understand feedback responses and potentially to adjust to new emerging social-ecological conditions and also to continuously inform policy development for the system **[30]**.

5. Ecosystem services link nature with human-wellbeing

Ecosystem services (ES) refer to the diversity of structures, functions and processes associated with natural ecosystems and the benefits they deliver to society **[31]**, **[3]**. According to the Millennium Ecosystem Assessment[1], ES are classified into four categories: provisioning, regulating, supporting and cultural **[3]**. While there exists a large number of studies on the role of land use in ecosystem services, researchers rarely consider all four categories of ES. Raudsepp-Hearne *et al.* **[32]** proposed the concept of ecosystem service bundles, i.e. a set of positively correlated ES, as the adequate approach to identify, analyze and manage ecosystem services in a spatially explicit context with clear trade-offs and synergies among the ecosystem services. However, planners and decision-makers are frequently unaware of the existence of the costs and benefits associated with integrated ES management **[33]**. Direct ES are those benefits derived from an ecosystem that are directly used by an economic agent (e.g. consumptive uses like harvesting goods) and non-consumptive uses (e.g. enjoyment of scenic beauty). In this case, the services are physically present. In contrast, indirect ES are those benefits derived from an ecosystem that are indirectly used by an economic agent and are not physically present where used (e.g. an agent at some distance from an ecosystem may derive benefits from drinking water that has been purified as it passed through the ecosystem) **[3]**, **[34]**.

The benefits of the ES that humans select or invest in are directly related to their activities and the purpose of the land use. Thus, consideration of an ampler use of ES could potentially result in a greater portfolio of benefits. People may increase the benefits of provisioning ES by investment into infrastructure, fertilizer use, irrigation, labor, or time. Moreover, the transformation from offered ES (i.e. the totality of ecosystem contributions that may provide benefits to humans today and/or in the future) into utilized ES requires deliberate and conscious actions and decision-making **[3]**, **[35]**. Von Haaren *et al.* **[36]** suggest that by adopting an integrated approach to ES, full understanding of the potential of this transformation may ensure that management of ES also includes unused services (i.e. offered but not used services). As landscape planning also influences the delivery of ES and thus human well-being, adequate knowledge of the full spectrum of ES by decision-makers is needed as well as policies that guarantee the sustainable use of ES. According to Mascarenhas *et al.* **[37]**, many decision-makers in landscape management know about the ES concept and its importance in spatial planning; however, this knowledge is frequently ignored in decision-making processes **[38]**, **[33]**. DeGroot *et al.* **[39]** stress the importance of incorporating ES in natural resource management and/or conservation planning. However, there remain doubts as to the usefulness of the concept of ES in the management of a region, for example because of a lack of knowledge about the ES and awareness of the opportunities and constraints of the concept of ES **[33]**, **[40]**.

The ES concept can be used as an economic test in debates between politicians and executives in decision-making processes **[33]**, **[40]**. On the other hand, the use of the concept of ES with an economic label (payments of ES) may be counterproductive in political decision-making, as a single-sided focus of ES on the economy will likely simplify the complexity of ecosystems **[41]**. This could mean that the ES concept does not take into account the complexity of an ecosystem, and this simplification may lead to the loss of the functioning of ecosystems, which may harbor additional significant biological and/or cultural wealth **[42]**, **[43]**. Undoubtedly, incorporation of the ES concept in decision-making processes may appear complex, particularly when actors are not fully familiar with this integrative approach. This calls for novel partnerships among the scientific community, land users and policy makers. For instance, in agricultural areas, apart from achieving high crop yields, integrated ES-focused management can also reduce pest infestation and effectively control soil erosion **[33]**.The importance of social participation and legitimacy in decision-making processes has to be further discussed **[40]**, as participation in decision-making processes is crucial to obtaining positive political outputs **[44]** and in this case improving the conservation of ES **[45]**. Finally, the concept of ES could simply be seen as a great opportunity to communicate complex issues related to nature and human well-being to a broad group of stakeholders in political, social, economic and environmental realms **[41], [40]**.

6. Rural livelihood development

According to Chambers and Conway **[46]**, people's livelihood refers to their means of living, food, income and assets and also includes knowledge about the natural resources that support their well-being and the strategies they adopt in response to changes in internal or external influences. A variety of determinants of a certain livelihood exist, such as birth place, gender, economy, society, and environment, and it is further influenced by education or migration of the people. A livelihood is considered sustainable as long as it can cope with and recover from shocks and maintain or enhance itself now and in the future, while not negatively affecting the natural resources a as their life-support system **[46]**.

1 The Millennium Ecosystem Assessment (MA) was called for by the United Nations Secretary-General Kofi Annan in 2000. Initiated in 2001, the objective of the MA was to assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being. [3]

The sustainable livelihood framework (SLF) identifies five assets or building blocks of livelihood: the social, the human, the natural, the financial and the physical capitals **[47]**. These five assets are in direct interaction with political institutions or processes influencing the livelihood strategy people adopt. They also influence livelihood outcomes, such as income, food security and the use of natural resources **[48]**. The use of the SLF as an analysis tool permits the understanding of the connection between social elements (cultural, political, and economic) and biophysical factors in a particular livelihood. It conceptualizes the local system by considering how the macro level (i.e. societal or governance system) influences the micro level (e.g. individual users, consumers, production systems, etc.). During the analysis of the interaction between the social and the ecological subsystems, the SLF helps demonstrate how the ecological subsystem (natural capital) relates to the social subsystem by considering the human, social, economic and physical/infrastructure capital. Using this framework can provide information for policy makers and extension workers on how to improve the livelihood of communities. It is recommendable to apply, when studying marginal groups or groups that depend on natural resources and are exposed to environmental changes with little capacity to mitigate their negative effects **[49]**. This is especially important for smallholders, as they depend mostly on their own farm and on the inherent productivity of the soil **[50]**, **[51]**. This makes smallholders highly vulnerable to climate change, neoliberal policies or land tenure reforms **[52]**, **[53]**, **[15]**. Diversifying livelihood and integrating different agricultural processes (e.g. livestock and different crops) may increase the adaptability and support the reduction of the vulnerability of smallholders to external perturbations like global environmental changes or to responses to global market fluctuations **[54]**, **[53]**.

7. Land-use change and livelihoods

Land use implies a human dimension or purpose for which the land is used **[55]**. Changes in land cover (biophysical attributes of the earth's surface) and land use (human purpose or intent applied to these attributes) are among the most important influences of human use of land **[6]**. Land-use change includes the conversion of natural ecosystems to croplands, pastures, plantations, and/or urban areas. It implies human appropriation of natural resources and ecosystem goods and services, such as food, fiber, shelter, and freshwater **[4]**.

All land use affects regional climates, because the vegetation (land cover) influences processes such as net radiation, the division of energy into sensible and latent heat, the partitioning of precipitation into soil water, evapotranspiration, runoff **[56]**, **[57]**, emissions of greenhouse gases, surface roughness, and the production of aerosols **[57]**. Land-use change influences the carbon cycle and thus potentially affects regional and global climates **[58]**. Land use and land-use change are tightly linked to local livelihood development; however, depending on the land management type, land-use change may have negative impacts on the long-term provision of ecosystem services, biodiversity conservation and thus human well-being **[59]**.

Rural livelihoods of poorer people with limited access to land may more frequently change land use in response to fluctuations in commodity prices than that of wealthier people. Alternatively, poorer people may have to shift from agricultural activities to non-agricultural wage-labor activities to meet their daily living, and sometimes migration becomes inevitable **[60]**, **[15]**, **[61]**. In case of diversification of an agriculture based livelihood, land-use change may still occur by increasing crop diversity **[62]**, **[63]**. Diversification is a strategy to increase the capacity of coping with and adapting to disturbances and/or to changing economy **[64]**.

Land-use change and livelihoods depend on each other **[65]**, **[61]**, **[66]**. They are influenced by external and/or internal socioeconomic or political drivers. Human activities influence land-use functions **[4]** in order to maintain or further develop livelihoods **[66]**, which makes land use an important factor in local, regional or global changes in biophysical and social structures.

8. Building adaptive capacity

Capacity building is the development of the abilities of people, institutions, and systems to deal with changes or unforeseen challenges **[67]**. It can help communities to better cope with changes or disturbances associated with global environmental change and to improve ecological or social resilience, for example after a pest outbreak or economic crisis, respectively **[68]**. In a community, an improved capacity in the decision-making of individuals can increase consciousness and alertness to change. A community with a diversity of accumulated individual skills increases the ability to adapt effectively to changes **[69]**, hence the system becomes more socially resilient **[70]**. Adaptive capacity is the capacity of human actors to respond to or induce change within a certain state of SES. E.g. in social systems, adaptive capacity may be expressed in networks that create flexibility in problem solving, but also by aiming to obtain equilibrium in power distribution among interest groups **[17]** and it requires continuous interest and willingness to learn **[26]**.

In an SES, the understanding of ecosystem processes and social memory are tightly linked **[71]**, considering past experiences, and present and future practices to respond to environmental, political, economic or social changes **[72]**. Capacity building in adaptive capacity is therefore fundamental in complex SES, where unpredictability and high uncertainty govern system dynamics. Hence, adaptive capacity refers to the ability of the community or institutions to respond flexibly to uncertain situations and to manage them in an adaptive way without jeopardizing the resilience of the system **[6]**

The ability of a farming community to target its resilience improves by continuously interacting and exchanging with all key stakeholders and within and among social networks. This ability should be separated into adaptation and learning, recognizing however that a complex system is self-organizing. The self-organizing nature of a system buffers potential impacts from other systems and "does not need to be continually invested in, subsidized, or replenished from outside to persist" (Ostrom, 1999; Carpenter *et al.*, 2001; Holling, 2001; cited by Lebel *et. al.* **[8]**).

Capacity building in adaptive capacity strengthens different stakeholders and allows collective access and use of knowledge to achieve a communal desired result **[73]**.

Environmental education is targeted towards achieving sustainability and solving related problems; it also plays an important role in capacity building and the reduction of vulnerability to environmental stress **[74]**. Environmental education in complex SES in particular may increase ecological or social resilience **[63]**. People with a higher level of education are usually less vulnerable to potentially unstable or fluctuating economic activities like farming **[75]**, **[76]**. People with a better education recover faster and handle the immediate as well as mid- and long-term impacts of a severe disturbance event (e.g. a natural disaster) better than those with less education **[77]**.

The interest of an individual to change and adapt to a new situation may include his or her ability to intervene in the labor market (age and education, among others), social network strategies to approach environmental consciousness, resource use and the use of technology **[78]**. Singh **[79]** argues that environmental education improves skills in decision-making processes, and makes a person take more responsibility for the environment. Change in an individual's attitude can support the resolution of environmental problems, which can be used as a tool for increasing environmental consciousness **[80]** and to broaden the perception of problems. Opinions, visions, and participatory actions of a community may greatly improve the decision-making process **[81]**, since one of the key strengths of environmental education is participation **[82]**. The Sustainable Development Goals (SDG) of the United Nations Agenda 21, in particular SDG 17, highlight the importance of partnerships and alliances in development negotiations **[83]**.

Capacity building plays an important role in obtaining a resilient SES. In the process of improving the management of resources and maintaining human well-being, local communities as well as institutions should be included in the decision-making processes. In particular, the adaptive capacity to respond in a resilient way to uncertainties and external perturbations should be priority in a sustainable development context. This includes the understanding of social-ecological functions but also the self-organizing principles of complex systems **[84]**.

9. Adaptive co-management

Adaptive capacity is a component of resilience that reflects the learning aspect of system behavior in response to disturbances **[16]**. This gives the system the possibility of managing perturbations without any significant loss in important functions like primary productivity, hydrological cycles, social or economic assets. The loss of resilience, and therefore of adaptive capacity, means the loss of opportunities for a system during the period of reorganization **[85]**. Adaptive management considers monitoring and accumulating knowledge and constantly adjusting the activities of human beings in response to changes or uncertainties in an SES. Adaptive management allows managers to learn from management results **[6]**. When resource management seeks social-ecological sustainability through cross-scale, multi-stakeholder involvement and intentional learning from experience and practice, this translates into adaptive co-management as collective action based on exchange of experience and consensus **[86]**, **[87]**. Active adaptive co-management is a useful approach for resilience-building in SES. It supports learning and the increase of adaptive capacity in system management. It requires and facilitates a social context in the system with flexible open institutions and multi-level governance systems **[88]**.

Building adaptive capacity as an immediate and/or long-term response to system change is fundamental in SES management; it is the basis for handling change as an inherent property of an SES at all levels from smallholder/producer to policy maker. It requires iterative learning and a continuous re-evaluation of policy actions based on mutual learning and knowledge sharing. Improving the adaptive capacity of management rises the adaptability to changes and maintains the provisioning of ecosystem services and thus human well-being.

10. Local strategies for sustainable management

Sustainable land management implies maintaining concomitantly the well-being of people and the conservation of natural resources. Hence, a social-ecological systems approach is fundamental and requires full understanding and consideration of the above discussed concepts: complex system dynamics, resilience, ecosystem services, land use change and livelihood development, building adaptive capacity, and adaptive co-management. As SESs are complex systems, it is fundamental to acknowledge the cyclic nature of system collapse and renewal and thus learn how to deal with and manage system change caused by external and/or internal drivers, as they may provoke shifts in system states or regimes. When managing for higher resilience, SES may be less vulnerable to changes, and the livelihoods and environmental resources may be maintained. Human activity and decisions can strongly impact adaptability to changes and hence the resilience of the system. That means that we have to include the people in local strategies.

To achieve sustainable landscape management based on ecosystem services and sustainable livelihoods, it is necessary to analyze all SES components, factors, and processes and identify participative strategies so communities will adapt to changes. A main interest should be how capacity development can work as an instrument to improve the resilience of a community in an SES through the inclusion and improvement of the available ecological services, land use and adaptive processes when facing system changes.

Folke *et al.* **[88]** suggest that policies should i) strengthen the perception that humanity and nature are interdependent and interacting and stimulate development that enhances the resilience of SES, recognizing the existence of thresholds, uncertainty, and surprise; and ii) create areas for flexible collaboration and management of SES, with open institutions that allow for learning and building adaptive capacity.

Resilience-based ecosystem stewardship recognizes managers as an integral component of the system with the goal of sustaining the supply of ecosystem goods and services in the light of continuous change. Resilience-based stewardship aims at sustaining SES considering all their socio-economic and biophysical variables and their interconnections **[85]**. The changes in one domain may influence another, for example debt levels in the economic domain may cause overexploitation of natural resources **[12]**.
Access to natural resources, diversity in varieties and types of crops, education and skill development, and social networks can strengthen groups like smallholder famers when having to cope with conditions of stress and change **[89]**, **[53]**, **[90]**. Diversifying income does not only have direct positive feedback on diverse aspects of livelihood development but makes individual livelihoods more adaptable to market changes, and less vulnerable to inter-annual variability in precipitation and crop yield **[90]**

According to Cowling *et al.* **[91]** there is importance in awareness raising, knowledge sharing, organizational and institutional capacity for integrating ecosystem structure and function in planning processes. Still the integration of the ES concept in policies and planning is poorly developed. The knowledge of practitioners and decision-makers should be included in the spatial planning of multifunctional landscapes as well as in assessment of the provisioning of ES and how they link to human wellbeing at the local, regional and global scale **[37]**, **[3]**. The conversion of traditional cultural landscapes to intensified agricultural landscapes or land abandonment may imply the loss or degradation of many valuable cultural and/or ecological elements, including ES **[92]**. Rural communities in cultural landscape rate several ES types as fundamental for their daily lives. In these areas, traditional land-use practices maintain ecologically valuable landscapes and give citizens the opportunity to earn their living. When the aspiration of the inhabitants is shifted toward other strategies there is the risk that socio-economic interest may impair the provisioning of important ES **[93]**.

11. Conclusions

Sustainable landscape management must include resilience thinking in decision-making processes. Resilience-based ecosystem stewardship is able to sustain the benefits for society, which are directly and indirectly related to the provision of ecosystem services. The maintenance of the well-being and the livelihood of the people as well as the resources and the ecosystem services of the ecosystem depend on the resilience of the system, which can be enhanced with a stewardship approach.

Land use and livelihood depend on each other and/or together transform ecosystems and the multi-functionality of landscapes, which feed back into the climate and the provision of natural resources and ecosystem services. The drivers responsible for changing land use or livelihoods may indirectly influence the resilience of an SES. Building the adaptive capacity of the community and adopting an adaptive co-management approach may greatly increase the ecological and social resilience of the system and thereby strongly contribute to the wellbeing of people.

Hence, aiming towards the sustainable management of a social-ecological system in a rural context requires an integrated cross-disciplinary, cross-sectorial approach that considers not only key variables or assets but rather emerging system properties such as resilience, cyclical transitions of system phases, interlinked ecosystem services bundles and continuous iterative learning and knowledge sharing. Only then is it possible to fully understand, manage and regulate the condition, tendency, and dynamic interactions of a social-ecological system in the light of sustainable development.

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Chapter III

SOCIAL-ECOLOGICAL DYNAMICS OF A TROPICAL AGRICULTURAL REGION: HISTORICAL ANALYSIS OF SYSTEM CHANGE AND OPPORTUNITIES

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ABSTRACT

Land use change arises from a variety of socio-economic and/or biophysical drivers, with direct and/or indirect feedbacks on the long-term functionality of the land as the fundamental life-support system for human wellbeing. Understanding the spatiotemporal dynamics of production systems is critical for decision-making to maintain both functioning ecosystems and land-dependent livelihoods. We applied the adaptive cycle metaphor to examine historic spatiotemporal changes in one of the largest communal regions (*ejido*) in the Northern most extension of the tropical forest biome in Mexico. This large-scale case study explores the effects of a series of exogenous and endogenous drivers that transformed a former dense tropical forest into an intensive industrial sugarcane plantation with parallel developments and adjustments of rural livelihoods. We demonstrate how integral knowledge on the historical development of a 70-year old social-ecological system (SES) helps build fundamental understanding of the vulnerability, resilience, and adaptability of land and people (livelihoods) to current diverse external and endogenous drivers. With the adaptive cycle metaphor, we identified stable system states and the current phase of our focal SES, which, before the 1940s, was covered by dense dry tropical forest. The current SES had passed all phases in the adaptive cycle more than once and is presently in the early conservation phase represented by a high input commercial sugarcane production system with reduced resilience to external drivers of change. We show which drivers and historical events best explained the regional social-ecological system dynamics including its vulnerability, resilience, and adaptability considering certain system states. Understanding system dynamics and phase changes considering the adaptive cycle metaphor helps identify both social and ecological resilience characteristics, and unexplored windows of opportunity for guided transformation of system states out of social-ecological traps.

Keywords: *land use change, resilience, drivers, legacy effect*

INTRODUCTION

Deforestation and other forms of land conversion to intensive agriculture have fundamentally reshaped the cover and multifunctionality of landscapes during the past five decades (Wassenaar et al., 2007; Grau et al., 2008; Steffen et al., 2015). This type of radical transformation from highly complex to simplified systems has been driven by continuous and often simultaneous pressures of international markets, fluctuations in commodity prices and the marginal situation of subsistence farmers (Kaimowitz, 2001; Grau et al., 2008; Ribeiro Palacios et al., 2012). Land use and/or cover changes have been the principle drivers to cause directional changes and losses of key characteristics of tropical ecosystems, e.g, decline in biotic diversity (Sala et al., 2000), fragmentation of ecosystems (Uddin et al., 2015) and loss of habitats (Lawler et al., 2014). Modifications caused by land use change have potentially positive or negative feedbacks on climate change and may trigger future changes in land use and functionality of human life-support systems (Chapin et al., 2008) likely with repercussions at the global scale (Steffen et al. 2015).

The need to provide food, water, and shelter to an increasing human population as well as competing interests to produce biofuels will necessarily augment the reduction in forest cover, and enhance farmland expansion and water extraction, and thus require novel management approaches both to protect natural ecosystems (Foley et al., 2005) and simultaneously to support livelihoods[1] and human wellbeing (MEA, 2005). Often, management of natural resources follows a command and

[1] According to Chambers and Conway (Chambers et al., 1991) peoples' livelihood refers to their means of living, food, income and assets.

control approach (Meffe et al., 2012), which is not sustainable in the long-term compared to an ecosystem or land stewardship-based approach (Foley et al., 2005; Chapin et al., 2009) as it may provoke loss and degradation of natural resources and ecosystem services (soil erosion, decline in soil fertility, etc.) both in communal and private land (Ostrom, 2005).

Several studies have shown that complex changes including public policy associated with the neoliberal economy model may be responsible for the observed patterns and rate of local land use change (Huber-Sannwald et al., 2012; Ribeiro Palacios et al., 2012; Eakin et al., 2014). Global economic market opportunities and resulting changes in national agricultural production policies may influence the decisions of local people and so induce sudden land cover or crop changes (Lambin et al., 2001; Ribeiro Palacios et al., 2012; Eakin et al., 2014). Also, increasing land scarcity associated with human population growth and shifts in land tenure systems in conjunction with increasing competition at the global food market may lead to the intensification of agriculture (Huber-Sannwald et al., 2012; Eakin et al., 2014). This may have adverse effects on smallholder production systems, such as loss soil fertility and water quality (Berka et al., 2001) and impoverishment of the diversity of agricultural products (Pingali et al., 1995). Diversification of agricultural production systems may counteract this trend and support sustainable livelihoods of rural households. Also, it allows local farmers to better cope with and recover from shocks, and it may enhance their adaptability to unpredictable future changes without necessarily exploiting the natural resources (Chambers et al., 1991).

Causes of unpredictable change are drivers; they may be endogenous, i.e. related to the social and/or ecological subsystem of a SES, and/or external, operating at higher spatial, organizational or institutional scale (Dearing et al., 2010). To understand the interactive nature of drivers and their potential effects on system change, it is necessary to elucidate the relationship between the nature of these drivers and the associated spatiotemporal changes of local systems, where both social and ecological aspects require full accounting. Holling's adaptive cycle (Holling, 1986) is an excellent heuristic tool to analysis a system change/recovery in response to alteration or disturbance triggered by external and/or internal drivers: the phases of renewal [Ω], reorganization [α], growth [*r*], and conservation [*K*]. The adaptive cycle has been applied in diverse studies on historical system change considering linked social and ecological dynamics (Abel et al., 2006; Beier et al., 2009; Huber-Sannwald et al., 2012).

For example, after the impact of a severe external driver, a well-developed mature system with clear rules and regulations (in the conservation phase, *K*) may collapse and enter the release phase (Ω phase), where resources and energy are liberated from previously accumulated capital (natural, social, economic). Depending on the environmental, social, political, and institutional conditions and contexts, once the system re-establishes (during the reorganization phase, *α*) it may adopt a new system state or return in a slightly modified fashion to the previous state; in both cases with similar system structure and function. Growth and development (during the regeneration phase, *r*) and accumulation of resources will then lead the new system to the stage, where social and/or natural capital will build up again and become conserved (conservation phase, *K*) (Gunderson et al., 2002; Holling, 1986; Alliance, 2002). Typically, the resilience of a system is high in the *r* phase, it declines in the advanced *K* phase, and increases in the transition from the *Ω* to *α* phase (Walker et al., 2012). The growth and conservation phase together are defined as the fore loop and the collapse and reorganization phase together form the back loop of the adaptive cycle. The fore loop usually takes considerably longer than the back loop (Walker et al., 2006).

Most local SES dynamics are influenced by interacting drivers that may occur at distinct spatial or temporal scales (Gibson et al., 2000). Land tenure and property right (define the uses which are legitimately viewed as exclusive and who has these exclusive rights) regimes are key local drivers that may change over time for political, constitutional or other reasons (FAO, 2002). For instance, in tropical Mexico, regional shifts from sugarcane to citrus production were triggered by the international NAFTA trade agreements in the 1990s; they provoked national changes in government help programs and subsidies (Ribeiro Palacios et al., 2012). Besides, these international neoliberal trends have been leading to the privatization of communal land and thereby influenced the agricultural sector in Mexico (García-Barrios et al., 1990; Lewis, 2002; Chappell et al., 2013), at the sacrifice of crop diversity and traditional sustainable cultivation forms (Ribeiro Palacios et al., 2012).

Current land tenure and local decision-making are influenced by both social-political legacies (temporal scale) and heterogeneous landscape functionality (spatial scale).

So it is fundamental to understand the immediate causes that control land use and management as they influence the mid- and long-term productivity of land (Bonilla-Moheno, 2013). Thus, more in-depth research on the diversity and dynamics of external drivers and their interactions with local system dynamics is necessary to elucidate the motivation of small-holder decision-making on resource management practices and land use change (Cash et al., 2006; Adger et al., 2006).

Highly dynamic SES rarely reach long-term stable states but rather pass through recurring developmental and recovering stages (Gunderson et al., 2010). Natural or human-caused disturbances may induce the collapse of a system, which in turn may re-organize and/or re-emerge (Rasmussen et al., 2012) in a new system state. Severe disturbances may cause a regime shift of a system (Folke et al., 2004; Walker et al., 2004), where a focal system may irreversibly loose its original structure, function and feedbacks, i.e. the system has lost its resilience (Walker et al., 2004). One example of such a disturbance could be the intensification of agriculture, which may cause a regime shift and transform a whole SES (Wood et al., 2000). The adaptive cycle metaphor in combination with social-historical analysis can serve as a useful framework to identify and examine how particular events in the past have influenced and/or transformed the structure and functioning of local SES (Gunderson et al., 2010).

The objective of this study was to identify key (external and internal) drivers and their role in the historical development of a relatively young SES in a tropical landscape of Northern Mexico, now dedicated to industrial sugarcane production. We use the adaptive cycle metaphor to identify and explain the phases and transitions the region of Laguna de Mante SES (LM-SES) went through since its origin in the 1940s. In particular, we address the following questions: 1) What have been the key political, institutional, social-cultural and biophysical drivers that have led to biophysical and/or social-economic changes in the LM-SES and thus triggered phase changes in the adaptive cycle? 2) Is the current state of LM-SES stable and resilient to the acting external drivers and potential future drivers?

METHODOLOGY

STUDY AREA

The *ejido* Laguna del Mante (LM), one of the largest *ejidos* in Mexico is located in the Northeast of Mexico, in the tropical region Huasteca Potosina (22° 12' 0'' LN, 98° 53' 0'' LW) of San Luis Potosi, state, at an elevation of 296 m. a. s. l. (CONANP-GIZ, 2012). This area was originally covered by tropical deciduous forest (Peralta-Rivero et al., 2014a) with *Bursera simaruba, Lysiloma divaricata,* and *Phoebe tampicensis.* The landscape is currently characterized by fragments of secondary forest (with predominantly *Sabal mexicana* and *Guazuma ulmifolia* (Rzedowski, 2006)) embedded in a matrix of sugarcane plantations, abandoned agricultural fields, citrus plantations, pastures, *milpa* (traditional polyculture system mainly used for corn production at subsistence level). 60% of the biosphere reserve "Sierra Abra Tanchipa" (21,464 ha) is located within the limits of the *ejido* LM. The La Lajilla dam (28,000 m^3) is located in the northern region of LM-SES.

The climate is warm sub-humid with the main rainy season between July and September and sporadic precipitation events falling between November and March. Mean annual precipitation is 965 mm ($\pm$ 209 mm S.E.) (INEGI, 2009; CONANP, 2013). The topography is characterized by plains and gently rolling hills and karstic relief (Newsham et al., 2012). Soil types are mainly Phaeozem and in the western part Histosol; near the dam, Gleysols and Rendzina can be found. In the Sierra de Abra Tanchipa, Phaeozom, Lithosol and Rendzina are the dominant soil types (CONANP, 2013; CONABIO, 2012). In 2016, agricultural production included 55% sugarcane, 16% livestock, 21% pure corn, and 8% mixed corn and beans. In the north, land use is dedicated to livestock farming, in the centre and west to sugarcane, corn and bean production. Corn and beans are used for consumption at the household level, while sugarcane and livestock are mostly used for commercial purposes.

In 2010, LM had 2036 inhabitants (SEDESOL, 2013), most of whom are mestizos with 13% being indigenous (Teneek and Nahuatl); only 41% of the population was economically active (INEGI, 2010). Of the total population, 23% are *ejidatarios,* these are men or women holding special rights and tenure yet no private possession over the common land (*ejido)* (Ley Agrario, 1993). Normally, only the head of the household has the status of *ejidatario,* and this person has the opportunity to transfer this status to someone else in the family. Before 1992, the land was governed communally. Since 1992, the communal area of the *ejido* could be privatized by *ejidatarios.* A person who is not an *ejidatario* can buy land in the *ejido* but cannot influence political decisions in the *ejido*. Of all LM *ejidatarios,* the majority (62%) possesses up to 60 ha, but only 13% cultivate their land, as access to remote land is limited (being up to 30 km from the village) or because of the high investment required to start agricultural activities. The Biosphere Reserve Sierra del Abra Tanchipa is situated within the limits of the communal land of the LM, however as protected area it has restrictions regarding its use; e.g. hunting, logging, land use change and the use of fire (CONANP, 2013).

Predominant economic activities in the LM are the cultivation of sugarcane for a nearby sugar factory, wage-labour in lemon plantations of a local citrus fruit company, wage-labour opportunities in the nearby town of Ciudad Valles, fishing and livestock breeding for local markets, and participation in government programs such as guards of the Biosphere Reserve Sierra de Abra Tanchipa or fire fighters. By 2005, 5% of the population of LM had migrated (INEGI, 2010), mostly to North America.

DATA COLLECTION AND ANALYSIS

This study employed multiple qualitative research methods such as semi-structured interviews, face-to-face “life history” interviews (Corbetta, 2007; Dhunphat, 2000), and archival research to identify and examine the type, scale and influence of historical events on the development and condition of the LM-SES.

<u>Semi-structured Interviews</u>

We interviewed 68 of a total of 466 *ejidatarios* in LM; most of them were men, as the *ejidatario* status is allotted to the head of the family. If a woman was *ejidataria* she mostly passed us to one of their male family members, because traditionally women work as a housewife. The interviewees were chosen based on their trajectory and experience of having lived and worked in LM for at least two decades and, in the process, have witnessed potential changes in land use. In a preliminary study, we conducted 15 interviews to fine-tune the questions and improve the structure of the interview. The semi-structured interviews focused on identifying the type of changes in the political, social, cultural, economic, and environmental dimensions of the LM-SES, as well as on potential adaptation strategies in response to these past internal and/or external drivers. Interviewed people were asked to reconstruct the history of their agricultural land use and to identify biophysical and/or socioeconomic reasons for any changes.

Based on these interviews, we identified key biophysical, socio-economic and social-political events and years that had triggered changes in land use, as well as general aspects of the households, agricultural practices, and place of origin. Data were analyzed with a descriptive analysis. We made cross-tabulations to determine relationships among land use change types and trigging events, as well as between land use change and agricultural aspects (for example, to relate how many farmers changed from corn to sugarcane because of climatic reasons; or in which year how many farmers changed from one crop to another one) with SPSS v24. Furthermore, cross-tabulations were realized to analyze the relations between agricultural practices and the place of origin and thus potential local knowledge of *ejidatarios*.

Life History Interviews

We re-constructed the life-history of ten farmers (men). They were chosen based on their experience before and after the declaration of LM as communal land (*ejido*). The persons were first contacted by the commissioner of the *ejido*. Intensive face-to-face "life history" interviews helped to create an overall picture of structural changes in the LM-SES and the interviewee's life in relation to changes in agriculture and potential land use. A supplementary chronological analysis was made by extracting dates and events from secondary information[2]. The historical analysis of change of land use including years when transitions were induced was linked to the reasons and decisions taken by the farmers.

The adaptive cycle

Once the drivers and key events of change derived from the interviews and chronological analysis were identified, we applied the framework of the adaptive cycle (Figure 1) (Gunderson et al., 2002) as a diagnostic tool to distinguish between past and present states/phases of the LM-SES system and to single out the causes

[2] "Registro Agrario Nacional" (RAN), Instituto Nacional de Estadística y Geografía (INEGI), and "Comisión Nacional de Áreas Naturales Protegidas" (CONANP).

of transitions between phases and or states. Furthermore, the adaptive cycle metaphor helped to organize the obtained results (if it belongs to growth, accumulation, reorganization, renewal; what is a driver) from the interviews regarding the key features for each stage of the adaptive cycle, and hence to identify the cyclic nature of the LM-SES.

To identify the different phases and decisive events that have induced changes and adaptations in the LM-SES, we first developed the historic timeline for LM. Subsequently, key factor types associated with those events that drove the system through the cycle were identified (Gunderson et al., 2010) and characterized for each phase change. For example, events like land tenure change, institutional change, new skills or practices or biophysical changes may have induced transitions between system phases (Ostrom, 2003; Westley et al., 2013; Fath et al., 2015).

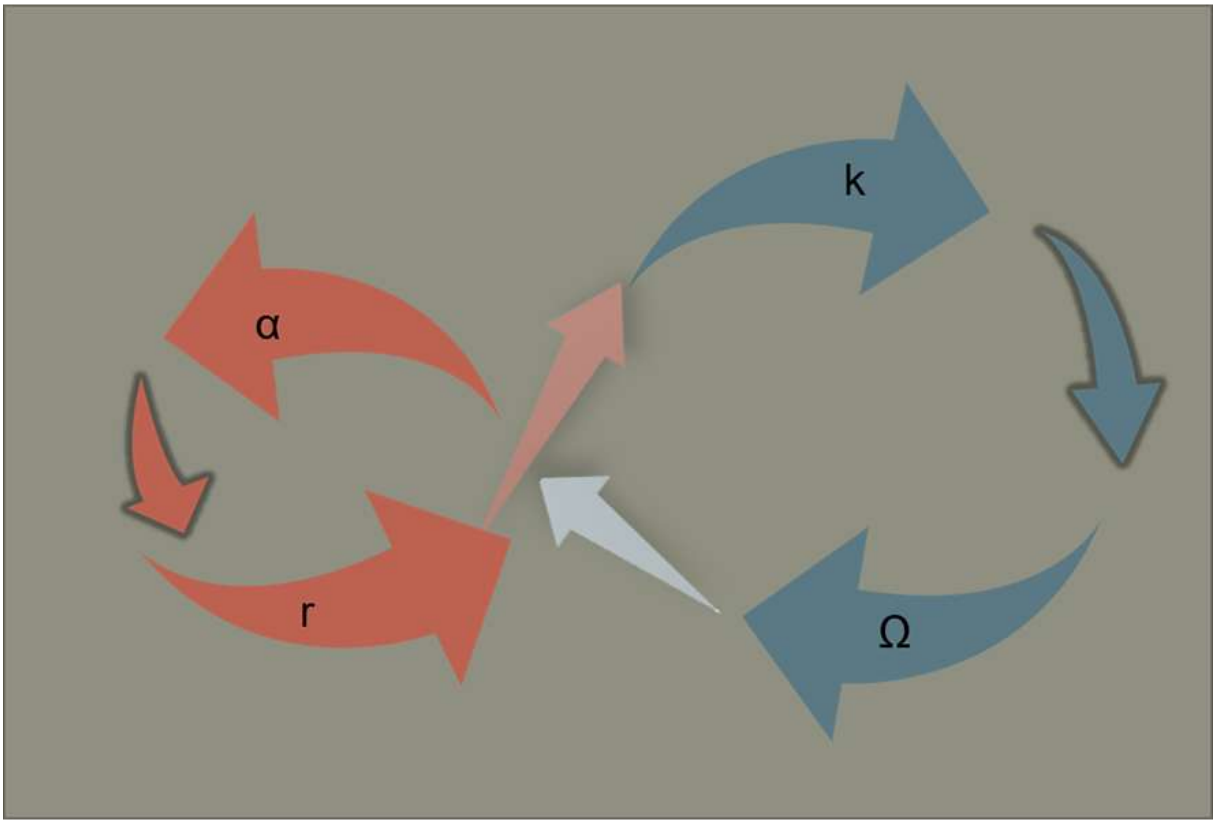

Figure 1: The adaptive cycle modified after (Holling, 1986): The figure shows the four phases of the adaptive cycle: exploitation phase (r phase), conservation phase (K phase), collapse/release phase (omega; Ω – phase, corresponding to the end) and reorganization phase (alfa; *α* - phase*,* corresponding to the beginning).

RESULTS

PHASES AND TRANSITIONS OF THE LM-SES

Community-based tropical forestry phase (before 1945)

Prior to 1945, the region of the current *ejido* LM had been covered by primary tropical forest and was sparsely populated by local communities, who depended on subsistence farming and extensive forest use. In 1945, the government of the state of San Luis Potosí licensed a total area of 45,040 ha to a new “owner”, the *latifundista* (land owner of a large estate) Mr. Jorge Pasquel Casanueva, for 30 years to develop a large-scale livestock enterprise in the then called ranch “San Ricardo”.

Latifundista Don Jorge Pasquel phase (1945-1954)

In 1945, the establishment of a large private livestock enterprise (with up to 20,000 animals) was the start of a new land use system, which restructured land cover and function of a large area. In 1945, this new regime initiated with massive deforestation that changed landscape cover and function. Mr. Pasquel set up new institutional rules; he dismissed most inhabitants of the area and replaced them with his own workers. He established a complex irrigation system consisting of 23 small dams as water supply for fodder production (corn and bean) of the livestock enterprise. He also started the construction of the artificial lake “La Lajilla” (around 1950) with the generous support of the federal government for this mega-irrigation system. In this way, the region experienced a notable transformation from conventional smallholder subsistence agricultural to a high-input production system including the expansion of transportation and irrigation infrastructure (road and dam construction).

The early 1940s marked the beginning of capitalism in Mexico, and national financial institutions (Banco Nacional de Crédito Agrícola) provided credit and technical assistance to landowners to increase agricultural production. Between 1940 and 1950, agricultural production in Mexico started to increase until 1960. Highest agricultural production stemmed from large capitalist farms on irrigated land (Hewitt de Alcantara, 1976) Eyewitnesses described this early period as stable, with Mr. Pasquel being a responsible employer, who supported his workers with access to basic services (e.g., health, education, etc.). At that time, about 100 people lived there.

Bank administration phase (1955 – 1973)

In 1955, Mr. Pasquel died in an airplane accident in the Sierra Abra Tanchipa, causing the collapse of the huge livestock production enterprise, and ultimately the end of the San Ricardo farming system. The administration of the area was temporally taken over by one of his brothers, however without any interest in maintaining or innovating the existing ranch. Local farmers did not feel responsible or capable to maintain and/or re-structure the existing agricultural production system. Hence, during the 1960s, the administration was handed over to the national "Agriculture-Livestock Credit Bank". The land was mainly cultivated with corn and bean for self-supply or nearby local markets. In 1960, in Mexico corn was grown by around two million rural families, who possessed on average three hectares of land each (seldom with irrigation) (Hewitt de Alcantara, 1976). Starting in 1972, local inhabitants of the former San Ricardo Ranch could apply to become a communal landowner (*ejidatario*) of this new to be formed communal landownership structure.

Development of the *Ejido* Laguna del Mante phase (1974 – 1991)

In 1974, the ranch was declared *Ejido* Laguna del Mante, which implied profitable use of a large communal land for registered *ejidatarios*. In 1972 and 1973, around 422 people had applied to become members; they came from nearby villages and other areas of the Huasteca Potosina, with a high proportion of indigenous people (Teenek and Nahuatl). The main attraction to migrate to the newly established *ejido* was access to land (80.6% of interviewed people) and to find better paid jobs as daily workers (19.4%). As the number of applications surpassed expectations and manageability, the candidates started organizing themselves in four groups. In 1974, was confirmed as "by Secretary of Land Reform.

Most (57%) local immigrants brought rich agricultural experience, as they had worked as agricultural day labourer on their own land or on ranches. While new *ejidatarios* brought diverse crop, cultivation, and/or other local knowledge, it was not always applicable to the conditions in LM due to distinct biophysical characteristics (climate, topography, soil, crop type, etc.), which required different land management techniques than they had applied on their previous farms. The conversion from the private to communal land tenure system fundamentally changed the land use system.

At the early transition from communal to private land, the *ejidatarios* attempted to maintain livestock production on communal land, taking advantage of the original infrastructure. In parallel, the new *ejidatarios* started agricultural production with a start-up loan from “Banrural” a national government bank for rural development. To pay back this credit (around 4000 US dollars), the *ejido* sold most of their livestock (around 5000 cattle). Furthermore, agricultural engineers (hired by the state) provided technical assistance in corn and bean production. They also developed prosperous apiculture, accomplishing the exportation of high-quality honey for international markets; besides they produced pigs and sheep, initiated fish farming, produced fibre of *Agave fourcroydes* (Henequen Agave) and planted fruit orchards (mango).

This diverse agricultural development converted the pasture landscape into a mosaic of crops, which were collectively organized, in that every production branch was managed by its own group of people with clearly defined governance structures. At that time, every *ejidatario* had around two hectares of land for personal use, where mainly corn and beans were cultivated. As the *ejido* land was large and not all was used as a commons, some *ejidatarios* started also producing corn or beans on this uncultivated land as personal cash crop. Furthermore, the *ejido* invested into infrastructure and acquired tractors and trailers for common agricultural use. As in 1984, a sugar mill (*ingenio*) “Plan de Ayala” established near LM (25 km distant from LM), a group of 25 persons started cultivating sugarcane. Sugarcane was promoted by people from nearby locations, who had ample traditional knowledge of sugarcane cultivation. One person of the nearby town Ciudad Valles founded the “National Union of Producers of Sugarcane” and thereby regulated harvest delivery to the sugar mill, located 25 km away.

The different cultural backgrounds and language barriers impeded continuous communication among these groups. The social organization of the *ejido* including the communal working structure developed extremely slowly, because of internal conflicts related to corruption, robbery (e.g. of livestock) and neglect by the government. As a solution to this problem, they applied for privatization of communal land, which became possible with the Agrarian Reform in 1992.

Privatization of the *Ejido* Laguna del Mante phase (1992 – 2000)

In 1992, the amendment of Article 27 of the Mexican Constitution included new regulations of land and natural resource use in Mexico. The reform opened the opportunity for each *ejido* to privatize and for *ejidatarios* to internally sell or lease assigned land. The Agrarian Reform intended to modernize the rural agricultural sector and increase agricultural production. Privatization was seen as a means to attract private investment, capitalize the rural sector and become competitive in international markets, especially with the formation of the North American Free Trade Agreement (NAFTA) in 1990. As a result, guaranteed prices (except for corn and bean) were eliminated (Gates, 1993). NAFTA also resulted in cheap importation of corn and bean from the USA, which triggered a severe crisis among Mexican smallholders depending on this staple food (Rubio, 1999)**.** Also, credit systems changed and allowed peasants to get loans from the Development Bank and commercial growers from commercial banks (Gates, 1993)**.**

During privatization, the community organized again in four groups of around 100 persons each, who shared common interests and/or friendships and helped in negotiations related to land sharing. In assembly meetings, representing the highest authority of an *ejido*, decisions were taken on which land should be privatized or remain communal. Every *ejidatario* of LM obtained eight cows and 60 hectares, either as a continuous piece of land or in separate land parcels/plots. The assignment of each 60 ha land unit was defined in a participatory manner among *ejidatarios.* The maximum distance between plots and dwellings was up to 30 km. Geo-referencing of each plot, and its legal and official registration were conducted by the "National Institute of Statistic and Geography" (INEGI) and "National Agrarian Registry" (RAN). Every *ejidatario* had to participate during the whole process of privatization and the official registration of each plot of land. In case a new land owner was not able to be present at the time of geo-referencing the property, the land was not assigned to that person. Once privatized, 69% of the interviewed farmers changed land use type or shifted crops. Some farmers took advantage of their alienation-rights and sold the land. In 1990, many new land owners switched from corn to sugarcane, because of higher profit, less labour, and an increasing demand by the nearby sugar mill. By 1995, most farmers were sugarcane producers and it is since then that sugar production in Mexico has been at rise. In 1995, the internal Mexican sugar market had its highest production (Castillo et al., 2005). However, in 1999, a sugar crisis hit Mexico, which many blamed on NAFTA, as this free trade agreement encouraged free importation of artificial sweeteners (Castillo et al., 2005; Muñoz Güemes, 2013). Interviewed farmers did not mention this crisis, nor did they seem to have been affected by obvious drops in prices. Many of the current sugarcane farmers had changed from corn to sugarcane, because of attractive benefits (e.g. health insurance) offered by the sugar mill to farmers. However, by that time the land did not yield enough output to be self-sufficient: 81% of the interviewed needed additional income beyond farming their own land.

In 1994, the “Sierra de Abra Tanchipa” was declared National Protected Area with the character of a Biosphere reserve (CONANP, 2013). This influenced both land tenure rights and land use/management. While the area remained communal land, the change in protection status influenced property rights as *ejidatarios* were no longer allowed to extract wood from the National Protected Area. For the extraction of fuelwood now is requested special permission. Also, the use of endangered species became strictly forbidden, which affected some inhabitants’ income source.

Sugarcane monoculture phase (2001-2017)

Nowadays extensive fields of monoculture of sugarcane, induced pastures for livestock production and pure lemon plantations characterize the LM-SES. Hence, cultivation of sugarcane, wage-labour in lemon plantations and, to a lesser extent, fisheries, and livestock breeding are the predominant economic activities. In 2001, a US lemon company (Paramount Citrus Mexico Services de rl de C.V.) settled in LM, as many *ejidatarios* sold their land to this company. Today, the company owns 19,000 ha with 16,000 ha covered by citrus plantations, near the dam “La Lajilla”. Currently, the company exports lemon to the United States (95%), Japan (3%), and Europe (2%) and provides full-time and temporary jobs for many people, during the harvest period (June-October) employs up to 2,400.

The harvest of sugarcane (November-May) and lemon (June-October) is staggered such that most of people work during the lemon harvest in the lemon company and during sugarcane harvest as daily workers for the sugar mill. Because of this wage labour opportunity, many farmers have abandoned their land in exchange for economic security; also, this wage labour opportunity has attracted many migrants to return back and has kept people from migrating elsewhere.

Associated with different land use types, different livelihood groups have developed in LM. One important factor controlling adjustments in livelihood development were shifts in dominant crops. 50% of the interviewed farmers have changed their original agricultural crop to a new one. 74% of those changed from corn to sugarcane, mostly because of a higher expected profitability. Furthermore, growing sugarcane requires less work and is less expensive. However, working for the local sugar industry implied giving away decision rights with respect to crop management, including harvest. While farmers remain land owners, the sugar mill controls the harvest and assigns daily tasks, decides on fertilizer and/or other chemical use, and is in charge of maintaining key infrastructures (e.g., streets) and providing tools for the harvest (e.g., machete). However, charges incurred for these inputs are deducted from farmer's salary. To sign a contract with the firm, a farmer needs at least three ha of land.

Besides the growing production of lemon and sugarcane, livestock production has also increased. During the interviews, many farmers mentioned that a rise in the price of meat in recent years has stimulated renewed interest in cattle production, but not yet at the level of massive investment into livestock. In 2009, a severe drought affected livestock production, however this did not trigger land use or land cover change. Besides to the agricultural income, government programs such as payment for ecosystem services in protected areas started in 2010, thus every *ejidatario* obtained the equivalent of US$ 27.00 annually.

DISCUSSION

Local land-use change is tightly coupled to the history of community development considering cultural and social backgrounds of community members, changes in land tenure systems and external drivers such as emerging national and international markets, neoliberal policies, and climate change. The adaptive cycle framework enables a non-linear analysis of cyclical social-ecological system changes and helps to identify external drivers that may have been responsible for inducing historical changes in the LM- SES and for explaining shifts between cyclic phases. This approach facilitates a critical analysis of the spatial and temporal coupling of a SES (Huber-Sannwald et al. 2012).

Local economic situations are frequently linked to global forces (globalization, global economic model, fluctuations in commodity prices, neoliberal policies) and thus are important drivers for local land use changes (Lambin et al., 2001), usually mediated by institutional factors at various scales (from municipality to international level). By using Holling's adaptive cycle metaphor (Holling, 1986), we identified key processes in the past that have left important legacy effects on the current LM-SES.

PHASES OF THE LM-SES IN THE ADAPTIVE CYCLE

The adaptive cycle framework enabled the identification of key events and drivers that have caused changes in the structure and functioning of the LM-SES over time. The LM-SES has experienced two complete runs through of the adaptive cycle over the past 70 years and is currently at an early stage of the conservation phase. We identified 10 different phases (Table 1): (1) Community-based tropical forestry (before 1945): **late conservation (*K*) phase**; (2) arrival of *Latifundista* Mr. Pasquel (1945): **collapse/release (Ω) phase**; (3) large-scale deforestation and land conversion for agricultural and livestock production (1946-1948): **reorganization/renewal (α) phase;** (4) expansion of pastures and livestock production system (1949-1950): **growth (r) phase**; (5) successful livestock enterprise (1951-1954)**: early conservation (*K*) phase**; (6) collapse of livestock enterprise (sudden death) (1955): **collapse/release (Ω) phase**; (7) guided transition to traditional a production system by bank administration (1956-1973): **reorganization/renewal (α) phase;** (8) development of the LM *ejido* and initiation of sugarcane production (1974-1991): **growth (*r*) phase;** (9) privatization of the *ejido* LM (1992-2000): **early (*K*) phase**; (10) sugarcane monoculture (2000-2017): **mid conservation (*K*) phase**.

Table 1: Phases of the LM-SES – the table represents the period, phase and name of the 10 identified phases of the LM-SES

Year	Phase	Name of the phase
before 1945	late conservation (*K*) phase	Community-based tropical forestry
1945	collapse/release (Ω) phase	arrival of *Latifundista* Mr. Pasquel
1946-1948	reorganization/renewal (α) phase	large-scale deforestation and land conversion for agricultural and livestock production
1949-1950	growth (r) phase	expansion of pastures and livestock production system
1951-1954	early conservation (*K*) phase	successful livestock enterprise
1955	collapse/release (Ω) phase	collapse of livestock enterprise (sudden death)
1956-1973	reorganization/renewal (α) phase	guided transition to traditional a production system by bank administration
1974-1991	growth (*r*) phase	development of the LM *ejido* and initiation of sugarcane production
1992-2000	early (*K*) phase	privatization of the *ejido* LM
2000-2017	mid conservation (*K*) phase	sugarcane monoculture

The community-based tropical forestry phase (before 1945) was likely rather stable and sustainable, as primary tropical forests deliver diverse ecosystem goods and services (Floren et al., 2005). No severe impacting anthropogenic influences on this ecosystem are known until political connections triggered a transition of the LM-SES to a country estate with Don Jorge Pasquel as the landowner. The new landowner and his land use plans caused massive deforestation of the primary forest leading to the collapse of the former sustainable forest production system. The change in land use not only affected land cover and function, but also the loss of habitat types and the connectivity to the surrounding areas. Deforestation induced the collapse of a well functioning resilient system, which was likely in the *K* phase, however local natural disturbances had maintained the rejuvenation of the when systems. Don Jorge induced the collapse and transformation of the system, which rapidly lost its original biophysical and social resilience.

Second phase characterized by (re)organization. (conversion of the large tropical region into a livestock production system) (alpha phase) thanks to the investment into irrigation and road infrastructure, and agricultural land to facilitate access to key resources like water and supplementary forage (Stokes et al., 2006). Also, the new landowner successfully managed to generate a regional market for his livestock products, which greatly helped convert what was initially a moderate-sized tropical livestock production system into a huge prosperous enterprise (*K* phase). A necessary increase in specialized human capital and top-down governed social system together with a substantial loss of the natural capital is what characterized the “Latifundista” Don Jorge Pasquel phase (1945-1954), which from a complex system’s perspective has become quite unstable and vulnerable to resist to and/or recover from potential unexpected disturbances. As predicted, upon the sudden death of the owner, the social subsystem collapsed due to the lack of capacity of self-organization, which then led to the top-down governance and reorganization through the “bank administration” between 1955 and 1973. Due to the loss and overexploitation of natural resources (Rasmussen et al., 2012; Salvia et al., 2015) the system had lost many fundamental sources of resilience including a strong weakening of stabilizing feedback controls (Gunderson et al., 2002); the local population was hit by a wave of increasing uncertainty with respect to land use potential, local livelihood development, social organization spread, both among land users and landowners.

The foundation of and thus immigration (1974-1991) and its associated fundamental structural and organizational shifts in land tenure and local political institutions coincided with the modernization and later globalization of agricultural production systems. In 1969, the annual income of smallholder farmers had dropped from US$40.00 to US$28.00 having forced many farmers to temporarily or permanently migrate to other regions of Mexico or to the United States (Hewitt de Alcantara, 1976). This explains the great need and interest of migrant farmers from nearby communities to become *ejidatarios*. New human and institutional resources led to a recovery of system resilience and the development of a new social-ecological system.

The modernization and industrialization of agriculture triggered a strong interest in smallholder farmers and day labourers, as it opened opportunities to diversify income both locally and in other regions of Mexico and the United States. Hence, the creation of the new *ejido* sparked great interest in migrating to this area (81% of the interviewed farmers). This social re-organization, including the convergence and accommodation of different indigenous and mestizo cultures, underwent a rapid process of self-organization parallel to institutional changes (including more flexibility) related to the land tenure system (from private to communal). A diversity of new social skills emerged as a product of influx of different traditional and/or local knowledge originating from a diversity of cultures and languages (Téenek, Nahuatl, and Spanish) associated with indigenous, urban and rural inhabitants.

As the resilience of a SES includes the capacity of self-organization and adaptive social learning (Carpenter et al., 2001) these new social structures clearly strengthened the potential for social resilience. Rojas (1990) showed that the rising importance of petroleum in the Mexican economy, in 1973, reduced livestock and agricultural production. However, in LM livestock production did not drop because of a decline in the meat market, but because selling livestock from the Pasquel enterprise after land partitioning of the *ejido* allowed ready access to cash for new local land use practices. The establishment of the sugar mill nearby LM also triggered a rapid transition from traditional subsistence agricultural production to the cultivation of commercial sugarcane.

After the *ejido* was formed (growth phase), the LM-SES has begun to grow in human population size, cultural diversity, social organization, and land use, where social, political and individual household structures were rapidly defined and established. This required complex social (re-)organization to resolve emerging social conflicts in parallel to a new political decision scheme associated with the *ejido* structure. The LM-SES consolidated by mechanisms of self-organization (Fath et al., 2015); they gathered in four groups; at that level, decisions were taken on privatization of land and lot assignments to *ejidatarios*. In this conservation phase, due to the amendment of Article 27 of the Mexican Constitution, most farmers decided to privatize the communal land in 1990.

According to the interviewees, all agricultural land had been changed into private land, driven by social conflicts. This change caused farmers to switch from producing staple food to cultivating sugarcane, as the economic output was significantly higher than that for cultivating corn (82% of the interviewees). Also, farmers consider sugarcane to be more resistant to climatic changes (drought) than corn (13% of the interviewees). The amendment of Article 27 brought an increase in local jobs in the sugarcane and lemon industries. The new legislations related to Article 27 created unforeseen feedbacks, with rigid internal links between land use and livelihood, in that local farmers slowly switched to a high-input monoculture production system at the cost of low-input corn and bean crops. While fertilizer and pesticides were subsidized with by the sugar mill, farmers' income depended principally on one commercial crop; income diversity decreased (Fath et al., 2015). This trend parallels similar effects in the conservation phase observed in the expansion of agricultural land in Australia (Allison et al., 2004). During the *K*-phase energy and resource use are channelled towards specialization and maximizing capital accumulation (Fath et al., 2015). In LM-SES, this was encouraged by intensifying high-input industrial sugarcane production. Globalization and new free trade agreements (like NAFTA) further enabled farmers to sell their land to a foreign citrus company. This added alternative opportunities of income to men and women as day labourers; it is currently one of the main sources of income apart from each household's own agricultural activities. The local growing economy could also be observed in the declining migration.

Currently, the LM-SES is in the mid *K*-phase ("monoculture-phase"), whose development has yielded a homogenous landscape with little buffer capacity (due to the loss of diversity in species and functions) in case of unforeseen disturbance events. The transformation from heterogeneity to homogeneity is a typical feature of the mid- to late *K*-phase, causing the system to become rigid and less resilient to surprises (Gunderson et al., 2002). While sugarcane and lemon production have greatly increased economic growth in LM, however, this has come at the expense of increasing vulnerability to shocks due to declines in diversity of natural resources and diversification of livelihoods (Ellis, 1999; McAllister et al., 2006; Hethcote et al., 2016).

EXTERNAL SYSTEM'S DRIVERS

External drivers at different spatial scales may interact with each other and directly or indirectly influence local social-ecological processes and the effect of these drivers may change over time (Rockström et al., 2009). The current LM-SES has undergone a wide range of social-ecological changes caused by a series of diverse drivers: abrupt shifts in land cover, or changes in local socio-economic, local to international political, land-tenure, social-cultural, or climatic conditions within a relative short period of time. The use of the adaptive cycle helps identify drivers that have led to these changes and also understand short- or long-term impacts of an external driver on system structure and function and on the changing sensitivity of the system to respond, resist or recover from those drivers (Figure 2).

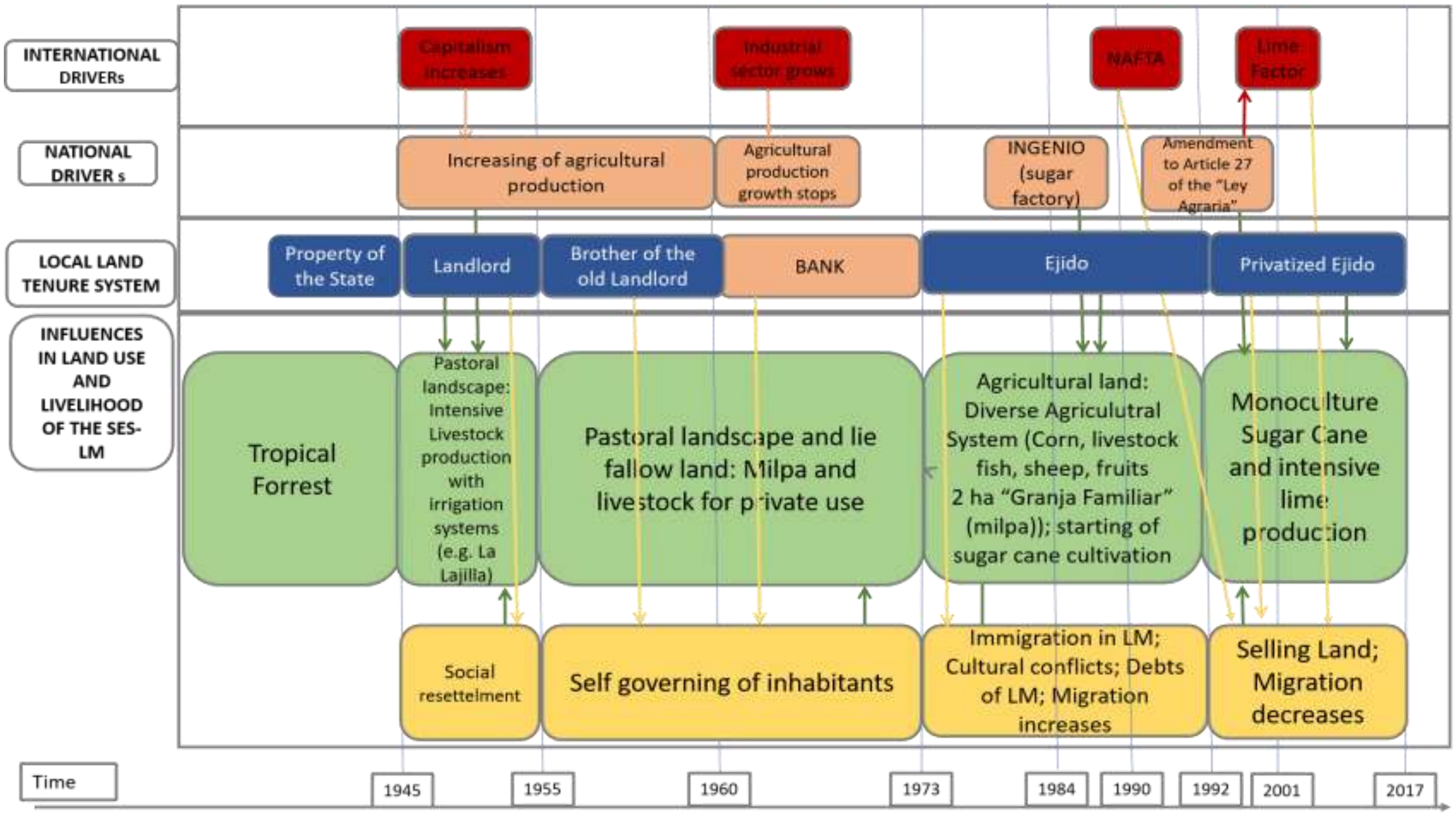

Figure 2: Drivers and dynamics of the LM-SES: This graphic depicts international, national and local drivers and their influences on changes in the local social-ecological system of Laguna del Mante in San Luis Potosi, Mexico. In the rubric of the "local land tenure system", we added the bank, even if the bank is national, because they were owner of the land. The local land tenure system, influences in land use and livelihood of the LM-SES, the length of the boxes represents the length of period of influence (see x-axis). In case of national and international drivers, particular events are associated with certain years, and thus are represented as short events influencing the Laguna del Mante social-ecological system. The arrows represent direct and indirect influences of internal and external drivers. The colors are representing the different scales: red represents the "international scale", pink the "national scale", blue the "local and tenure systems" and yellow the "land use and livelihood of the LM-SES". The arrows are representing the color of the scales they are directed to.

The LM-SES was driven by a series of social, economic and political drivers, such as changes in the governance structure, in international commodity (sugar and corn) prices, emerging local opportunities for farmers from nearby communities and hence influence a of different languages, cultures, knowledge systems, and political, international trade agreements. Local, national and international political systems triggered phase changes: The collapse of the tropical forest phase in 1945 occurred, because of the insertion of a highly influential landowner in a small farmer community and the conversion of a sustainable subsistence farming system to an exploitative, high-input livestock production system. The economic situation of the landowner and its workers prospered and stabilized with this enterprise leading the system into the conservation phase. The second back loop was induced by the lack of clear local governance structure (death of the landowner) and a missing administration of the LM-SES: the political and economic system had collapsed. The constitution of the *ejido* triggered a new fore loop.

International political changes (NAFTA) lead to the amendment of Article 27 of the Mexican Constitution and the farmers decided to change the administrative structure from common to privatized land, which built the structure for the sugarcane monopoly. Interviewees mentioned that this series of land use change had occurred in response to changes in regional and national markets (like corn prices) induced by NAFTA in 1994, political structures and land tenure (possibility to change from common land to private land) (Figure 2). New opportunities in land tenure and use attracted a large farmer population from the Huasteca region conferring local cultural changes (tradition; languages). New knowledge on crop cultivation induced the cultivation of sugarcane and changed the agricultural production system. Relatively frequent changes in property rights were one of the key drivers of internal changes. Changes in property rights were mostly associated with and triggered by top down higher-level institutions.

Also in the industrial forest system in Alaska (Beier et al., 2009), policy decisions moved the system into the fore loop but also into the back loop. The “Tongass Timber Act” induced the fore loop. The monopoly policy brought stability to the system against external legislation, until the realization of the Tongass Timber Reform Act, which initiated the collapse of the timber production system (Beier et al., 2009). In response to increasing dry climate conditions, governmental decisions in the broadacre agricultural system in Western Australian influenced the market prices of wool and wheat and caused the collapse of the existing food crop and livestock production (Allison et al., 2004). In contrast, in an agro-pastoral system in the Sahelian area (Rasmussen et al., 2012), drought was the key biophysical driver that had detrimental impacts on the financial situation of farmers causing them to sell their livestock. The installation of the cereal bank helped improve the financial situation of the farmers, which basically freed people from necessary social self-help group formations.

New knowledge referring to crop-cultivation induced the cultivation of sugarcane and changed the agricultural production system. It was only at the *ejido* level, when local governance structures evolved and decisions on land distribution were made among farmers. Property rights are an external as well as internal social-ecological driver, that influences land property and land use rights. Change in property rights and thus changes in access to land and its use and management may induce important shifts in a production system. Lewis (2002) discovered, for example, a drastic shift towards land privatization in the *ejidos* in the Yaqui Valley, Sonora. Many *ejidatarios* in that study started to lease their lands to private farmers to increase income. In LM many *ejidatarios* sold their land to a foreign company and migrated. At present, many migrants have returned from the United States or other regions, because of job opportunities offered by the foreign lemon and sugarcane factories

THE ADAPTIVE CYCLE AS A HEURISTIC TOOL

The complex dynamics of a SES (Figure 2) can be analysed by adaptive cycle independently of the legacy or age of a given SES. The adaptive cycle has been applied to explain and analyse specific phases in the cyclic behaviour of complex systems (Abel et al., 2006). There are a few case studies where the cyclic nature of production/agricultural systems have been analysed through adaptive cycle. Those studies include the analysis of the boom and bust dynamics of the largest National Forest in the US, Alaska, with the name “Tongass National Forest” between 1908 and 2008 (100 years) (Beier et al., 2009). Beier et al. (2009) used the adaptive cycle as a diagnostic approach to identify all drivers that induced changes in “Tongass National Forest” and consequently in management~~,~~ which together shaped the governance of the “National Forest” area in Alaska during the 20th century. Another study is the analysis with the adaptive cycle of the agro-pastoral SES in the Sahelian area (Yomboli; Northern Brukina Faso) between 1975-2004 (29 years) (Rasmussen et al., 2012), where the cycle passed through once. The study explored the dynamics of an agricultural village. One more study it the one relized by. In Western Australian (Allison et al., 2004), the broadacre agricultural system (food crops and livestock) passed through the adaptive cycle twice between 1889 and 2000 (113 year), where economic dynamics were fundamental in system dynamics.

Considering the LM-SES started with the arrival of the land owner, the system is relatively young (72 years old). In contrast to the industrial forest management system “Tongass National Forest and Sahelian’s agro-pastoral system, which both passed through the adaptive cycle only once, the LM-SES underwent the adaptive cycle twice, like in the case of the broadacre agricultural systems in Western Australia (Allison et al., 2004), however in the latter case this occurred during more than 100 years. Lasting only six years (1945-1950), the first cycle in the LM-SES was extremely short, while the second cycle took 66 years (1951-2017). In the first pass through of the adaptive cycle (from 1945-1950), the late conservation phase of the system was followed by a short 4-yr back loop (started with the collapse-phase in 1945), which then transitioned into a 6-yr fore loop (1949-1954). The collapse of the system occurred because of the sudden local political change (induced by regional politics) and the drastic local change from a community based tropical forest to agricultural land. The second cycle started with the sudden death of the big landowner, the unorganized local land administration and the loss of the local economic stability, which caused a 19 yrs back loop (1955-1973). The new local land administration under national laws and the increasing local economic capital triggered the transition to the fore loop, which until now have taken 43 yrs (1974-2016). In the Western Australian broadacre agricultural systems (Allison et al., 2004), the first adaptive cycle had a much slower fore loop (40 years) than back loop (20 years), while in the second cycle, both loops lasted 20 years. In both cycles, the fore loop was initiated with the increasing local economic capital: expansion of agricultural area occurred. Low international prices, national market regulations and local land degradation induced the collapse and hence the back loop of the system. In the agro-pastoral system in the Sahelian area (Rasmussen et al., 2012), the back loop took 21 years and the fore loop 10 years. The back loop was induced by local climatic conditions: droughts influenced in the local economic situation of the farmers. Recovery of the local economic situation with the assistance of governmental support transmitted the system into the fore loop. The “Tongass National Forest” system started with the reorganization phase and the organization of the local government and the mobilization of local resources which had moved the system into the fore loop. The loss of the local monopoly policy and the loss of the local timber production started the vulnerability of this system to external drivers and ultimately to its collapse. The back and fore loops of the different systems lasted for different periods, yet similar characteristics could be identified: the back loop was initiated by the sudden loss of a government system or economical resources; the fore loop was initiated by new availability of economic resources and the organization of the local policy or management system. Some drivers were induced, others occurred in an unexpected way. The sudden death of the land owner and hence the loss of the political system in the SES-LM induced the collapse. The collapse of the Australian system was induced by the national market regulation and non sustainable land management, and in the “Tongass National Forest” an inadequate governmental decisions. The fore loops were induced by planned changes in political structures aimed an increasing economy.

The adaptive cycle allows: i) a systematic simultaneous analysis of social (Lebel et al., 2006; Daedlow et al., 2011) and ecological system changes (Allison et al., 2004), ii) to identify specific characteristics related to system adaptability to any kind of changes in the biophysical, social-economic or social-political conditions. Although Rasmussen and Reenberg (2012) argue that the adaptive cycle cannot be used as an analytical tool, since it considers exclusively qualitative data, we argue that a high diversity of qualitative data plus the histories of people offer an in-depth, integral understanding of the direct and indirect effects of events on system change, as we show in this regional case study.

Information from interviews and historical analysis of external events allowed us to understand the spatial and temporal dynamics. The LM-SES has undergone repeated structural and functional system changes in response to social, institutional, governance, and economic changes (e.g. change of land ownership, land tenure laws, international agreements like NAFTA). This relatively unstable nature may have its roots in the original (1945) top-down “brutal” transformation from a low-input balanced diverse community-based tropical forestry system to a single commodity system that ignored and eradicated much of the inherent natural and social capital.

The LM-SES it was principally the change in social structure schemes, in particular the rapid change from poly- (prior to 1945) to mono- (Landlord, bank) and back to polycentric (ejido groups) governance schemes (Kofinas, 2009) that were fundamental in the alternating vulnerability and resistance of the system to disturbances, phase changes and regime shifts, as has been acknowledged in other studies (Biggs et al., 2010; Lebel et al., 2006).

RESILIENCE OF LM-SES AND FUTURE OUTLOOK

Every phase of the adaptive cycle is characterized by a specific resilience of the system, we are discussing the current resilience and future outlook of the system. Agricultural production in LM-SES currently focuses on sugarcane and lemon, which both are commercial monoculture systems with attractive economic returns. This change did not only imply massive land use and cover changes but also massive modification of the multifunctionality of the landscape (Pasari et al., 2013), loosing economic, social and environmental services (Jones-Walter, 2008). The current production system is not sustainable as sugarcane requires high fertilizer and pesticide input. Besides, sugarcane requires large amounts of water; while in the tropical region, long drought periods have jeopardized the stable production regime; thus cultivation requires a significant expansion of the irrigation system.

However, the lack of dam water management, different water rights, and access among farmers have emerged and are currently new challenges for the LM-SES, as the income of many households depends on sugarcane. Hence, we consider the system is currently at an early conservation phase exploiting the natural resources to maximize and stabilize sugarcane production. Simultaneously the social and ecological resilience may slowly decline, while the vulnerability of the LM-SES to economic and biophysical changes increases (Hsing-Sheng, 2015). There is ample evidence that crop mixtures or crop diversity in general may improve agricultural resilience (Folke et al., 2004; Lin, 2011; Vandermeer et al., 1998), and support for the opposite – with the monocropping of sugarcane – seems to be apparent. Diversification of crops improves the resilience by minimizing crop susceptibility to pest outbreaks or pathogens (Lin, 2011). Crop diseases may become an increasing problem under existing climate change conditions (Newsham et al., 2012).

Ecological and social resilience are directly linked because of the dependence of the community on the ecosystem goods such as food, fodder, fuel and their economic activities (crop production) (Altieri, 1999; Adger, 2000). Intensive sugarcane production decreases the biophysical resilience of the LM-SES and this could trigger an increase in the vulnerability of farmers to economic changes. Potential future volatility in the sugar industry may influence the regional social resilience as has been shown also in a sugarcane region in Japan. There drop in the price of sugar, caused migration accelerated, affected the ecological system as consequence of massive use of fertilizer and water with a resultant decrease in groundwater levels (Hsing-Sheng, 2015).

In the LM-SES, a tendency of an increase in temperature and decrease in precipitation has been observed (Newsham et al., 2012). This may have important implications for the future resilience of this land use type. According to the physiological requirements of sugarcane, for an effective growth it needs large quantities of water (minimum annual precipitation of 1,500 mm unless under irrigation) (FAO, 1990). The current monoculture of sugarcane has increased water use and with the use of fertilizer will impoverish the supporting and regulating services. Intensive monocultural production systems are associated with high water consumption, loss of soil health, use of agrochemicals, and emissions of greenhouse gases (N_2O, CO_2) (WWF, 2005; Dominy et al., 2001).

CONCLUSION

A historical analysis of SES change permits the identification of indicators of system-specific social and/or ecological resilience and vulnerability to changes caused by internal and external drivers, and feedback processes. This study shows that land use policy and tenure regimes are tightly interconnected and changes in these SES characteristics seemed to have induced structural (phase) changes in LM-SES. It demonstrates the importance of human agency in a historical context to develop strategies towards the protection and management of agrarian decisions besides landscape development. It shows whether current land use systems are multifunctional and if agricultural production is sustainable. Furthermore, interesting potential cross-scale interactions between global (economy, markets) and local conditions (land use policies) emerge. The adaptive cycle was applied to identify system phases and transitions with particular land use and livelihood types. Social adjustments to new social-political structures triggered a re-organization of local governance systems which ultimately influenced land tenure and land use types in the LM-SES. Insight into the underlying causes of the dynamics of external and internal drivers, property rights and decision-making processes, inform political decision making. Hence, adaptive capacity building may guide the management and functioning of the social and ecological structures. A declining resilience in LM-SES was identified, because of the transition toa monocutlural system. It would need further research if the farmers of LM could adapt to perturbations with the degraded exploited land, which is the life support system of the ejido LM or if it needs to develop and implement new land use strategies to maintain the ecological and social wellbeing.

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Chapter IV

FARMERS' LIVELIHOODS BASED ON LAND USE AND LAND COVER CHANGE IN A TROPICAL SOCIAL-ECOLOGICAL SYSTEM

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ABSTRACT

Understanding the causes of land use dynamics and land cover change is fundamental in the light of targeting sustainable development. It requires insight into land use types and management practices and their complex relations to local farmers' livelihoods. This study examined the diversity of household livelihood groups in the tropical region of San Luis Potosí, Mexico. In particular, we examined how socioeconomic, political, institutional, and biophysical drivers contributed to differentiation in livelihood development and its respective changes in land use and management. Participatory observations and 70 structured interviews were conducted to identify the key characteristics of different households with specific economic activities. The focus group of interviewees included owners and farmers with certain rights of communal land use. We applied a hierarchical cluster analysis to identify different livelihood groups considering the selected criteria, which distinguished four groups of livelihoods. Livelihoods mainly depend on sugarcane production in combination with wage labor opportunities both in a near-by foreign lemon-factory and as employee at the sugarcane mill. Income from wage-labor in nearby factories may buffer temporary fluctuations in sugar or lemon prices, however for these livelihoods it will be more difficult to adapt to unpredictable external drivers such as pest outbreaks, shifting markets, and climate change, among others. The change from a diverse landscape to a monocropping area still permits livelihood differentiation.

Key words: *Adaptive capacity, livelihood diversification, sugarcane production*

INTRODUCTION

In tropical regions, small holders' livelihoods often depend solely on agricultural production (Rigg, 2005) and thus on local, regional and/or global demands and markets of the commodities produced. When rural households establish a diverse portfolio of activities and social support to safeguard their survival and improve their wellbeing, it is defined as livelihood diversification (Ellis, 2000), which helps to improve the ability of people to cope with and adapt to unexpected events (Davis et al., 2010) like external perturbations (e.g. climate or market change) which may affect natural resource availability or the social system (Ribeiro Palacios et al., 2012). The diversification of responses to external perturbation is a key aspect of resilient livelihood strategies (Walker et al., 2006). Under livelihood resilience is understood the capacity of a household to respond to, recover and learn from perturbations (climate change, market fluctuation) in a way to secure their earnings and livelihood patterns (Nyamwanza, 2012). Livelihood diversification offers alternatives and buffers against risks to livelihoods (Davis et al., 2010). Livelihood diversification increases social resilience to external perturbation, because key functions (food, income, etc.) are not easily endangered and extreme climate events like drought (Quandt et al., 2017; Rasmussen et al., 2012) or market changes (Allison et al., 2004) are absorbed without affecting the reproduction and well-being of people (Speranza et al., 2014). Rural livelihood diversification can be realized through agricultural (i.e., production of multiple crops or few high-value crops) and/or non-agricultural diversification (i.e., undertaking small enterprises, migration, or nonagricultural income sources) (Khatun et al., 2012).

Worldwide approximately 90% of rural households[3] are involved in farming activities (Davis et al., 2010). Almost 40% of the world population depends on agriculture for their livelihood (FAO, 2014). In Latin America about six million families, who realize commercial farming, belong to the smallholder sector and 11 million to subsistence farming (IFAD, 2011). Predominantly in developing countries, smallholder agriculture refers to farmers, where farm activities are the principal source of income. The work

[3] A household can be defined as a human group which shares the same roof and resources. Categories of a household include: • People—that is, the individuals and their livelihood capabilities. • Activities—which encompass what they do. • Assets or possessions—this is what they own be it food, property, clothing, houses, livestock, stocks and all things that provide material and social income. • Gains and outputs—these are the resources derived from what they do that allows them to earn a living. (Ellies, 2016)

is mainly conducted through family labor (Cornish, 1998). Often, small-scale farming requires supplementary income by non-farm activities (Ellies, 2016) and due to the small size of those farms; they can’t response to risks (Lal, 2000) of drought, flood, crop or animal disease, as well as market shocks (FAO, 2016). Over the last six decades global and local biophysical (Foley et al., 2005) and socio-economic (Wilson, 2012) changes have increased rapidly. In order to increase social resilience to climatic and/or economic shocks (Hethcote et al., 2016), it is fundamentally important to understand the underlying mechanisms of dynamic changes in agricultural systems and how they link to local livelihoods (Dougill et al., 2001; Fischer et al., 2008; Dalle et al., 2011). For example, practicing agroforestry significantly improved livelihood resilience to climatic change, as the perceptions of the farmers to flood and drought risks changed (Quandt et al., 2017). To compensate risk, farmers may supplement income in addition to their agricultural activities by diversifying income (Wan et al., 2016) or by participating in off-farm and/or non-farm[4] activities (Ellis, 2000; Barrett et al., 2001). In Latin America, the neoliberal market forced many small-farmers to work in the industry or to supplement their income with additional permanent jobs (Kay, 1997). In Mexico (Huber-Sannwald et al., 2012; Ribeiro Palacios et al., 2012), and many rural areas in other developing countries non-farm activities are increasingly important (Rigg, 2005; Davis et al., 2010), with marked influences on the extension of agricultural areas (Davis et al., 2010). Rapidly changing socio-economic conditions reduced the value of crops in rural land areas, and increases the livelihood activities of farm households outside rural areas. As a result, farmers have to change their income strategies and so changed from agricultural to non-agricultural activities (Eakin et al., 2008; Eakin et al., 2014).

Human activities cause land-use change with direct influences on ecosystem functioning, which then feedback on climate and the provision of natural resources and ecosystem services (Foley et al., 2005; Chapin et al., 2008). These changes, in turn, affect livelihood and land use/cover change dynamics (Ricketts et al., 2004; Vedeld et al., 2012). Livelihood change can occur hand in hand with land use change (Wood et al., 2000) /or land cover change (Ribeiro Palacios et al., 2012) or vis-a-vis (Eakin et al., 2014; Vedeld et al., 2012). In general, poorer farmers are affected by negative impacts of land use changes and are often forced to switch from agricultural

[4] Off-farm income refers to labor on other farms; non-farm income refers to income besides agricultural work (Ellis, 1998).

to non-agricultural activities to ensure their daily living. Otherwise migration would be inevitable for them. Livelihood diversification may substantially decrease social impacts (e.g. necessity to migrate, market changes), caused by land use change (Liu et al., 2015; Huber-Sannwald et al., 2012; Ribeiro Palacios et al., 2012; Eakin et al., 2008; Sunderlin et al., 2005).

In Mexico, economic and political drivers were found to have changed smallholder livelihoods from agricultural to wage-laboured activities, which consequently caused a replacement from traditional *milpas* (traditional polyculture plots mainly used for corn production at subsistence level) to intensive agricultural production, for example citrus plantation (Ribeiro Palacios et al., 2012). The change from traditional to intensive agricultural production systems increases the use of fertilizer, irrigation, and pesticides. Changes to monoculture systems have ecological and social impacts (Matson et al., 1997; Hsing-Sheng, 2015). Mexico is one of the ten most important sugar producers worldwide (ISO, 2017); of the total land (close to 800 thousand hectares) devoted to this crop, 76.3% occur in five-ha or smaller sized plots, and only 4.9% in areas larger than 10 ha (Singelmann, 2002; Senties-Herrera et al., 2014). In Mexico, as in many countries sugarcane production is associated with environmental impacts (air, water and soil quality as well as carbon releases and biodiversity loss) and forces of land use changes like deforestation for agricultural areas (Martinelli et al., 2008; Aguilar-Rivera et al., 2012; Senties-Herrera et al., 2014).

It would require a new management strategy for sugarcane farmers and sugar factories to provide a sustainable production (Aguilar-Rivera et al., 2012). Air pollution is mainly caused by pre-harvest sugarcane burning, influencing health like respiratory disorder (Ribeiro, 2008). Soil degradation (erosion, loss of nutrients, soil compaction) is caused by an increasingly mechanized cultivation including harvesting (Martinelli et al., 2008). The use of fertilizers, or agro-chemicals transport directly chemicals to the water, reducing its quality. As shown in Brazil, monocultures of sugarcane have vastly expanded at the cost of arable land for food production (Fischer et al., 2008). As a resource for energy or as a food crop, sugarcane gains on importance as a source of rural livelihood (Aguilar-Rivera et al., 2012). Understanding the dynamics between land use and livelihood of farmers can help advance decision-making processes about sustainable livelihood strategies and simultaneously improve both land use (Jakobsen et al., 2006) and agricultural management programs in order to achieve sustainable agriculture (Aguilar-Rivera et al., 2012).

This study examines current rural livelihood groups in the tropical community Laguna del Mante, San Luis Potosí, México, where the change from traditional agriculture to sugarcane monoculture is visible. The research question of this study is: “Has the regional conversion of land cover and land use change, which implied a change from traditional production to a commercial monocropping[5] system, also homogenized livelihood groups in Laguna del Mante cultural?” The objective is to identify the land use /cover change in Laguna del Mante since 1974, when the area turned into an *ejido.* Furthermore, we want to contribute to the understanding of the relation between land use/cover change and livelihood groups, finally we analyze the impacts on the resilience of livelihood groups to external changes in relation with land use/cover change.

METHODOLOGY

RESEARCH AREA

The “ejido[6]” Laguna del Mante (LM) is located in the Northern part of the tropical region Huasteca Potosina in San Luis Potosi, Mexico (LN 22° 12', LW 98° 53' West). Until 1945, this area was covered by tropical dry forest. Currently, the landscape is characterized by fragments of secondary forest embedded in a matrix of sugarcane plots, abandoned agricultural fields, citrus plantations, pastures, *milpa* and the dam La Lajilla (1026 ha), which collects water from the watershed “Panuco”. More than half (60%) of the Protected Area Sierra Abra Tanchipa”[7] (21,464 ha) occupies 29% this territory. The climate is warm sub-humid with the main rainy season from July to September and sporadic precipitation events (10%) in the months of November to March. Mean annual precipitation is 965 mm ($\pm$ 209 mm S.E.) (INEGI, 2009; CONANP, 2013a; CONANP-GIZ, 2012b). The topography is characterized by plains and gentle rolling hills and karstic relief (Newsham et al., 2012). Soil types are mainly Phaeozem and in the western part Histosol. Near the dam, Gleysol and Rendzina

[5] Monocropping: defined as continuously growing one crop species season after season (FAO, 2017).
[6] In Mexico exists the so-called “ejido”, which is a form of land tenure which is characterised by common and individual land use (Rodríguez et al., 1990). It is also the place name of the land that has this type of tenure.
[7] A biosphere is an ecosystem, nominated as such by national governments. It promotes solutions reconciling the conservation of biodiversity with its sustainable use (UNESCO, 2017).

can be found. (CONANP, 2013a; CONABIO, 2012). Agricultural production includes 55% sugarcane, 16% livestock, 21% corn, and 8% corn mixed with beans. In the north of LM, land use is dedicated to livestock farming, in the central part and in the west to sugarcane, corn and bean production. Corn and bean are generally used for personal consumption, while sugarcane and livestock are mostly for commercial use but also for subsistence. Furthermore, in the centre of LM a US company is cultivating lemon.

In 2010, LM had 2036 inhabitants, of which 1018 were men and 1018 women (SEDESOL, 2013). Most inhabitants are mestizos and 276 are indigenous (Teenek and Nahua). Of this population, 41% is economically active, and 66% of them are men (INEGI, 2010). Of a total of around 675 households in LM, 466 (69%) belongs to the focus group of this study, for the head of these families has an ejidatario status, which means he is entitled to land. Predominant economic of the *ejidatarios* are the cultivation of sugarcane for a nearby sugar factory, wage-labour in the lemon plantations of a foreign citrus company, fishing, livestock breeding, and/or the participation in governmental programs, for instance as state-financed guards of the Sierra de Abra Tanchipa or in fire prevention programs. Economic activities of non *ejidatarios* is mainly wage labour in the sugar factory or lemon plantation. According to the INEGI (2010), in 2005, 5% of the population of LM migrated mainly to the United States. Regarding education, 3% of the children (between 6 and 11 years) do not attend school; 15.6% of the population of 15 years or older obtained secondary or higher education, while 25.4% of the population of 15 years completed basic school education (INEGI, 2010).

DATA COLLECTION AND ANALYSIS

We conducted 75 structured interviews to identify land use/cover change over the last four decades and different agriculture-based livelihoods that characterize LM today. Data collection was based on snowball sampling. Our focus group of the interviewees were “*ejidatarios*” and male children of “*ejidatarios*” who possess land in the village. We differentiated between the social status, because they have different rights (e.g. land right, political rights) in an ejido. Traditionally the land belongs to the “*ejidatario*” who has to assign the property rights of land to one or all of his children. Mostly children of “*ejidatario”* do not have their own land and are working with their fathers. During data collection we observed that most women “*ejidatarios*” had handed over the responsibility of agricultural work of their land to their husbands. As six interviews had missing data, we took into account 69 interviews for the analysis. The missing data occurred when the interviewee did not have or did not want to give any information.

Land Use/Land cover change

In Laguna del Mant we can identify four different main elements of land use: a Natural Protected Area Sierra del Abra Tanchipa, sold land, cultivated land, and fallow land. As we wanted to analyze the historical land use/land cover changes of the land from *ejidatarios*, we interviewed farmers about their agricultural (livestock or crop production) changes: how many hectares of possessed land underwent cover changes or land use changes, the years of these changes, as well as the reasons. When asking about the reasons of these changes, answers about profitability ranged from the amount of money obtained, profitability of the crops produced, and the time spent in obtaining crop, livestock or fish. When asked about the motivation for change, we accepted more than one reason as an answer. Furthermore, for the historical development of the area of land use and land cover change we exclusively used the information given in the interviews and elaborated a diagram to visualize the changes over the years between 1982, when the first land use changes were mentioned, and 2016. To link and analyze land use/cover change with the indicated reasons of changes we used Cross tabulation of SPSS24.

Furthermore, land cover and land use maps were obtained from the satellite imagery interpretation of SPOT satellite images, Landsat TM and digital orthophotos of the year 1989, 1996, 2008, 2012 and 2016.The satellite image of 2016 was analyzed and classified using the supervised and unsupervised classification methods in the ENVI 4.8 software, considering the protocol for the evaluation of the use of the soil and vegetation in protected natural areas of Mexico (SEMARNAT -CONANP, 2007). The classification (in raster format) was transformed into a vector format and put on the satellite image in the ArcGIS 10.3 software, which analyzed the correspondence between the different classes and the tonalities, shapes and textures present in the satellite image. The polygons of the areas that were mistakenly classified or when there were doubts were directly verified in the field and georeferenced with a GPS. During field trips, the type of vegetation, physical conditions of the land and land uses were corroborated. Furthermore, workshops with local inhabitants were realized to identify and confirm the actual land use/cover where access was difficult.

In the ArcGIS 10.3 software, the vector layer of the 2016 classification was superimposed on the 2012 image and, based on the visual analysis, directly on the monitor, the polygons were classified, re-labeled and delimited where there was no correspondence between the class and the image. Subsequently, the corrected 2012 layer was superimposed on the 2008 image and modified. This was than superimposed on the layer of 1996 and so on until the 1989 image. From the land use maps for the years 1989, 1996, 2008, 2012 and 2016 the areas corresponding to each land use were calculated for the dates indicated and hence the trends of change in the *ejido* identified.

Livelihood

We linked social and land use variables to different categories of a household: age, education, sources of income, size of possessed land, and possessed land in agricultural use, percentage of sale or auto consumption of the harvest, type of crop, access to irrigation system, impacts of migration in the personal economic situation, and access to governmental support (Ellis, 1998; Ellies, 2016). We included age, because of different obtained skills during one's life cycle and different energetic capacity of younger and older people (Ellies, 2016). Education is a relevant variable as it provides the possibility for further skill trainings to improve livelihood. Furthermore, better education and skill development help reach a diversification of livelihood (Ellies, 2016; Porter et al., 2010). Different sources of income increase livelihood diversification (Ellis, 1999). Size of possessed land is important as it represents the basic source, which allows growth of the agricultural business (Ellies, 2016). The size of land in agricultural use refers to the part of possessed land that is actually producing and is directly linked to the income of the farmer (FAO, 2014). For the livelihood analysis, we defined different ranks of cultivated land: <1 ha, 1-2 ha, 2.1-5 ha, 5.1-10 ha, 10.1-20 ha, 20.1-60 ha and >60 ha (FAO, 2014)[8]. The type and amount of crop and agricultural production systems reflect agricultural diversification and hence, livelihood diversification (Ellis, 1998). The access to an irrigation system

[8] Our definition of the ranks was oriented by the defined ranks of the FAO (2014), who had the following ranks: <1 ha, 1-2 ha, 2.1-5 ha, 5.1-10 ha, 10.1-20 ha and >20 ha. As each "*ejidatario"* during the construction of the "*ejido"* in 1973 originally obtained 60 ha, we additionally defined the ranks 20.1-60 ha and >60ha.

can help increase farmer's income (Ellies, 2016). Migration often helps to diversify income sources of a household (Thiem, 2008). Access to credit and ability to obtain loans allow the farmer to increase livelihood diversification and to start up or improve a business (Ellies, 2016). The percentage of sale or auto-consumption is used because the income or use from the own harvest and agricultural wage-labour can increase livelihood diversification (Ellis, 1998).

Information about crop management was included. During data collection and analysis, we found that sugarcane cultivation is managed by outsourcing, which means that the farmers are employed as labor force of the sugarcane-mill and obtain from the sugar mill knowledge and technology regarding soil preparation, fertilization, pest control, and harvest techniques.

For the livelihood analysis we used the hierarchical cluster analysis in SPSS v24 software, as we were interested in defining different groups (Ribeiro Palacios et al., 2012; Solano et al., 2003; Baltenweck et al., 2003). With cluster analysis, one can categorize a system by organizing observations, in this case farmers, into groups where members of the groups share properties in common (Solano et al., 2003). We used for the measure of similarity the "*Linkage between the groups"* to measure the correlation between variables and for the cluster algorithm the *chi-square measure* (for nominal and ordinal variable) (Norusis, 2009). If there is a high degree of collinearity between the variables, they are not sufficiently unique to identify distinct marked segments. If highly correlated variables are used in cluster analysis, specific aspects covered by these variables will be overrepresented in the clustering solution. Prior to cluster analysis we used Pearson's correlation analysis to determine collinearity of the variables (Mooi et al., 2011).

Unfortunately, hierarchical methods provide only very limited guidance to decide on the numbers of clusters to be retained from the data (Norusis, 2009). In order to present the results graphically, we employed the commonly used dendrogram and compared the different variables in a classified group; hence we could compare and identify the crucial variables for the group in relation to land use (Norusis, 2009). For the characterization of the different groups we used the descriptive and cross-table analysis by SPSS24.

RESULTS

LAND USE / LAND COVER CHANGE IN LM

We reconstructed the historical land use change of the land of the interviewees. In this context, it is important to note that in 1973 the ejido Laguna del Mante was declared. During this time, every *ejidatario* possessed two hectares of land. Since 1994, as a result of the amendment of Article 27 of the Mexican Constitution, the people in LM decided to change their land management from common to privately owned land. An outcome was that every *ejidatario* in LM obtained eight cows and 60 hectares land. Today, 92.2 % of the *ejidatarios* sold at least part of the originally allotted land and does not possess the full 60 ha anymore. In the year 2000, many farmers sold their land nearby the dam La Lajilla to a foreign citrus company. During these twenty-three years, 7.8 % could buy land and these *ejidatarios* now possess between 60-75 ha.

Results of Interviews of land use and land cover change

Currently, 64% of all interviewed farmers possess between 21 and 60 ha land; 17% own between 11 and 20 ha land. A minority of the farmers (14%) has less than 10 ha divided into 6% owning between 6 and 10 ha, 4% owning 3-5 ha, 1% owning 1-2 ha; 3% sold all their land. Since 1994, 5% increased their land property and now possess up to 75 ha.

66 % of the possessed land is fallowed land and 34 % is in agricultural use, which means it is either cultivated (*milpa*, sugarcane) or used for livestock. The majority of the land in agricultural use is cultivated with sugarcane (24%), 8% is used for livestock and 2 % *milpa*.

17% of the households cultivate between 21 and 60 ha, followed by 15% who cultivate between 3 and 5 ha, and another 14% cultivate between 6-10 ha. The minority of all households (3%) cultivates up to 75 ha. 29% of all households are not depending on agricultural work and hence do not obtain cultivated land. Mainly, if the farmers have a land property between 3-5 ha, they cultivate 1-2 ha land. Even if the farmers possess between 11 and 20 ha, they just use between 3-5 ha for agricultural use, because of missing financial resources to cultivate all the land. Farmer who possess more than 60 ha, are using at least 21 ha for agricultural processes.

Currently, the main crop is sugarcane, as a result of evolutionary changes in its production system. The systems changed from high agrobiodiversity in the nineties to monoculture of sugarcane in 2000. 65% of all farmers realized some sort of land use/cover change. The main reasons were high profitability of the crop (86%), establishment of the sugar-mill factory (20%), and adverse climatic conditions (13%). Farmers changed from corn to sugarcane (65%), because of better profitability (it needs less time to cultivate sugarcane than corn) (49%) and benefits provided by the sugarcane mill (offered social insurance) (16%). 19% of the interviewed farmers changed from livestock production to sugarcane cultivation, because of the profitability (9%) and adverse climate conditions (7%) (sugarcane is more resistant to highly variable climatic conditions than corn, which means a secure income). 20% changed from livestock production to fallowed land, because of the sinking meat prices (16%) and climatic conditions (4%). 13% of the farmers abandoned part of their corn production, which turned their land into fallow. 11% mentioned failing profitability as the driving reason, 2% the sugarcane factory, because they preferred to invest into sugarcane production and hence, changed some of their land into sugarcane and let the rest in fallow.

Between 1990 and 2008 the main reason for land use/cover change was the influence of the sugarcane mill. Farmers mentioned profitability as a reason for the change mainly in the years 1990, 1995, 2008 and 2014. In this tropical region, agricultural area was increasing in general (from 537 ha in 1980 to 686 ha in 2016). Expansion of fallow land started in 2007.

Since 1982, a continuous increase in sugarcane cultivation and a decrease in corn cultivation can be observed. In 1995, livestock was losing importance in LM, but after 2014 land use for livestock increased by more than 50% (Figure 1). That the agricultural system is facing the development towards an intense monoculture can be observed in that the land cover is dominated by sugarcane. The increase in livestock in 2016 can be explained by the increasing meat prices. Also, returns from migrated inhabitants could be observed, who inverted the gained money into agricultural activities.

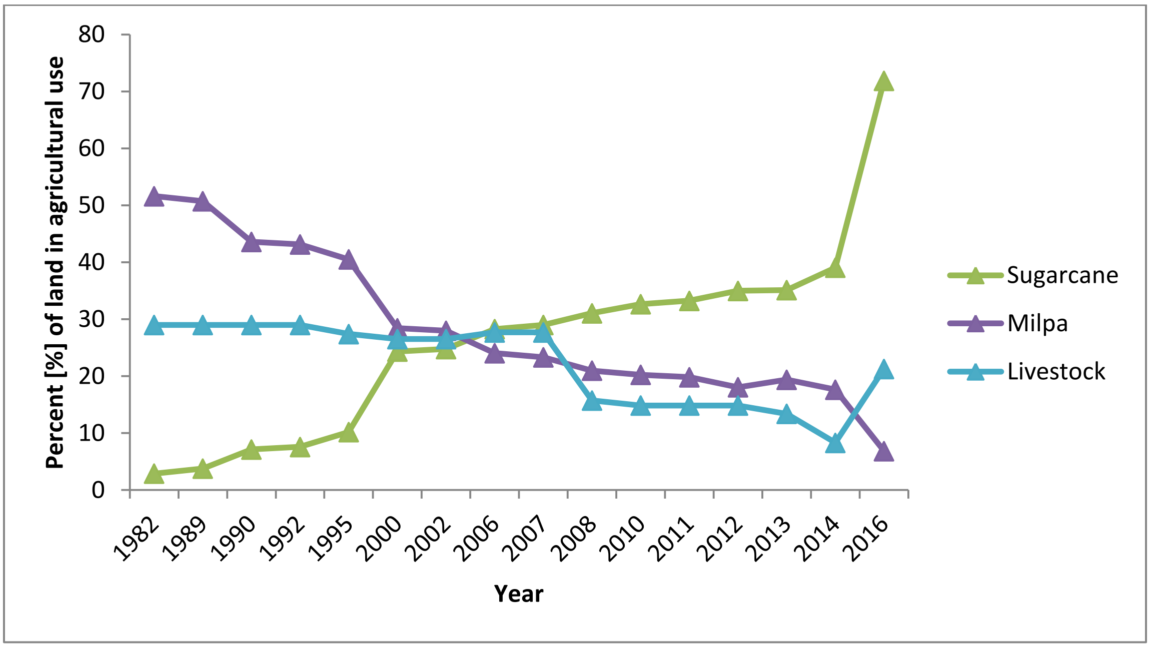

Figure 1 The development of different agricultural production systems in LM

Spatiotemporal land use and land cover change

Figure 2 shows a decrease in forest area, and a small increase in agricultural area in 2008. Secondary vegetation increased especially in 2008 but between 2008 and 2016 was declining. Livestock production was decreasing between 1989 and 2016.

Between 1989 and 1996 forest area decreased (2%) and livestock area increased (2%), mainly in the west of the *ejido* Laguna del Mante. Livestock area was mainly identified near the dam La Lajilla and close to the settlement area. In the period between 1996 and 2008, the decline in forest area continued (6%), and livestock production dropped (8%). The agricultural area increased by 7% and the area of secondary vegetation almost doubled in size. Changes can be especially observed in the north and south of the *ejido* and, furthermore on the eastern side of the dam. Near the La Lajilla occurred the change from secondary vegetation to pasture. In the south of the community Laguna del Mante pasture converted to secondary vegetation. In the north, deforestation occurred near the Sierra Abra Tanchipa. Between 2008 and 2011, changes were mainly observed in low growth of livestock area (2%) in the south of the community Laguna del Mante and the decline of forest area (16%) and secondary vegetation (2%) (south of the community). According to the images, between 2011 and 2016 almost no land use/land cover change occurred, yet a low growth in pasture area (0.5%) and cultivated land (1%) could be detected (Appendix 1).

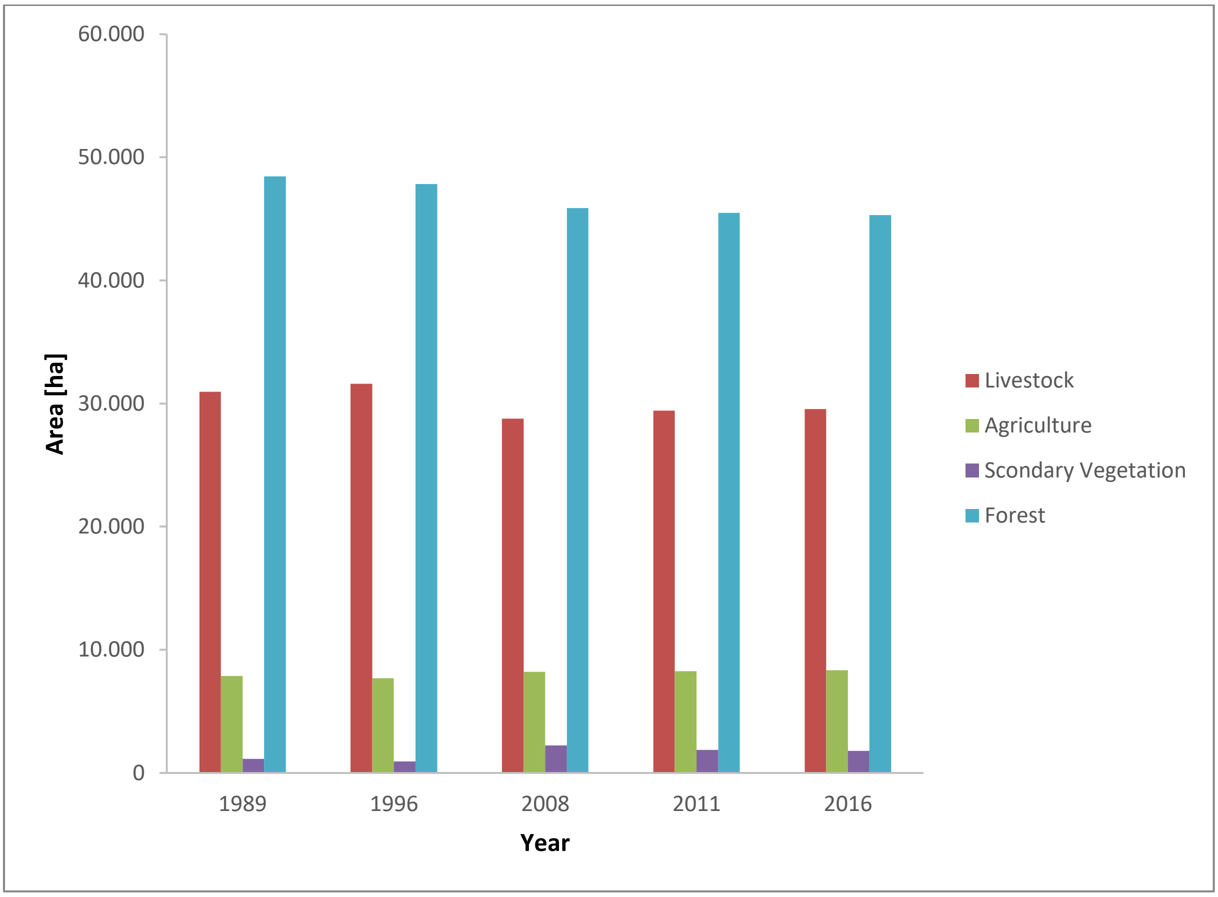

Figure 2: Land cover in Laguna del Mante between 1989-2017

LIVELIHOOD GROUPS

Four different livelihood groups were identified (Figure 3). Conspicuously all members of the four groups are working as wage labors in the near-by citrus factory or in the sugarcane harvest and in every group we could document farmers who still obtain 21-60 ha land.

Group Sugarcane: includes farmers, who mainly (89%) finance their subsistence with the cultivation and commercial production of sugarcane, accompanied by wage labour. Some of them possess between 11 and 20 ha while others own 21-60 ha, but the majority of this group (44%) cultivated 6-10 ha of their land with sugarcane. Most of them are using agricultural supply (pesticide and fertilizer). The age of the farmers ranges between 59-84 years, and they are mostly without any school education. Group members obtain governmental support (Procampo, Pension, “70 y más”). Migration is not considered for additional economic income but they all obtain remittances of family members who had migrated to the USA between 1990-1998.

Wage labour with self consumption group: Even if farmers are owning large areas of land in this group, most of the farmers are not cultivating any land but finance their subsistence with wage labor in the nearby lemon factory or during sugarcane harvest without any governmental support. A minority is using a small area of land for livestock production or the traditional *milpa* system. The crop or livestock is mainly used for self-consumption. Two thirds of these farmers are using pesticide, fertilizers and herbicides. The prevalent age is between 27-68 years and more than half of these farmers finished primary school. Almost half of the farmers of this group migrated but more than half obtains remittances of migrated family members.

Livestock and sugarcane group: Group members are cultivating sugarcane and also have livestock production for commercial purpose. Some of these farmers also do small-scale fishing. Beside this income they work as wage laborers. Almost half of the group members obtain government support (Procampo, Prospera, 70 y más). The majority of the group members possess 3-5 ha and a minority owns 21-60 ha or even 61-75 ha. The majority of the group cultivates 3-5 ha sugarcane, yet some of the group members cultivate sugarcane on land up to 75 ha. In this group, farmers own an irrigation system that is used in 1-2 ha of their sugarcane cultivation. For livestock production, 10-20 ha is used, with up to 5 cows per household. Farmers are using pesticide or fertilizer. The age of the group members is between 35-83 years and they have finished secondary school.

Diversifier Group: Farmers in this group cultivate sugarcane, maintain the traditional *milpa* system, produce livestock, and do small fish production. All agricultural yields apart from the production from the milpa system are used for commercial purpose. All group members are additionally working as wage laborers during the sugarcane harvest or in the nearby lemon factory. Most of the group members mentioned that they do not obtain any governmental support. In that group farmers possess land either between 11-20 ha or between 21-60 ha. Half of the group members are using 6-10 ha for sugarcane production. The minority is cultivating sugarcane in 21-60 ha. 11-20 ha is used for livestock production (with up to 5 cows), 3-5 ha for the traditional *milpa*. Furthermore, they work as small-scale fish producers to complement their increase. Farmers are 20-51-year-old; nearly half of them finished primary school and some finished preparatory school. The majority of the group members migrated or obtained remittances from migrated family members.

In this study we classified the group of livelihood by the factors age, education, additional sources of income, size of possessed land, size of cultivated land, and crop destination (Ellies, 2016).

- *Age:* We identified an influence of age on the livelihood group. Our first group "Sugarcane" is characterized by older farmers of around 60 years old. On the other hand, in the "Diversifier"-group the youngest group members could be observed: between 20 and 50 years old. The "Wage labour with self consumption"-group is more mixed, with group members between 27 and 68 years old. In group 3 "Livestock and sugarcane" members in their mid 30ties could be identified.
- *Education* plays an important role in the classification of the groups. Higher the education, the higher the area of cultivated land. Also, the higher the education, the more farmers are diversifying their agricultural production.
- *Additional sources of income:* "Governmental support", "migration and revenues", and "wage labour income"produces the same result: additional financial support is obtained through work during the harvest period of sugarcane or lemon.
- *Migration*: Migration played an important role in LM, especially in the cultivation of a larger area of land, because the economic capital of farmers increased. With migration earnings or revenues they could invest in the preparation and cultivation of the land. In all groups except for the "Diversifier"-group at least 50% of the group-members obtain governmental support.
- *Size of possessed land:* In the "Sugarcane" group this is 44%, in the "Wage labour with self consumption" group 65%, in the "livestock and sugarcane" group 46% and in the "Diversifier" group 78%.
- *Size of cultivated land*: In LM 34 % of the possessed land is in agricultural use. Mostly the economic situation does not allow any further investment into the cultivation of land. The size of cultivated land shows high differences between the groups. Often it is not equal to the size of possessed land. The majority of the group members of the group "Sugarcane" cultivate up to 6-10 ha land exclusively with sugarcane. The rest of the land is fallow land. The "Wage labour with self consumption" group is mostly defined by group members cultivating 2 ha *milpa* and 5 ha livestock. Most members of the group

"Livestock and sugarcane" group cultivate 3-5 ha sugarcane, use 10-20 ha for livestock and have 1-2 ha of irrigated land. The minority of the group members cultivate between 21-60 ha with sugarcane. The "Diversifier" group is defined by group members cultivating 6-10 ha with sugarcane, 3-5 ha *milpa* and they are using 11-20 hectare for livestock. A minority of the farmers cultivates between 21-60 ha sugarcane.

- *Crop destination:* Every identified livelihood group, except the group "Wage labour with self consumption", is characterized by exclusively use of the products for self consumption. Most group members of the group "Diversifier" are using their crop for both commercial and subsistence use.

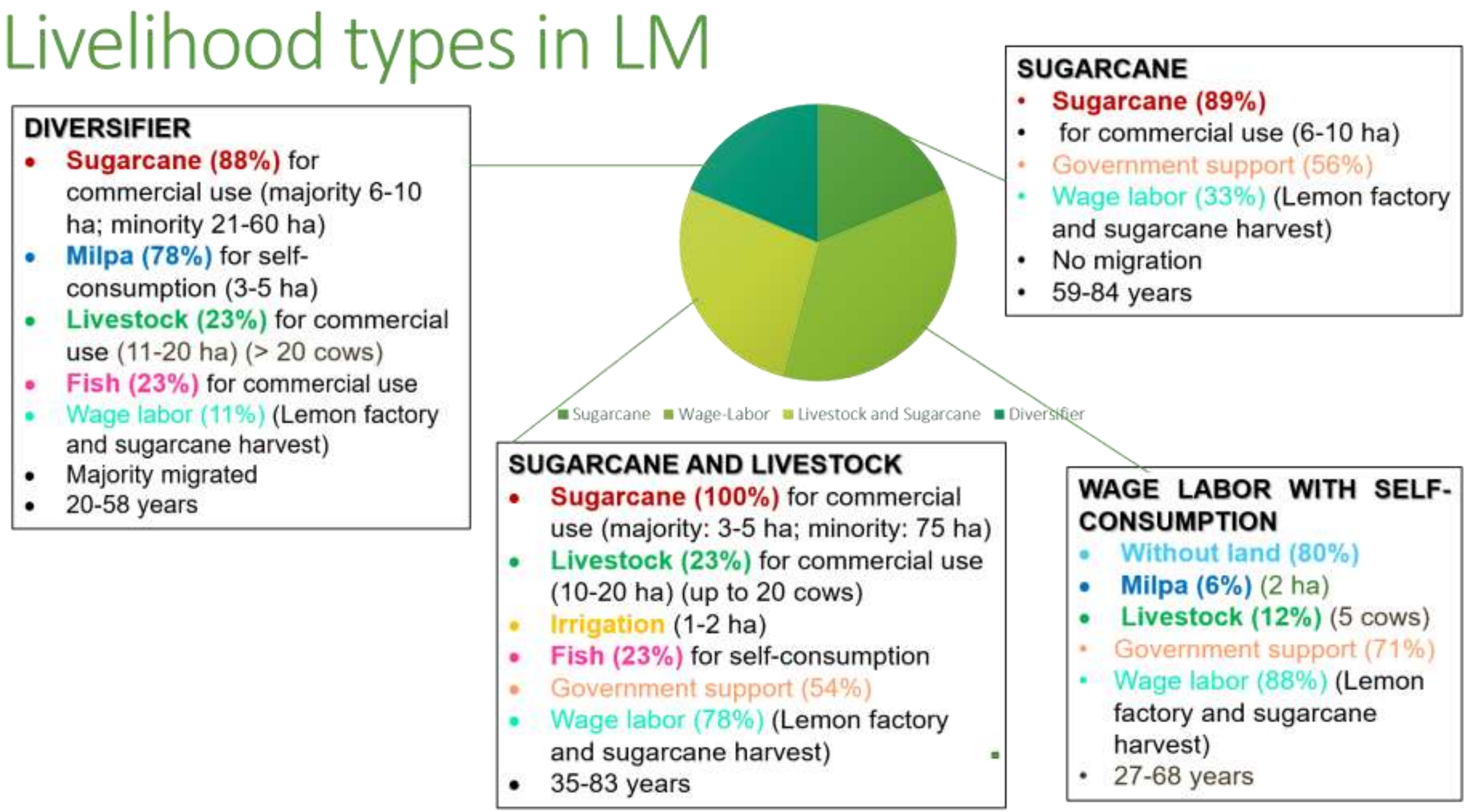

Figure 3: The four identified livelihood groups with its characcteristics: age, education, additional sources of income, size of possessed land, size of cultivated land, and crop destination

DISCUSSION

External and internal socioeconomically and biophysical drivers are causing changes in land use and livelihood in Laguna del Mante. With the conversion to the *ejido* in 1974, all *ejidatarios* possessed the same amount of land (2ha), which could be cultivated under their own decisions, mainly by the traditional *milpa* system. The use of the communal land was diverse and represented uses like the cultivation of corn, mango, sheep, livestock, and henequen, which caused a high resilience of the system. During the last 30 years, drastic changes in the agricultural system occurred in relation with the development of four different livelihood groups.

HISTORICAL LAND USE AND LAND COVER CHANGE IN LM

Four significant dates in land use/cover change (1995, 2000, 2007/2008, 2014) (Figure 2) were identified. In the year 1995, we observed an intense increase in sugarcane cultivation and a decrease in corn production. The majority of farmers decided to change from corn to sugarcane production, because of high expectations on the profitability of sugarcane as well as other benefits (like health insurance) to be obtained from the sugarcane mill. This change in land cover can be brought in context with the enactment of NAFTA and the related amendment of Article 27 of the "Ley Agraria" in 1992 (Gates, 1993). Ultimately, the conversion of land use to sugarcane promised an increased likelihood to enter international markets and to improve the economic situation of farmers (Lewis, 2002). NAFTA massively influenced the international market, for example in the citrus prices, which in turn caused modifications and adjustments in rural livelihoods of small farmers in the Huasteca Potosina (Ribeiro Palacios et al., 2012).

As a result of the new agrarian law, land tenure and access to land in LM changed in that land could be privatized. The inhabitants of the ejido LM voted for the privatization of land. Once privatization of communal land was in place, each *ejidatario* in LM obtained 60 ha of land. With the change from common to private land each farmer could decide independently what kind of crop to cultivate; now land use did not depend on common politics but on individual decisions. *Ejidatarios* could now rent or sell their land. Many farmers started selling but not renting their land to the private sector. In an example in Sonora (Lewis, 2002), the amendment of Article 27 of the "Ley Agraria" (1992) caused the decline of governmental agricultural support like water for irrigation system. Many farmers could not afford to cultivate crops any longer and preferred to rent their land and migrate to the USA to increase income. In another study in northern Mexico (Luers et al., 2006), this amendment of Article 27 of the “Ley Agraria” also caused the privatization of land and the selling of land to the private sector. Based on that, commercial shrimp farming was growing extremely fast in the area. As a result, since 1995 the production of sugarcane has been increasing fast in LM, based on the opportunity that every farmer could decide independently and also on the higher profitability of sugar cane at that moment. Cartographic comparisons show during 1989-1996 an increase in pasture area and a decrease in forest cover. Cruz-Fernández (2006) mentioned an established process of land use change from forest or secondary vegetation to agricultural area in the Huasteca Potosina. These land use changes mostly led to the loss of fertile soil, soil erosion, decrease in biodiversity and impacted natural protected areas (Cruz-Fernández, 2006; Reyes-Hernández et al., 2006).

Between 1985 and 2000, in the whole Huasteca Potosina the forest area and secondary vegetation decreased, whereas pasture lands increased (Reyes-Hernández et al., 2006; Mballa et al., 2011). In the year 2000, the area dedicated to agriculture and fallow land kept did not change (Figure 7), however sugarcane production had almost doubled compared to 1995 and corn production decreased. No strong changes in livestock production were observed (Figure 8). Furthermore, in 2000 farmers sold land near the dam “La Lajilla” to an international lemon factory. The lemon factory brought about new job opportunities and consequently regular income and health insurance. Luers et al. (2006) identified that selling of land to the private sector was an important driver of land use change. In that case, it implied conversion of coastal areas to intensive production of shrimp aquaculture ponds.

A further change in the access and use of land was triggered by the declaration of the Natural Area of the Biosphere Sierra de Abra Tanchipa (SAT). Within this declaration (in 1994), the whole area of the SAT could not be used any longer for agricultural activities or to collect natural resources like fuel wood, as this community accustomed to do. Apparently, SAT used to serve for livestock production as well. Today, SAT entered the program of the payment of ecosystem services for *ejidatarios*. According to Melo-Gallegos (2002), natural protected areas managed as Biosphere reserves positively impact integral conservation in Mexico. In LM, currently people do not directly depend on the natural resources of the SAT, as is the case in other natural protected areas, where sustainable use of natural resource can be observed within the Biosphere reserve (Melo-Gallegos, 2002). Other studies showed that natural protected areas favor both decrease (Sánchez-Azofeifa et al., 1999) or increase of deforestation (Liu et al., 2001).

Biophysical factors are important in land use/cover change. Huber-Sannwald et al*.* (2012) defined external and internal biophysical drivers, which both directly and/or indirectly influence the natural capital in an impairing way. Increasing water scarcity produced through anthropogenic activities (climate change, excessive extraction) is one of the most important factors for the reduced capacity of an ecosystem to provide ecosystem goods and services. Rasmussen et al. (2012) analyzed and described the collapse of livestock production because of droughts, in that case almost all farmers had to migrate. In LM, during the years 2007/2008, interviewees mentioned a high amount of precipitation, which led to flooding of crop fields. Literature data confirm heavy rains and flooding in 2007 and droughts in the following years (CONANP, 2013a; CONANP-GIZ, 2013). According to eyewitnesses not just heavy rains affected agricultural production but also strong droughts.

Especially the droughts led to an enormous loss of livestock. Also, land use cover change maps document the decrease of livestock between 1996 and 2008. Most of the interviewees mentioned profitability of sugarcane and the influence of the benefits of the sugar mill as the main reasons for land cover change in that year. Farmers changed from corn to sugarcane and the land, used for livestock, became fallow land. The photo interpretation reflected the decrease of forest and the increase of both secondary vegetation and agricultural area. Both analysis showed an increase in secondary vegetation and fallow land since 2008. Deforestation is nothing new to this area: from 1822 until the year 2011, 80% of the tropical forest got lost in the Huasteca Potosina because of land use change (Peralta-Rivero et al., 2014a; Peralta-Rivero et al., 2014b; Peralta-Rivero et al., 2016). In 2007, almost 60 % of the whole area of the Huasteca Potosina region was identified as agriculture or pasture area (Peralta-Rivero et al., 2014b).

Eakin et al. (2014) show an example of corn as the primary crop in a rural area in Sonora and how rapidly changing socio-economic conditions reduced the value of corn production, and increased livelihood activities of farm households outside of the rural residence (Eakin et al., 2014). People had to change their income strategies and so change livelihood from agricultural to non-agricultural activities. Richards (2015) mentioned the price as an influencing factor for land use change with an example of increasing soya production and the connected decrease of livestock production and increase in deforestation. The most important factor in deforestation is that farmers want to invest into valuable agricultural land properties. Agricultural land use increased for sugarcane and livestock production, as a result of decision-making processes of land use/cover change based on economic reasons (Aguilar-Robledo, 1995). Between 2013 and 2014, sugar prices rose in San Luis Potosí from 18.17 $ USD to 21.11 $ USD (bulk of 50kg) (SNIIM, 2017). Also, in 2013 meat prices rose from 0.95 $ USD in 2011 to 1.53 $ USD (per kilo).

Migrants coming back to LM and start to invest into livestock production because of attractive meat prices. Prior to that, during the years 2010-2012, 23% of the migrated farmers had come back to LM, which might also have influenced the increase of sugarcane production because the returned farmers may have invested in agricultural production. People started to invest in livestock production since 2014. Maps showed similar results.

LIVELIHOOD GROUPS IN LM

Over the last three decades, historical land use changes as well as external and internal drivers developed four different livelihood groups in LM. With permanent migration the economic situation of the farmers improved, and they could invest into agricultural activities and cultivation of land. Since the main agricultural activity in LM is the cultivation of sugarcane, sugarcane is a fundamental asset for almost all livelihood groups, however with different contributions. Apart from agricultural activities, farmers adopt additional work as helpers during the harvest period of sugarcane or in the lemon factory to supplement their income. In general, it can be said that the diversification of crops and the traditional *milpa* system decreased in LM. Different tendencies could be observed in other regions in the Huasteca Potosina. For example, in the Southern region farmers used the access to more land to maintain the *milpa* system and to diversify crop production (Ribeiro Palacios et al., 2012). The need of additional work to compensate agricultural income is currently a common strategy to diversify livelihood especially in the younger generation in LM. Until now, fish production has not turned into a reliable income sustaining livelihoods.

In the livestock and sugarcane – and diversifier group only a minority realizes small-scale fish farming as part of their subsistence.

Khatun et al. (2012) defined in a study of a crop agriculture system in West Bengal, the livelihood group "labourer", which provided less livelihood diversification. The same phenomena occurred in the labour group in the study in LM. Khatun (2012) mentioned that lack of education caused that people did not have access to well-paid activities. In LM, people with higher education could be found in the group with a larger cultivated land and diversified livelihood. Khatun et al. (2012) identified that older people had higher livelihood diversification, whereas in LM the younger farmers had a higher diversity as also confirmed by Huber-Sannwald et al. (2012). The size of possessed land did not play the most important role in LM, as it did in the study by Khatun et al. (2012), where the size of possessed land was directly connected with livelihood diversification.

Boru et al. (2015) showed the importance and increasing wealth with increase in access to cultivated land according to a case study in Ethiopia. In LM we found that groups with a more diversified livelihood usually had larger areas of cultivated land. Furthermore, the group with higher livelihood diversification considers crop use either for auto consumption or for sale. Ellis (1998) explained that the use from own crop harvest and agricultural wage-labour may substantially increase livelihood diversification. Migration as a source to increase the income played an important role in the livelihood of the farmers and in the possibility to invest in the cultivation of land. In every group, we identified that almost all farmers had some support from migration, mostly from remittance of family members and/or from own migration mainly to the United States of America. In the "diversifier group", migration supports income mainly from own migration. Only in case of the "sugarcane group", we found that farmers themselves did not migrate but exclusively received remittance. Commonly people who migrated, kept their land, however it was mostly abandoned land.

There exist only a few case studies, where different livelihood groups have been named and explained in the tropical region of NE Mexico. A livelihood group analysis (Ribeiro Palacios et al., 2012) in the Palzoquillo watershed in the southern Huasteca identified three groups: diversifiers, sugarcane producers, and semi-proletarianized citrus growers. Elder farmers had access to more land and hence, could maintain the traditional *milpa* system and diversify crops. Younger farmers had access to less land and were forced to increase their income with temporary wage labour in agribusinesses and citrus monoculture (Ribeiro Palacios et al., 2012). In contrast to LM, where permanent migration contributed importantly to livelihood development, Ribeiro Palacios et al. (2012) demonstrate that temporary migration has been an important source of financial income of the livelihood group “semi-proletarianized citrus growers”. In LM, most migration was permanent, yet its dynamically changing depending on opportunities in the local sugarcane or lemon agriculture industry. Many migrants still possess part of their 60 ha. In the study of Palzoquillo, farmers have maximal access up to 3 ha, whereas in LM the access to land can reach up to 75 ha.

In Amapola in the drylands of Mexico (Huber-Sannwald et al., 2012), three different livelihood groups were identified: 1. livestock producers, 2. semi-proletarian farmers, 3. migrants. The livestock producers in the Amapola system possessed between 40 and 80 animals, which contrasts with the livestock producers in LM, who possessed mainly 5 animals and maximum 20. Both depend directly on meat prices and markets, but the livestock producers in LM also have an income from their wage labor and obtain government support. Like in LM, the most resilient group is represented by the youngest group members. Their livelihood depends on the diversification of income sources. Also migration played an important role to supplement the income. In contrast to LM, where permanent migration occurred, the farmers in the drylands of Mexico gained their income from temporal migration. In both systems, the migrant group, instead of selling their land, conserved it, yet without cultivation.

LIVELIHOOD DIVERSIFICATION AND RESILIENCE OF LM

A households’ livelihood that is resilient to changes in its income sources needs a high diversity in financial sources (Hertel et al., 2010). Among the viable options to improve the resilience of farmers’ families is the diversification of crops or the engagement as a temporal day labourer in off-farm and on-farm activities (Chapin et al., 2006; Ellis, 1998). In LM the different livelihood groups depend on farm and off-farm activities, which normally represent a high economic source diversity (Ellis, 1998). Off-farm activities in LM are realized seasonally, depending on the period for the lemon or sugarcane harvest. In contrast to sugarcane, which is used as a crop for on- and off-farm activities, lemon is cultivated by only one foreign company. However, despite of the fact that individual group members (households) of the different livelihood groups depend on farm and off-farm activities, we argue that the resilience of the livelihood in LM is relatively low, because both farm and off-farm activities are based mainly on one single crop, sugarcane, which is principally commercially used. Hsing-Sheng (2015) analyzed how a whole community in Taiwan that depended on sugarcane had to migrate when sugar prices fell at international markets, which triggered the collapse of the sugar industry in that region. From 6000 inhabitants, only a few hundred inhabitants left in the village. Kabir et al. (2016) show in a case study in Bangladesh, how a community increased their economic status with the help of lemon production, starting in 2000. Furthermore, cultural habits, like also observed in LM changed, because women could earn their own money and participate in decision making processes. But the lemon production was not sustainable, because of the lack of financial and technical support. The unsustainable production provoked pest and disease outbreaks in lemon plantations, and consequently intensive use of pesticides and water, which fed back and impacted negatively farmers' livelihoods.

Regarding to the agricultural system an intensification of sugarcane production was documented, with a tendency to increase in the future. Turner et al. (1993) observed some of the negative consequences of agricultural intensification, in particular involution, diminished well-being, and environmental degradation. Involution occurs when increasing demand is met by output intensification but at the cost of decreasing or small marginal and average returns to outputs. They note that intensification can lead to real losses in social, cultural and economic well-being. Intensive land use may mean increased competition and conflict over land - especially in areas of high density. Ellis (2000) mentioned how farmers with monoculture production systems are losing the potential for livelihood diversification considering number of crops, alternative economic activities and the use of different agricultural productions (commercial, own use), which also could be combined with livestock or/and fish production, or a combination of agricultural activities and other occupations (Ellis, 2000).

Livelihood and land use depend on each other (Foley et al., 2005; Chapin et al., 2008). Paudel (2016) mentions how the intensification of sugarcane production reduces crop diversity, which would be one factor to cope uncertainties and changes and hence reduces the resilience of the farmers to climate and market changes. Multiple cropping supports the farmers and could improve the resilience; for example, while prices may fall for one crop this may not jeopardize income, as farmers could sell other crops of this mixed production system. The growing sugarcane production and its potential negative impact on social and ecological subsystems require the development of new cultivation strategies for sugarcane production increase livelihoods resilience to climate and market changes and maintain social and ecological wellbeing.

If current livelihood persists in the future it is expected that even for the livelihood groups that develop off-farm activities in the lemon factory, seasonal migration could become unavoidable if the lemon factory had to close or to reduce the number of seasonal harvest workers. The lemon production depends on the international lemon market but also on access to water. Actually, the lemon factory obtains water from the near-by artificial dam “La Lajilla”, but the water use is increasing in LM. Today, there are just a few sugarcane farmers using the water from “La Lajilla” for their irrigation system, but the tendency is increasing. Furthermore, there are more droughts observed than before in LM (Newsham et al., 2012), what probably causes a limited access to water in the future. Till now, there are no water management plans. Based on this situation, the resilience, and hence the adaptability to shocks, of some farmers of the livelihood groups could decrease to external events (climate change, market fluctuation) (Adger et al., 2002; Quandt et al., 2017). The decrease of the water resource could be a future driver for triggering migration (Chokkalingam et al., 2007) and hence, influence and change livelihood groups.

The similarity between the different identified livelihood groups in the LM is triggered by the nearby established sugarcane mill, the growing sugarcane industry, the international NAFTA trade agreements in the 1990s and its impacts in the amendment of the Article 27 of the Mexican Constitution in 1992. This change included new regulations of land and natural resource use in Mexico. The *edjidatarios* changed common to private land. As a result, 92% of the farmers sold part of their land and it was possible for the lemon factory to be established in LM. 32% of the interviewed farmers changed the cultivation to sugarcane because of a higher profitability.

The most resilient group of households to climate change and market fluctuation are the "Diversifier" as they depend on various agricultural crops, livestock, fishery, off-farm or governmental support and do have a higher school education, which improves the capacity for decision making processes and thus improve their consciousness and alertness to changes (Fazey et al., 2007). But, the resilience of the system depends on the diversity of the identified livelihood groups, hence on diverse households. In LM the community finally depends mostly on sugarcane production and as wage labour in the sugarcane and lemon production. As livelihood resilience is known that households are responding to perturbations (Nyamwanza, 2012), we identified that it is not enough to analyze the diversity of each livelihood group and agree with Goulden (2013), who mentioned that the increase of the resilience of the households livelihoods does not mean that the resilience of the system increases and that the resilience of the livelihoods can not only be identified on its diversity of the households, but also it has to be taken into account different livelihood groups and the source of its incomes.

A community with a diversity of accumulated individual skills increases the ability for adapting effectively to changes (Fazey et al., 2007) and hence increase social resilience (Chawla, 2008). Governmental support should facilitate livelihood diversification and improve capabilities to extend the livelihood groups in each local community. Skill training, education, micro-loans, and employment opportunities have been identified as a means to improve livelihood diversification (Yan et al., 2010), all applicable to LM. Multifaceted management and policy strategies are needed to control resources degradation, minimize economical risk and improve livelihood stability (Chokkalingam et al., 2007). But, coupled interrelations between human and ecological systems are dynamic, which makes it necessary to cultivate an awareness of those dynamics and adaptive capacity to be able to react to different situations (Goulden et al., 2013). Interventions to provide natural resources and the wellbeing of the human-being should include adaptive management and the participation of different stakeholders (Kuzdas et al., 2016).

CONCLUSION

In LM land use and land cover change occurred in parallel to the development of four different livelihood groups. The change from traditional *milpa* production systems to an intensive monoculture sugarcane crop allowed the development of four distinct yet sugarcane based livelihood groups. Especially political and economic drivers triggered land use/cover changes. NAFTA and the amendment to Article 27 of the "Ley Agraria" played an important role for land tenure changes and preparing a new situation for land use/cover changes. Also, prices of the international market had enormous influences on land use/cover decisions.

Even if the agricultural production system is homogenised, a diversity of livelihood types still exists, but with similar income sources, such as commercial sugarcane production and wage labour in the nearby lemon factory or in the sugarcane harvest. In Laguna del Mante, we identified that the group of the diversifier is likely the most resilient. The other livelihood groups in relation to land use seemed to lack resilience due to the lack of economic alternatives to cultivate their land. Income of farming and off-farming activities can not automatically be defined as a diversification of livelihood, if land use is not included in the analysis. We found potential risks for Laguna del Mante to lose its resilience, especially because the regional economy depends on one single crop.

We could observe that in 40 years, land use change has fundamentally changed land cover matrix of a former diverse landscape. This conversion from milpa system to sugarcane and lemon monocultures likely decline resilience of the farmers to external perturbation like climate change and market fluctuation.

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Chapter V

CONCLUSION

Since in rural settings, land use and livelihood depend on each other and/or together transform ecosystem and landscape multi-functionality, targeting sustainable landscape management should take into account the dynamics of both of these fundamental social-ecological systems features. The maintenance of a functioning production system or agricultural ecosystem as the source of livelihood of people depends on the system's capacity to recover its structure and function after a disturbance event, which can be achieved or enhanced by resilience thinking in decision-making processes. The resilience framework could greatly enhance the adaptive capacity of a community including adaptive management and thereby increase the ecological, social and social-ecological resilience of a system to surprise and/or shock events and thereby contribute to the wellbeing of people.

To fully understand how social-ecological systems (SES) work, it is important to analyze their spatiotemporal dynamics and the influences of different types of external drivers that influence these dynamics. Drivers that affect land use and/or land cover change may directly or indirectly also influence people's livelihoods with potential influences on the resilience of the focal SES. When external drivers alter the spatiotemporal dynamics of a SES beyond its capacity to auto-regulate its inherent feedback mechanisms, the system may collapse and/or undergo a regime shift. Hence, understanding key system characteristics including potential thresholds of important variables is fundamental for the development of management options.

We addressed the research question of what external drivers triggered spatial and temporal biophysical and socioeconomic changes in the social-ecological interactions of the SES "*ejido*" Laguna del Mante (LM). With Holling's adaptive cycle metaphor it was possible to identify important historical processes that shaped the current land use/land cover type and contributed livelihood development. The LM-SES is a relatively young, highly dynamic system that has undergone several phase changes in social processes coupled to land use changes and institutional changes. The first conservation (*K*) phase represents a tropical dry forest with a well-established social structure based on subsistence farming and community forestry. Drivers transforming the system were land conversion to agriculture and the top-down governance of as new landowner. A development of a large livestock enterprise led to the reorganization of the social-political and economic structure of the original forest-. Yet, the sudden death of the landlord triggered the collapse of the livestock-based system, likely as a consequence of the mono-centric top-down governance system and the lack of previous empowerment of farmers. Subsistence livelihoods and the expansion of the *milpa* production system resumed in this region. Formation of the new *ejido* Laguna de Mante, increased the population through immigration from other nearby regions favouring agricultural diversification, new cultural structures, social organizations and the convergence of diverse sources of local knowledge. New neoliberal policies at the national and international level associated with NAFTA triggered local changes in the newly established structures of the LM-SES causing the demise of the *ejido* land tenure system and the expansion of both industrial sugarcane production in form of monocultures and lemon plantations associated with the arrival of an international citrus factory. Today, the socioeconomic structures depend almost exclusively on these land use types.

The adaptive cycle is a highly useful heuristic tool to understand the short- or long-term impacts of drivers in a system and how the system responds to, resists to and recovers from changes triggered by external drivers. Land use policy and tenure regimes are tightly interconnected and that changes in these particular SES characteristics seemed to have induced structural (i.e. phase) changes. Also, decisions taken at higher institutional levels influence processes and structures directly at local scales. We acknowledge the importance and necessity in future studies to include the effect of potential cross-scale interactions that may also influence local system dynamics; for instance, the interrelatedness of the global economy and national markets may control local production schemes and land use policies.

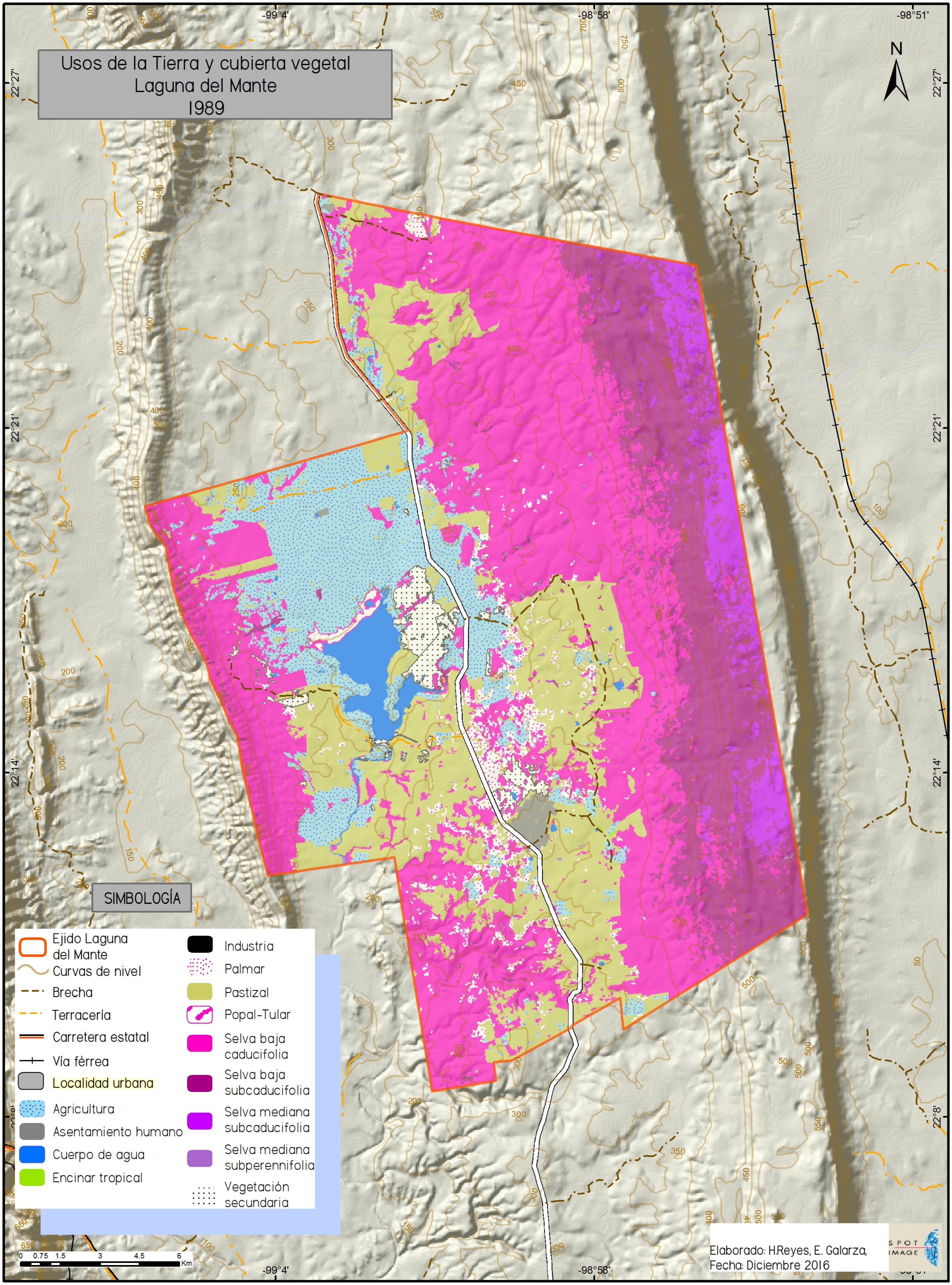
Historical land use and land cover change from traditional *milpa* to intensive monoculture sugarcane production systems in the LM-SES, are responsible for the four different livelihood groups that currently characterize the LM-SES: 1) the Sugarcane group 2) the Wage labour group 3) Livestock and sugarcane group 4) Diversifier group. These four groups depend directly (cultivation) or indirectly (wage labor) on the same intensive agricultural production system. This dependency may decrease the social and ecological resilience and decrease the adaptive capacity to external drivers like market changes and/or climate change. We argue that the income of farming and off-farming activities can not automatically be considered a process of diversification of livelihood. The young generation of farmers has a more diverse livelihood including the *milpa* farming system and new emerging agricultural (fishery) alternatives; hence they seem more responsive to new opportunities and likely will better cope with unexpected constraints.

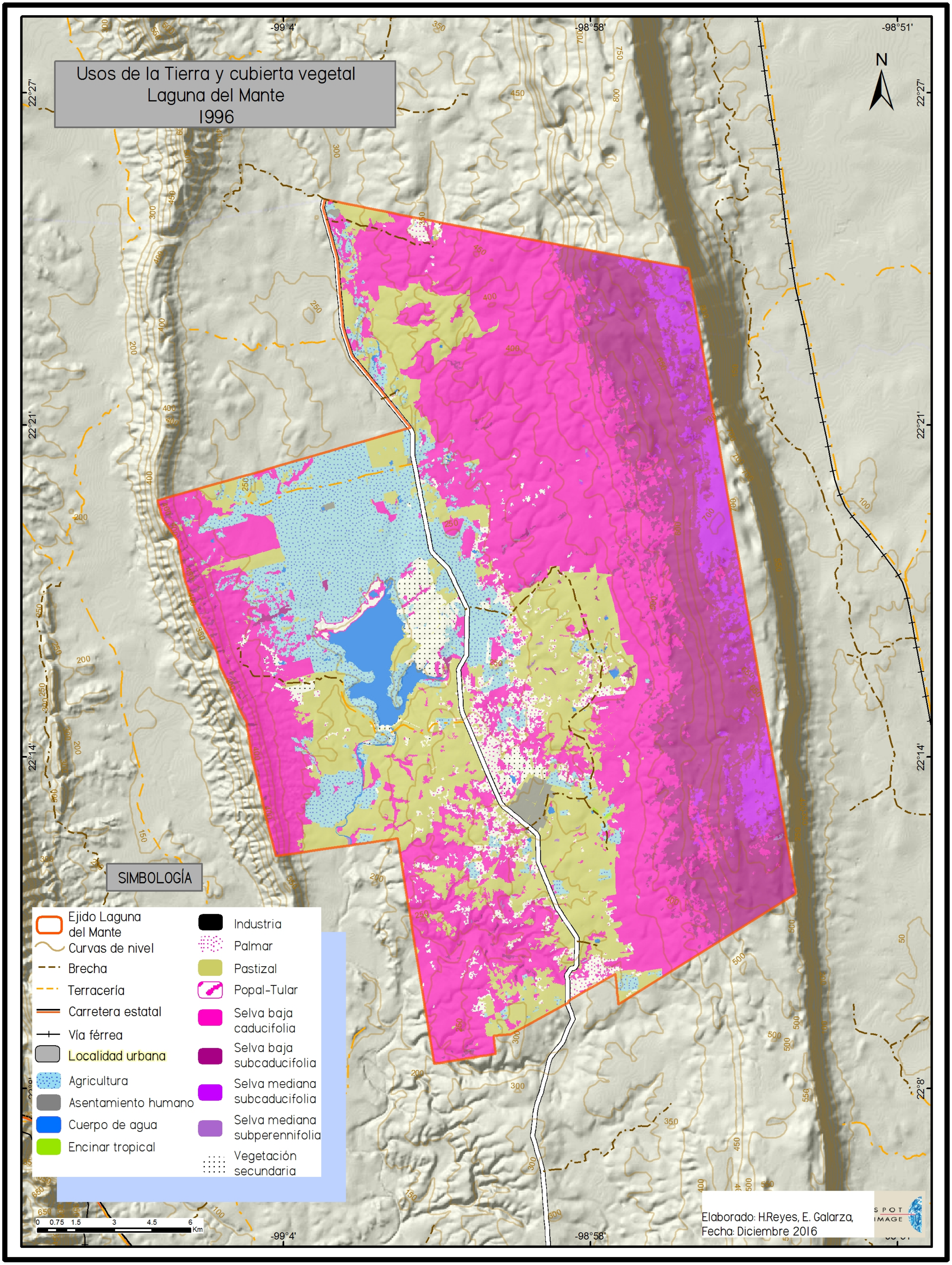
The results of this cross-scale study (from household to *ejido*, from agricultural plots to landscape land use matrix) may be useful to explore potential local strategies of some farmers and hopefully the sugar and lemon industries to consider an adaptive approach to crop management and to include concepts of ecosystem stewardship to increase the resilience of the complex LM-SES.

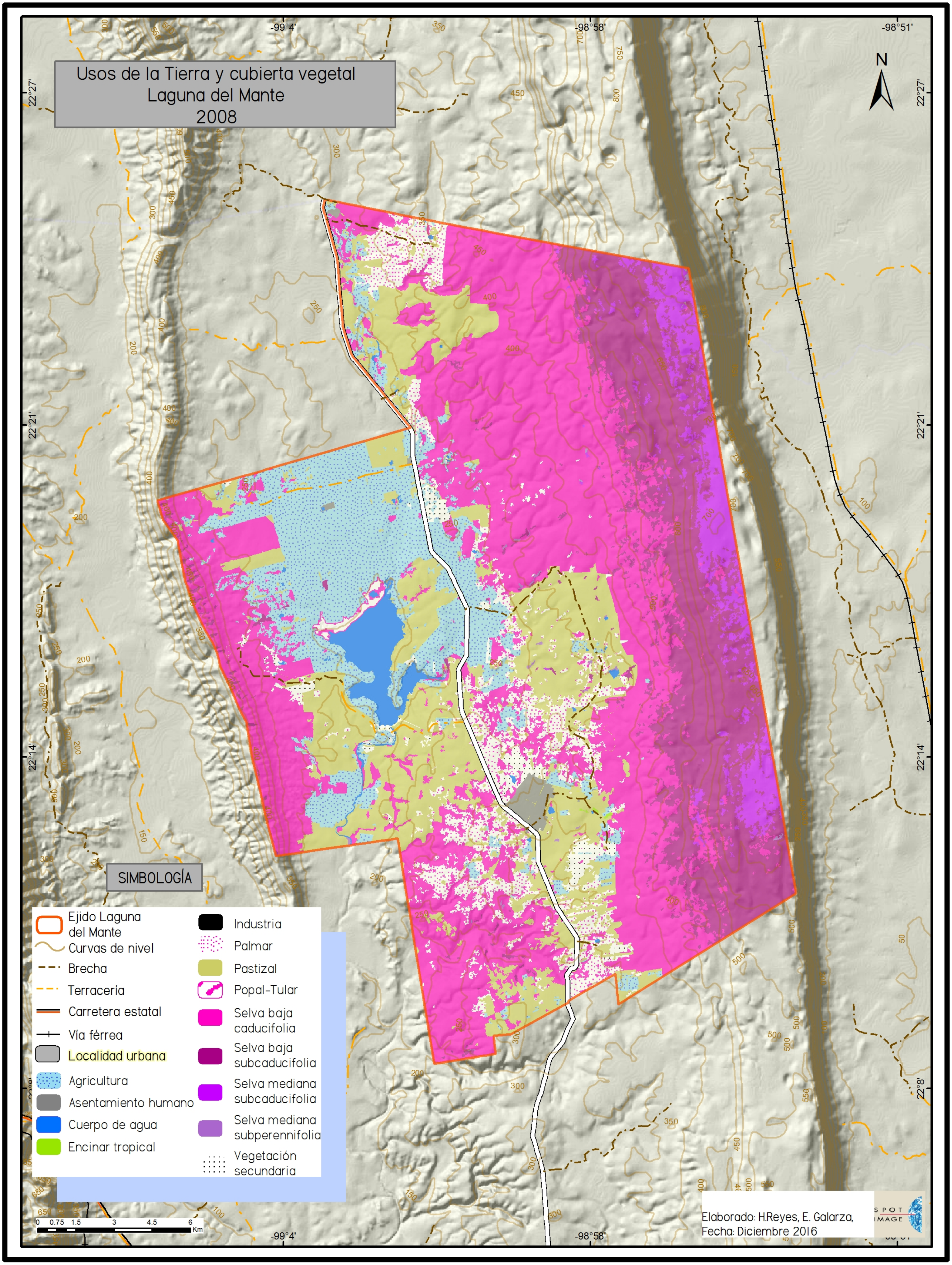
Considering the Sustainable Development Goals of the United Nations (UN, 2015) sustainability research will have to take a new direction moving away from a pure sector oriented “descriptive-analytical” approach to an integrative “transformative” one. The latter is clearly solution-oriented and based on actions to change an existing problem. Stakeholder partnerships and participatory approaches encourage the co-generation of solution-oriented, relevant knowledge to achieve desired co-defined outcomes. In particular, the implementation of novel partnership-based strategies of management of natural resources in SES requires an integral analysis and understanding of the interrelatedness between and the transformative nature of social and ecological subsystems. Suitable system specific governance schemes will promote co-defined mutual social-ecological goals, where decisions are taken collectively across sectors and actors. The development and implementation of an adaptive local governance type in the LM-SES requires integral understanding and inclusive participation of all stakeholders.

Future research should address the adaptive capacity of the LM-SES considering the advancement in land degradation associated with the industrial sugarcane production, which is currently the principal life support system. Alternatively, how could livelihood diversification develop considering alternative land use strategies to maintain the ecological and social resilience of the system and human wellbeing. A more detailed analysis of the reasons of changes in farmers’ livelihoods could help understand their potential adaptive capacity to future changes, to amplify the methodology from qualitative to quantitative methods also is necessary. To include also detailed analysis of soil and water samples to identify potential ecological impacts of different human activities on these natural resources and also to include, blood samples to analyze potential impacts of intensive agricultural practices on human health is needed. Finally, the participatory development of social, ecological and social-ecological indicators of resilience could help to better understand the resilience of the LM-SES.

APPENDIX 1:
Maps of Laguna del Mante of the years 1989, 1996, 2008, 2011, and 2016


Usos de la Tierra y cubierta vegetal
Laguna del Mante
1989
N
-99°4'
-98°58'
-98°51'
22°27'
22°21'
22°14'
22°8'
SIMBOLOGÍA
Ejido Laguna del Mante
Curvas de nivel
Brecha
Terracería
Carretera estatal
Vía férrea
Localidad urbana
Agricultura
Asentamiento humano
Cuerpo de agua
Encinar tropical
Industria
Palmar
Pastizal
Popal-Tular
Selva baja caducifolia
Selva baja subcaducifolia
Selva mediana subcaducifolia
Selva mediana subperennifolia
Vegetación secundaria
0 0.75 1.5 3 4.5 6
Km
Elaborado: H.Reyes, E. Galarza,
Fecha: Diciembre 2016
SPOT IMAGE


Usos de la Tierra y cubierta vegetal
Laguna del Mante
1996
N
-99°4'
-98°58'
-98°51'
22°27'
22°21'
22°14'
22°8'
SIMBOLOGÍA
Ejido Laguna del Mante
Curvas de nivel
Brecha
Terracería
Carretera estatal
Vía férrea
Localidad urbana
Agricultura
Asentamiento humano
Cuerpo de agua
Encinar tropical
Industria
Palmar
Pastizal
Popal-Tular
Selva baja caducifolia
Selva baja subcaducifolia
Selva mediana subcaducifolia
Selva mediana subperennifolia
Vegetación secundaria
0 0.75 1.5 3 4.5 6 Km
Elaborado: H.Reyes, E. Galarza,
Fecha: Diciembre 2016
SPOT IMAGE


Usos de la Tierra y cubierta vegetal
Laguna del Mante
2008
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-98°58'
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22°27'
22°21'
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SIMBOLOGÍA
Ejido Laguna del Mante
Curvas de nivel
Brecha
Terracería
Carretera estatal
Vía férrea
Localidad urbana
Agricultura
Asentamiento humano
Cuerpo de agua
Encinar tropical
Industria
Palmar
Pastizal
Popal-Tular
Selva baja caducifolia
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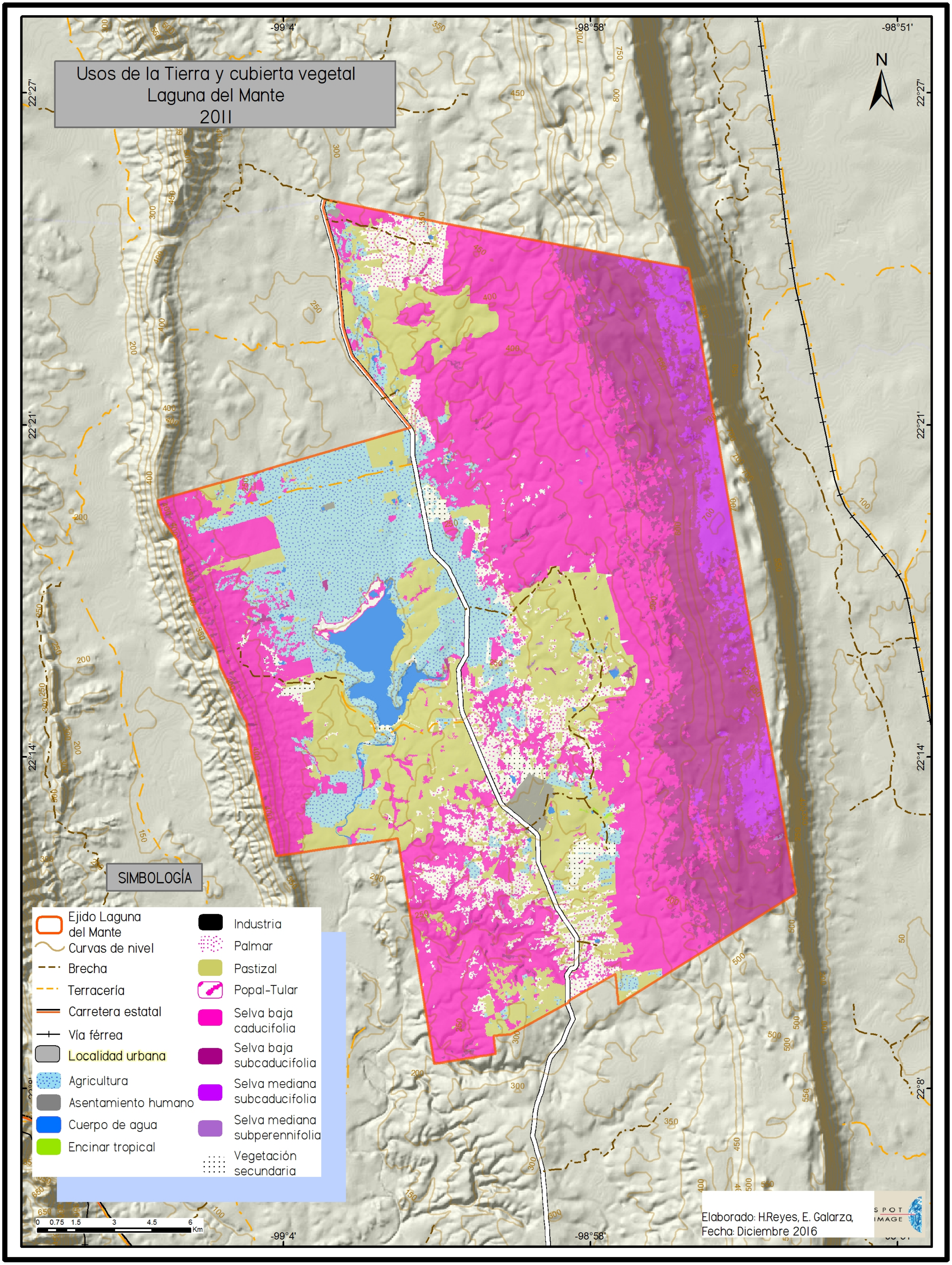
Usos de la Tierra y cubierta vegetal
Laguna del Mante
2011
N
SIMBOLOGÍA
Ejido Laguna del Mante
Curvas de nivel
Brecha
Terracería
Carretera estatal
Vía férrea
Localidad urbana
Agricultura
Asentamiento humano
Cuerpo de agua
Encinar tropical
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Vegetación secundaria
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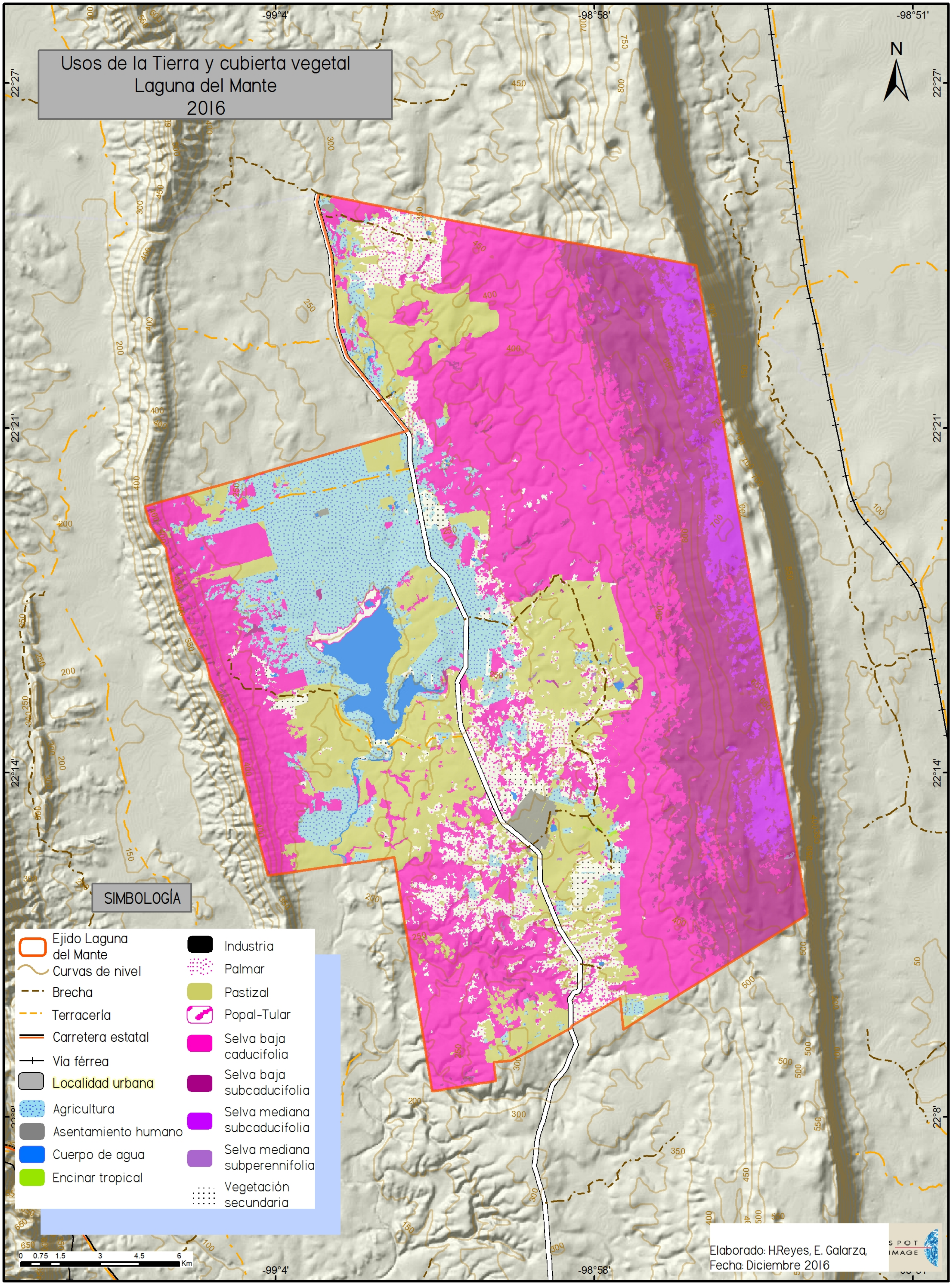
SPOT IMAGE


Usos de la Tierra y cubierta vegetal
Laguna del Mante
2016
N
-99°4'
-98°58'
-98°51'
22°27'
22°21'
22°14'
22°8'
SIMBOLOGÍA
Ejido Laguna del Mante
Curvas de nivel
Brecha
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Elaborado: H.Reyes, E. Galarza,
Fecha: Diciembre 2016
SPOT IMAGE