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Los hombres hacen su propia historia, pero no la hacen como quieren; no la hacen en circunstancias de su elección sino en aquellas con que se enfrentan directamente, legadas y transmitidas por el pasado.

Karl Marx (18 Brumario de Luis Bonaparte)

Dedicatoria

A Silvana,
esperando que logres construir tu historia
de la manera más libre y sabia que se pueda.

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Resumen

La Huateca Sur es la extension más septentrional de los bisques tropicales den el continente Americano, cuya población indígena se ubica en las laderas de la Sierra Madre Oriental. Sus sistemas de producción son típicos de ladera caracterizados por el minifundismo e incluyendo cultivos de auto abasto y cultivos comerciales (café, caña y cítricos). Durante los últimos 40 años, múltiples factores exógenos y endógenos como el acceso a la tierra, eventos climáticos extremos, nuevas tendencias del mercado, fluctuaciones económicas y oferta de trabajo asalariado asociados a las políticas neoliberales han llevado a repetidas transformaciones de este sistema socio-ecológico. Los sistemas socio-ecológicos se caracterizan por ser acoplados y por lo tanto auto-organizarse bajo nuevas condiciones, dando lugar eventualmente a cambios de uso de suelo y nuevos modos de vida los cuales influyen directamente en el funcionamiento de los servicios ecosistemicos que soportan el funcionamiento de estos sistemas. El objetivos de este trabajo fue identificar: 1) Los factores (socio-económicos y biofísicos) clave y procesos responsables de la transformación histórica y actual del paisaje; 2) que tipo de modos de vida emergieron como consecuencia de esos factores clave 3) como estos modos de vida llevaron a la dinámica espacial y temporal del cambio de uso de suelo; 4) como diferentes usos y manejos influyen la dinámica y la interacción de múltiples servicios ecosistémicos. Hicimos un estudio multi-escalar en una cuenca de la Huasteca sur, San Luis Potosí, México aplicando el Paradigma para el Desarrollo de las Zonas Aridas (DDP por sus siglas en ingles) como marco conceptual del análisis. El DDP, considera simultáneamente la dimensión biofísica y socioeconómica de la degradación del suelo. Aplicamos entrevistas detalladas con campesinos y actores clave para identificar factores clave y modos de vida potenciales, comparamos cambios temporales y espaciales en el uso de suelo (con fotos aéreas de 1978, 1996, 2006), examinamos las diferencias potenciales en la fertilidad del suelo y los aspectos hidrológicos en los usos de suelo actuales (caña, cítricos, milpa, bosque secundario). Con esos datos, identificamos posibles paquetes de servicios ecosistémicos correspondientes a cada uso de suelo. Considerando multiples factores críticos, identificamos tres modos de vida: dos grupos de campesinos mayores de 50 años que reciben subsidios de gobierno; ambos esencialmente orientados a la agricultura, los diversificadores con a) cítricos, caña y milpa o con b) caña y milpa y c) un grupo de jóvenes menores de 50 años "proletarizados", especializados en producir cítricos para mercados externos, aunado a la migración temporal para hacer trabajo asalariado. La diversificación de modos de vida a llevado a la transformación local. En las últimas décadas, grandes áreas con huertos de cítricos han remplazado al bosque secundario y las plantaciones de café, caña y milpa. La conversión a monocultivos de cítricos ha causado la degradación de servicios ecosistémicos de soporte que son fundamentales. Mientras que la caña, la milpa y el bosque secundario favorecen los servicios de soporte, regulación y culturales, los monocultivos de cítricos solo favorecen la productividad del propio cultivo, sacrificando otros servicios esenciales. Este estudio muestra que en las areas rurales, el desarrollo y diversidad de los modos de vida está estrechamente ligado al uso del suelo y el cambio de la cubierta vegetal. El desarrollo de los medios de vida se rige básicamente por la toma de decisiones de los agricultores impulsados por las limitaciones y oportunidades a multiples escalas en un entorno cambiante. Nuestros hallazgos tienen importantes implicaciones para futuras investigaciones que deben centrarse en que cuestiones son pertinentes para formular políticas que conduzcan al mantenimiento a largo plazo de los agroecosistemas.

Key words: Sistemas socio-ecológicos, diversificación de modos de vida , cambio de uso de suelo, servicios ecosistémicos.

Abstract

Huasteca-Sur is the northernmost extension of humid tropical forests in the American continent and home to a large indigenous population whose territories are located in the steep slopes of the Sierra Madre Oriental. The life-support systems of these small-holder communities in this mountainous region are characterized by corn-based subsistence and cash crops (citrus, sugarcane and coffee). Over the past 40 years, multiple endogenous and exogenous factors like land access, extreme climate events, new market trends, economic fluctuations and wage labor offer associated with neoliberal politics have invoked repeated transformation of these socio-ecological systems. Socio-ecological systems are typically coupled and thus self-reorganize under new land use conditions potentially giving rise to land use change and new livelihoods which will feedback on the functioning of these systems and their life-supporting ecosystem services. The objective of this work was to identify 1) key socio-economic and biophysics drivers and processes involved in historic and current land transformation; 2) what types of livelihoods have emerged as a consequence of these external drivers; 3) how has livelihood led to spatial and temporal dynamics of land use and cover change and 4) how different land use/management types influenced the dynamic and interactions of multiple ecosystem service types. We conducted a multi-scale study in a watershed in Huasteca-Sur, San Luis Potosí, Mexico applying the Drylands Development Paradigm as an integrative framework of analysis which considered simultaneously the biophysical and socioeconomic dimension of land degradation. We conducted detailed interviews with farmers and stakeholders to identify key drivers and potential livelihood strategies, compared temporal changes in land cover/use (with aerial photos from 1976, 1996, 2006), examined potential differences in soil fertility and hydrological aspects in current land use types (sugar-cane, citrus, milpa, secondary forest). With these data, we identified possible ecosystem services bundles corresponding to different land use and cover types. Considering multi-factor crises, we identified three distinct livelihoods: two groups of elder-generation farmers receiving government subsidies; these are essentially typical “farming-oriented” livelihoods diversifying production with a) citrus fruit, sugar-cane and corn, or with only b) sugar-cane and corn, and c) a younger-generation “proletarianized” livelihood, which mainly specializes in producing citrus fruit for external markets combined with temporary wage-labor migration. Livelihood diversification resulted in local land transformations. Over the last four decades, large areas of orchards of citrus crops have replaced a rather diverse landscape with secondary forests and shade-coffee plantations, sugar-cane agro-ecosystems and corn crops. The conversion to monocultural crops has caused degradation of fundamental supporting ecosystem services. While sugarcane, *milpa* and secondary forest enhanced supporting, regulating and cultural services, citrus monocultures only enhance crop productivity sacrificing other essential services. This study showed that in rural environments, livelihood development and diversification is tightly coupled to land use and land cover change. Livelihood development is basically driven by decision making processes of farmers driven by shifting multiscalar constraints and opportunities in a spatiotemporally changing environment. Our findings have important implications for future research which should focus on policy-relevant novel questions leading towards long-term adaptive agroecosystem stewardship.

Key words: Socio-ecological systems, livelihood diversification, land use change, ecosystem services

Life is full surprises. Sometimes we take them in stride; sometimes they trip us up

Walter V. Reid (Resilience Thinking)

1. Introduction

Human wellbeing depends on the capacity of the earth’s natural systems to provide ecosystem goods and services (Duraaiappah, 2005; Mainka et al., 2005). We rely on four ecosystem service categories: 1) provisioning services such as food and fiber, fresh water, and forest products; 2) regulating services, which regulate climate, pest and disease outbreak, water quality/quantity and erosion; 3) cultural services, which provide recreational, aesthetic, and spiritual benefits, as well es contribute to knowledge generation and cultural identity; and 4) supporting services, such as soil formation, carbon, nutrient and water cycling and maintenance of biological diversity (MEA, 2005; Chapin, 2009). Supporting services are fundamentally the structure and functioning of ecosystems. When ecosystems are impacted by external drivers such as climate change, human population growth or by human induced alterations in natural disturbance regimes, direct and indirect, immediate and long-term effects on ecosystem structure and function will feedback on the regulating services and in turn on the provisioning and cultural services and thereby increase the vulnerability of human well-being.

However, since 1950 human driven changes on the terrestrial surface have been unprecedented on Earth both with respect to speed of change and directionality marking the “Age of Great Acceleration of the Anthropocene (Steffen et al. 2007). This holds wide-ranging effects on the structure and functioning of earth ecosystems, with equally far-reaching consequences for human well-being (Turner et al., 1994; Erb et al., 2009; Persson et al., 2010). Approximately 60% of ecosystem services are being degraded or used unsustainably (MA, 2005). In rural areas of the developing world, farmers are important players in the appropriation of natural resources and continuous land use and management change, because their livelihoods depend directly on ecosystem services (Maass et al., 2005; Sherbinin et al., 2008) while urban areas are directly connected with rural areas and their delivery of provisioning services (food, fibers, water, etc.) (Chapin et al., 2009).

Over the last 20 years, rural livelihoods and interactions with ecosystem services in tropical mountain landscapes of developing countries of Latin America have undergone rapid transformations, principally by globalization and the expansion of neoliberal politics (Liverman and Villas, 2006). Furthermore, regularizations in land rights and agrarian reforms (Deininger and Bresciani, 2001) and the strengthening of top-down governance institutions have replaced local land use policies, governance structures and knowledge systems with market-based mechanisms (Stafford Smith et al. 2009; Liverman and Villas, 2006). All these changes emerged in response to the scheme of trade liberalization and global transitions to market-driven economies (Liverman and Villas, 2006). These global socio-political and socio-economic shifts have undermined the natural, social, and human capital of rural households and communities at local scales, thereby jeopardizing the fundamental local assets needed to adapt to change i.e. to maintain social-ecological resilience (Chapin et al., 2009).

In consequence and response to this global socio-economic transformation, local rural livelihoods followed two main options; 1) they expanded from being strictly agricultural based to wage-labor based (Reardon and Escobar 2001) frequently leading to agriculture abandonment or 2) they opted for maximizing the production of a single crop/commodity or good (e.g. livestock in drylands), i.e. investing in provisioning services at an unintended or often overseen decline in regulating, supporting and/or cultural ecosystem services (MA, 2005). Any of these rural transformations led away from the intrinsic multifunctionality of landscapes. These changes have presented daunting challenges for ecosystem management, as rapid growth in human population and food production seemed to justify maximizing yield production rather than considering integrated whole system management. The findings of the Millenium Ecosystem Assessment (2005) on the severely degraded state of many ecosystem services of the global ecosystems has called for a paradigm shift in ecosystem management and for the necessity to consider multiple ecosystem services when defining landscape scale management practices. While some of the interactions between ecosystems, their services and human well-being are well known, other aspects are poorly known and difficult to monitor. Local livelihoods depend on and interact directly and indirectly with ecosystem services. However, appropriation of ecosystem services not necessarily confers negative impacts on ecosystem functioning. Hence, approaches are required, that examine synergies and trade-offs among ecosystem service types (Steffan-Dewenter et al. 2007; Bennett 2009; Raudsepp-Hearne 2010) how these interactions change with time.

This emerging socio-environmental setting in a transforming global environment calls for novel policy relevant research that considers simultaneously local dynamic adaptation of livelihoods and multiple ecosystem services as fundamental elements of sustainable social-ecological complex systems (Ostrom, 2009; Perrings et al. 2012).

1.1 Social-ecological Complex system characteristics

Human societies constantly coevolve with their environment through change, instability, and mutual adaptation. As a result, land use change in rural environments is a non-linear, self-organizing process associated with complex societal and biophysical changes leading to transitions and adaptations across scales. High uncertainty and unpredictability in all these characteristics classifies socio-ecological systems as complex (Costanza et al., 1993; Walker and Abel, 2002; Folke, 2006; Lambin and Meyfroidt, 2010).

Complex systems are characterized by a set of subsystems, which are coherently interconnected and internally organized resulting in a certain structure and a range of emerging functions (Meadows, 2008). Complex system attributes include nonlinearity, uncertainty, emergent properties, scale, resilience and self-organization. Complex systems are inherently highly dynamic and organize around one of several stable states; moving from one stable state to another may be triggered by external drivers and imply a reorganization of system elements without losing the interconnectedness, structure, function and feedback responses of the system. The capacity of a complex system to navigate between a number of alternate stable states within the same stability domain / regime determines the resilience of socio-ecological systems (Walker et al. 2004, Walker and Salt 2006, Huber-Sannwald et al., 2012)

It is the high levels of diversity (biotic: species and functional groups, ecosystem services, cultural: high response diversity, flexibility to develop alternative livelihoods, social: community organizations, social networks, adaptive local governance) that increase insurance and redundancy and thus provide complex systems with a broad adaptive capacity to resist to, tolerate, re- or self-organize in response to unexpected disturbance or surprise events that may otherwise trigger regime shift (Fig 1.1A), preceded by crossing a critical threshold (Chapin et al., 2009; Scheffer et al., 2001; Berkes et al., 2006). A system's capacity to build resilience and self-organize is a critical factor, when external, internal or interacting drivers induce system change, which may occur rapidly, yet unpredictably (global population growth, migration rate, soil erosion), directionally (climate change, availability of freshwater) (Steffen et al., 2007) or as an emergent phenomenon (loss of resilience, landscape dysfunction, land degradation, desertification) (Huber-Sannwald et al., 2012).

Complex systems by definition never reach a stable state but go through a four phase - adaptive cycle (Holling, 1986; Gunderson and Holling, 2002) in the process of re-organization after a disturbance event. Reorganization is not random but determined by a system's memory, i.e. historic path-dependence, its overall condition and a given set of social and ecological opportunities. Resilience thus can also be understood as the system's capacity to reorganize (Walker et al., 2006). Depending on the severity, type, magnitude and frequency of a disturbance event, the system collapses (omega phase=release phase) and enters an unspecified system state. Depending on the adaptive options (natural, social and cultural capital) of a system, the system reorganizes (alfa phase=reorganization phase) in the same state, takes the path of a new state or because of a loss in adaptive capacity organizes in a new state in a new regime. Based on the capital assets available and the dominant external and internal drivers the system then exploits all available resources (r phase=growth phase) and finally transits into the phase of conservation (K=phase) (Gunderson and Holling, 2002). Humans tend to skip the “backloop phases” (omega and alfa phase) and concentrate on “fore-loop management” (*r* and *K* phases) by “command-and-control” approaches. Frequently, humans interfere in the adaptive cycle and prolong the *K*-phase by maximizing e.g. livestock production (focus on a single provisioning ecosystem service) and optimizing control by excluding natural disturbance, and eradicating unwanted system variability and redundancy (diversity) at the cost of future adaptation to disturbances (drought, fire, insect outbreak, etc.) (Colding et al., 2006). Prolonging the *K* phase reduces system resilience which is highest in the transition of the *r* to *K* phase. Hence, for a system to maintain long-term resilience implies systems will have to go through low resilient phases (Gunderson and Holling, 2002, Huber-Sannwald et al., 2012).

System resilience is an emergent property of system dynamics characterized by cyclical adaptive cycles acknowledging that systems will never return to the very same state as before (Fig 1.1B). Less though in the current world which is undergoing changes in human population, culture, connectedness to global economy and international markets, institutions, paradigms, technology, infrastructure (Falkenmark and Rockström, 2005). Reducing the system’s options to maintain itself within a set of desirable states, i.e. when ecological, social, economic and political conditions make the existing system untenable, the system may transform, i.e. the capacity of a system to create a fundamentally new system with new structures, function and feedback mechanisms (Walker and Salt, 2006).

Most complex system dynamics result from cross-scale interactions and hierarchical nesting of subsystems both in the biophysical (plot-landscape-watershed) and social (local governance, community organization, land property rights systems, institutional) context (Ostrom, 2007) but also by going through hierarchically linked adaptive cycles (panarchy) operating at different scales in time and space (Gunderson and Holling, 2002).

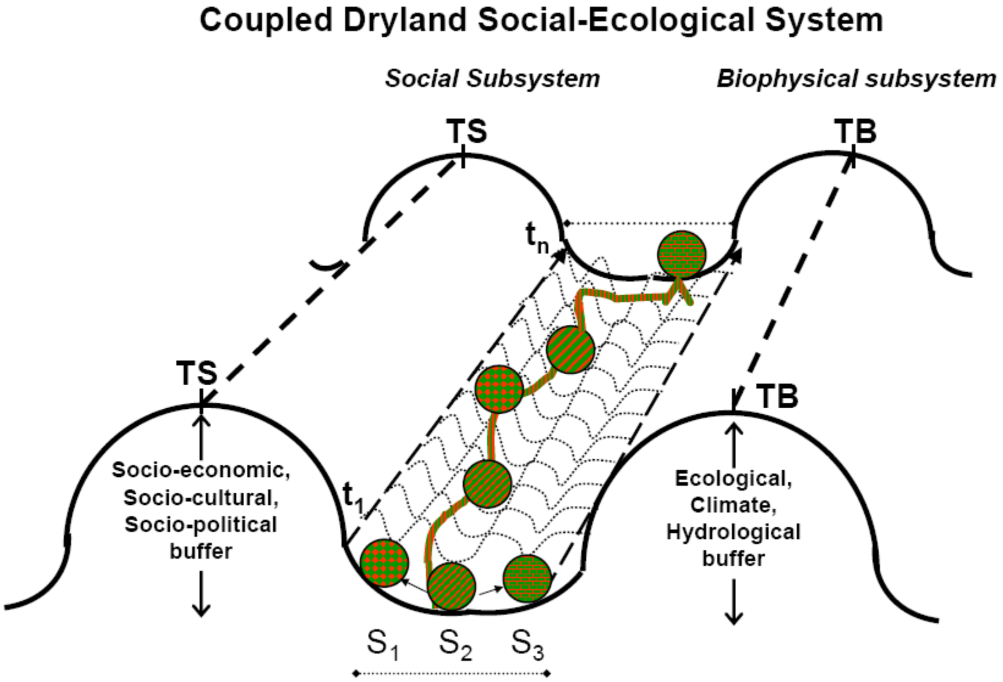

Figure 1.1A: Resilience (A) and loss of resilience (B) of coupled dryland socialecological Systems (DSES). A: the social (left) and biophysical (right) subsystems are coupled through a mutual basin of attraction, which represents the social-ecological landscape of opportunities and constraints as a function of the social, cultural and physical, financial and natural capital. In response to unpredictable disturbance events between time t1 --- > tn, the DSES has gone through three adaptive cycles of change and reorganized three different stable states (S1, S2, S3) without having changed its fundamental structure, function and feedback mechanisms and without having crossed a biophysical (TB) or socioeconomic (TS) threshold (Huber-Sannwald et al., 2012).

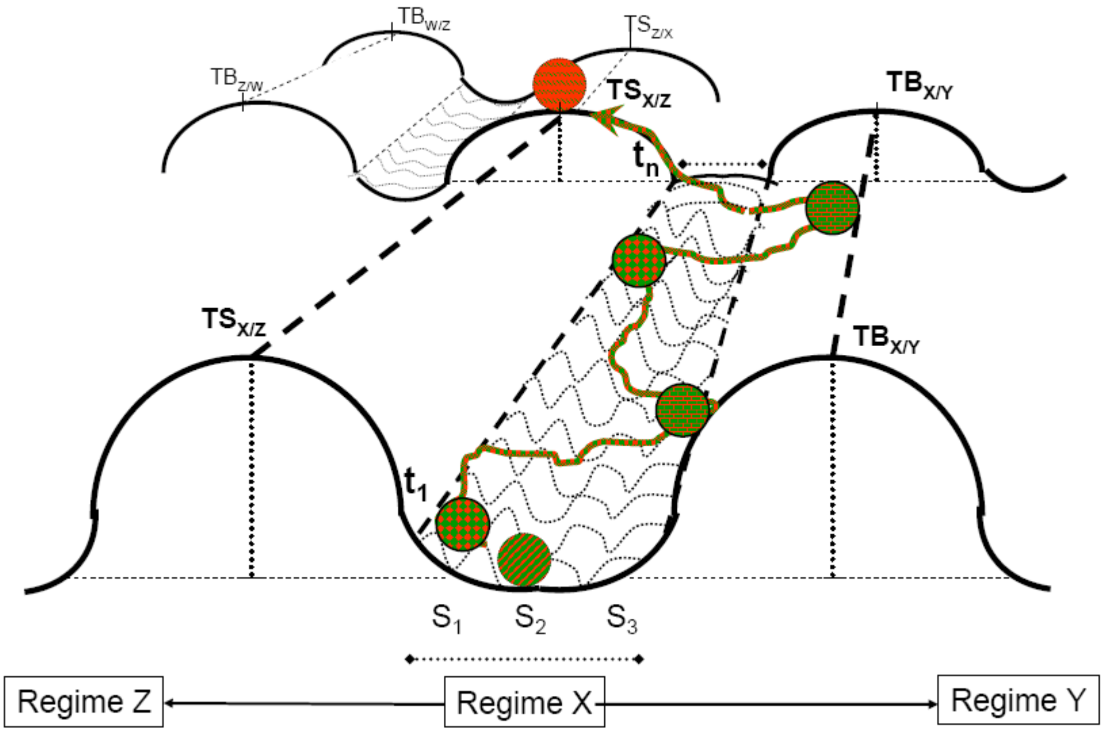

Figure 1.1B: In response to past disturbance events (triggered by external or internal drivers) and as a consequence of decline in socio-economic and natural capital (slow variables), S2 and S3 of regime X are better adapted to the new social-ecological conditions than S1. However, S2 and S3 are increasingly vulnerable to disturbance, as they approach and finally reach critical TBX/Y (e.g. shrub encroachment – slow variable, is inhibiting grass recover), which separates regime X from Y. While the DSES can temporarily recover in regime X, continuing drought (slow variable) and a lack of rapid recovery of the financial and social capital (slow variable) (see difference in height of vertical dotted lines at t1 and tn) ultimately lead to massive death of livestock and by tn, DSES finally crosses TSX/Z and enters a new regime Z (regime shift from X --- > Z). In Regime Z, the DSES either continues as a highly degraded system or it is intentionally transformed by human intervention to generate new livelihood options (diversify by introducing rain-fed agriculture; ecotourism) (Huber-Sannwald et al., 2012).

1.2 Framework for the analysis of social-ecological systems

For the study of social-ecological systems it is necessary to use a holistic framework for understanding all components of complex system dynamics. The Drylands Development Paradigm (DDP) (Reynolds et al., 2007; Stafford Smith et al., 2009; Reynolds et al., 2011) is an integrative framework for the analysis of the causal relationships and dynamics of social-ecological systems affected by land degradation. The DDP is based on five principles stating that the biophysical and socioeconomic dimensions of land degradation have to be addressed simultaneously, the focus should be on key variables and processes and their thresholds, spatio–temporal dynamics have to be analyzed in the light of cross – scale interactions; and an analysis of social-ecological system always needs to consider scientific, technical and local knowledge (Reynolds et al. 2007). In particular and unlike other frameworks, the DDP permits an integrated analysis of complex adaptive SES considering past, present and future policy, governance and management (Huber-sanwald et al., 2012).

1.3 Mountain social-ecological systems

Mountain areas cover 24% of the world's land surface (UNEP-WCMC 2002) and are home to 12% of the global human population (Huddleston and Ataman 2003), with a further 14% living in their immediate vicinity (Meybeck et al. 2001). Nearly 90% of the mountain population live in developing countries (Huddleston and Atamon 2003) and the vast majority live in rural settings (Hassan et al., 2005). Mountain areas provide important regulating and supporting ecosystem services and are repositories of high biological diversity together influencing local climates. Also, they provide vital provisioning services with a tangible economic value – such as water, power, tourism, minerals, medicinal plants, and fibers – to mountain communities (Macchi, 2010). Mountain areas are home to ethno-culturally diverse communities with a high diversity of languages and cultures worldwide; thus mountain regions are important sources of cultural ecosystem services. The proportion of indigenous peoples living in mountain areas is also high (UNEP-WCMC 2002). However, mountain environments are highly fragile as a result of their high relief, steep slopes, shallow soils, adverse climatic conditions, and geologic variability (Sonesson and Messerli 2002). Mountain socio-ecological systems are subject to a variety of drivers of change including globalization; economic policies; and increasing pressure on land and mountain resources due to economic growth and changes in population and lifestyle (Macchi, 2010). These stressors have serious repercussions on mountain people's livelihoods. Livelihoods in the mountains are considerably more susceptible to environmental and economic change than those in the plains, because the vast majority of rural mountain people engage in some form of agricultural activity and are thus highly dependent on natural resources (Huddleston and Ataman, 2003). Therefore the weakening of mountain ecosystem services due to climate change and other drivers of change will affect the lives (Viviroli et al. 2003).

In Latin America, population growth, the expansion of the agricultural frontier, little technology for agricultural activities and the new market requirements in mountain areas have resulted in extensive reduction of forest cover, non-sustainable practices and increased runoff and soil erosion (Hellin y Higman, 2002; Hellin, 2006; Ayarza et al., 2010). The resulting loss of soil productivity and biodiversity has exacerbated rural poverty (Ayarza et al., 2010).

1.4 Southern Huasteca Case Study

Mexico has large extensions of mountain tropical areas in the east and southeast region of the country inhabited by rural indigenous communities. The Southern Huasteca is the northernmost extension of humid tropical forests in the American continent located in the steep slopes of the Sierra Madre Oriental. Southern Huasteca is a tropical mountain area inhabited by a large population (ca. 60%) of rural indigenous people (Tenek, Nahuas and Pames) living in economically, and politically marginal conditions, as the land is highly vulnerable to degradation, soil erosion and loss in productivity worsening the poverty trap (INIFAP 1996). Between 1970 – 2000, close to 90% of the natural vegetation was transformed from tropical forest to subsistence and underdeveloped agriculture (Reyes et al. 2008) and population density increased (95 inhabitants / km^2) without access to basic services. These features make this site a suitable place to study the spatio–

temporal dynamics of drivers for livelihood diversification and land use change, and their feedbacks on multiple ecosystem services.

The objective of this study was to elicit the underlying causes and dynamics of livelihood development and the associated transformations of a rural mountainous landscape and impacts on multiple ecosystem services in Southern Huasteca in San Luis Potosi, Mexico.

This thesis is structured in two chapters:

A) In **Chapter 2** I addressed questions related to livelihood development in the light of global and regional environmental and social change. In particular, I adressed the following questions:

1) What are the key socioeconomic and biophysical drivers and processes that explain “decision-making processes” related to land-use and economic activities at the household level?

2) What types of livelihood have emerged in this tropical watershed landscape as a consequence of these external drivers?

3) How has livelihood development and diversification over the last 40 years led to spatial and temporal dynamics of land use and cover change in the watershed area?

B) In **Chapter 3** I explain how different land use/management types characterizing current livelihood diversification influenced the dynamics and interactions of multiple ecosystem services, thereby enhancing or impairing multifunctional agroecosystem in a rural mountainous landscape context.

I addressed the following questions:

1) What is the current status of the provisioning, cultural, regulating and supporting ecosystem services under four land uses/management types in the Palzoquillo watershed?

2) How are ecosystem services distributed spatially in the Palzoquillo watershed and how does this distribution affect landscape function?

3) What are the dominant interaction types between different ecosystem service types associated with different landuse types?

4) Considering different land use and associated livelihood types in the watershed landscape, to which degree do these socio-environmental interactions benefit (synergies between ecosystem service types), impair (tradeoffs between ecosystem service types) landscape function.

5) Will the adoption of the ecosystem services bundle concept serve to develop adaptive ecosystem management practices required for sustainable development?

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Landscape diversity in a peasant territory: emerging land use mosaics coupled to livelihood diversification

2.1 Abstract

Over the past 20 years, the multifunctionality of tropical mountain rural landscapes has been encouraged to enhance the provision of numerous commodities, as well as ecological and cultural services. However, globalization and neoliberal policies have boosted agricultural production for global markets and simultaneously marginalized fundamental rural activities related to self-supply agriculture. This trend has modified smallholder livelihoods from being mostly agricultural to becoming increasingly wage labor oriented. This shift in household income feeds back land use configuration and landscape function. We examined origins, development and current states of farmer livelihoods and associated land use and cover changes that occurred in a tropical watershed landscape of the Huasteca Potosina in Mexico between 1970 and 2009. For this purpose, we adopted the Drylands Development Paradigm (DDP) as our analytical framework (Reynolds et al. 2007). Based on aerial photographs and interviews applied to farmers and key stakeholders, we identified local, regional, national and international socio-economic and biophysical drivers that led to current livelihood diversification in several communities sharing the same watershed, and the extent and rate of land use change that has occurred over the past 40 years. We found an increasingly fragmented landscape with a diverse mosaic of land use types (citrus, sugar-cane, *milpa* and secondary forests) yet increasingly dominated by citrus plantations. This reflects an intergeneration livelihood transition towards land use decisions driven by the interaction of diverse and contrasting rural development policies, changing markets, price fluctuations and extreme climatic events. We suggest that the diversity of livelihood strategies and land use types is dynamic and continuously in transition; this creates a complex and changing landscape. The watershed landscape has responded to global markets at the cost of local needs, knowledge systems and social networks. Thus, landscape multifunctionality, preservation of ecosystem services and human well being could be at stake under current trends of globalization and global environmental change.

Keywords: Livelihood diversification, tropical rural landscape, land use transition, Drylands Development Paradigm, Mexico

2.2 Introduction

In tropical regions, farmers play an important role in the appropriation of natural resources both to feed their own needs and to respond to global markets (Sherbinin et al., 2008). Since 1970, Mexico has experienced a series of fundamental changes in its agriculture sector as a consequence of trade liberalization and expansion of market-oriented policies, land tenure reforms, the elimination of producer price support of basic crops, reduction of public investment in the agricultural sector, and the increasing import of staple foods (OECD, 1997; Davis, 2000; Hamilton, 2003; Yunez-Naude and Barceinas, 2004; Escalante, 2006). These changes had enormous impacts on the livelihoods of small-holder farms and land use in rural Mexico. Frequent land use transitions (Martens and Rotmans 2002; Lambin et al., 2003), e.g. from annual crops to fruit tree plantations, degrade ecosystems and their ability to provide goods and services needed for human well-being (Ojima et al., 1994; Turner et al., 1994; Reid et al., 2005; Erb et al., 2009; Lambin and Meyfroidt, 2010). This trend is wide-spread in rural regions of Latin America as they increasingly depend on and respond to global market dynamics and ignore increasingly the production limitations of local small household farms (Lambin and Meyfroidt, 2010; Pacheco et al., 2011). This is of great concern, as rural environments are the long-term basis for the development of agriculture based livelihoods (Maass et al., 2005), particularly in the densely populated, mountainous region of the Huasteca in central east Mexico, where marginalization and land degradation are high (CONEVAL, 2009; SEMARNAT, 2009).

Livelihood considers the income of both cash and in kind, as well as the social institutions, gender relations and property rights that support and sustain a certain standard of living (Chambers and Conway, 1991; Ellis, 1998). In recent years, rural livelihoods have increasingly shifted from subsistence agriculture to incorporating non-agriculture, off-farm wage-work and government subsidies (Barret et al., 2001; Reardon et al., 2001; Haggblade et al., 2007). This diversification reflects a survival strategy in response to climatic, economical, policy and demographic changes (Steward, 2007). Facing and adapting to these changes implies taking risks and opportunities for individual rural households, which results in continuous transformations of rural landscapes (Bürgi et al., 2004; GLP, 2005; Trujillo, 2008). Hence, a rural landscape is a highly dynamic, non-linear human-environmental system, where socioeconomic, policy, cultural and biophysical drivers constantly interact and feedback on each other in space and time (Santos, 2000; Matthews and Selman, 2006) synergistically shaping a multifunctional environment (Naveh, 2001).

The continuous transformation of rural livelihoods during the last four decades has been accompanied by farmer migration to urban areas; this pattern has been observed in the Huasteca region of Mexico and in different parts of the world (Bell et al., 2010). While in some tropical regions, migration has resulted in the abandonment of agricultural lands and their eventual reforestation (Grau and Aide, 2003; Rudel et al., 2005; Barbier et al., 2009), in some underdeveloped countries, farmers living in precarious social conditions have not completely abandoned their lands for external labor, but instead have restructured land use and management in order to combine agriculture work with temporary off-farm work and thus have become semi-proletarianized (Steward, 2007; Gómez-Barrera, 2008; García-Barrios et al., 2009). The restructuring of livelihoods, and consequently, the change in land use are determined by a complex set of drivers related to human needs, socioeconomic and biophysical risks, rapid transitions in rural development policies, and new options such as emerging markets, temporary migration, or new social networks (Ellis, 2000; Soussan et al., 2000; Mabogunje, 2010). As a result, the diversity in livelihoods that develop in certain landscapes is a reflection of the heterogeneity and interaction of external drivers, and the adaptive capacity of each household to respond to these drivers (Batterbury, 2001; Lambin and Meyfroidt 2010). Drivers may be slow such as human population growth, cyclical climatic phenomena, regime shifts of ecosystems or fast such as change in commodity prices, government policy, and annual crop yield. Drivers of land use change may be endogenous forces of social-ecological systems such as the exhaustion of natural resources, or exogeneous forces such as economic development and globalization (Lambin and Meyfroidt, 2010). Independently of their rate of triggering change they may emerge in a highly dynamic temporal and spatial context, influence different levels of organization and processes (family, legislation, institutions, etc.) (Reynolds, 2002; Zimmerer, 2004; Geist and Lambin, 2004) and induce new cross-scale linkages (Stafford Smith et al., 2007). Today, the main drivers of local transformations of rural landscapes in tropical regions such as the Huasteca in Mexico are globalization, neoliberal economy (Bebbington, 2001; Bebbington and Batterbury, 2001; Rudel et al., 2005; GLP, 2005; Moseley et al., 2010), policy reforms (Mannion, 2002; Mattison and Norris, 2005) and climatic and environmental conditions such as droughts, frosts, soil degradation and a decline in the environment's provision of ecosystem services (Ellis, 2004; Sallu et al., 2010).

Despite Mexico's new social, political and economic context, few studies have systematically evaluated its impact on the adaptability of farmers' livelihoods (Gary, 2002; Márquez, 2004; 2005) and their potential influence on the transformation rate and dynamics of landscape configuration and function.

The objective of this study was to elicit the underlying drivers and dynamics of livelihood development and the associated land use transitions in a rural mountainous landscape in the tropical Southern Huasteca in San Luis Potosi, Mexico. In the following sections we aim to 1) identify key socioeconomic and biophysical drivers and processes that explain "decision-making processes" related to land-use and economic activities at the household level, 2) identify and characterize the emerging livelihoods as a consequence of these drivers 3) examine how livelihood development and diversification over the last 40 years have led to spatial and temporal dynamics of land use and cover change in the watershed area. To examine the interrelatedness between livelihood adaptation and landscape transformation in response to external drivers, we applied the Drylands Development Paradigm (DDP), an analytical framework based on five principles created to study complex social-ecological systems (Reynolds et al., 2007).

2.3 Methods

2.3.1 Study location

The Southern Huasteca is located in the Sierra Madre Oriental in the east of San Luis Potosí, Mexico. This region is of great importance: 1) historically and culturally for its large rural indigenous population (60% Tenek, Nahuas and Pames) and 2) ecologically because it is the northernmost extension of the tropical forest biome of the American continent (Rzedowski, 1978). Between 1970 and 2000, 90% of the natural vegetation was transformed from tropical forest to underdeveloped and subsistence agriculture (Reyes et al., 2008). The steep hill-sides of the Southern Huasteca are highly marginal from a political, economic and environmental perspective; these limiting conditions and a high population density (95 inhabitants per km^2) (CONAPO, 2005) have caused increasing trends of farmers to migrate to other regions in Mexico and the U.S.A. (Gallardo, 2004).

The study area included the Palzoquillo watershed with a north and south-facing slope covering an area of 774 ha; it is located between the municipalities of Huehuetlan and Coxcatlan (latitude 21º 33’ N; longitude 95º 58’ W) (Fig. 1). Elevation ranged from 160 to 500 m a.s.l. The climate is sub-humid with an average annual precipitation of 1938 ± 600 mm (30 year average) (CONAGUA, 2010) between July and September (García, 1973), and an annual average temperature of 24 ºC (Algara, 2009). Over the last 60 years, the region has been affected by extreme climatic events with frosts, droughts, and tropical cyclones

(Avila, 1996). The landscape is a mosaic of small plots with different land use types characteristic to the area: 1) citrus orchards (orange and mandarin) for sale, 2) sugar-cane for piloncillo (traditional brown sugar) production for sale and self use, 3) Litchi (as monoculture or combined with citrus) for sale, 4) pastureland, 5) *milpa* for subsistence; this is a policulture system (corn, bean and squash and occasionally additionally mixed with chili, papaya, banana, or tomato) maintained by traditional rotational slash and burn practices, where after 5 to 7 years of crop planting the land is allowed to rest for 2 to 10 years (Alcorn and Toledo, 2000), and 6) secondary forest (they are either semi-abandoned and used to cultivate shade grown coffee for subsistence or form the resting stage of the *milpa* cycle). The watershed is inhabited by three communities (with 230 to 320 inhabitants) (INEGI, 2010) all with a high level of exclusion (CONAPO, 2005): 1) San Pablo I and II, 2) Tanleab II and 3) Tzinejá II. The latter two are extensions of the communities Tanleab I and Tzineja I located outside of the watershed (Fig. 2.1 and 2.2).

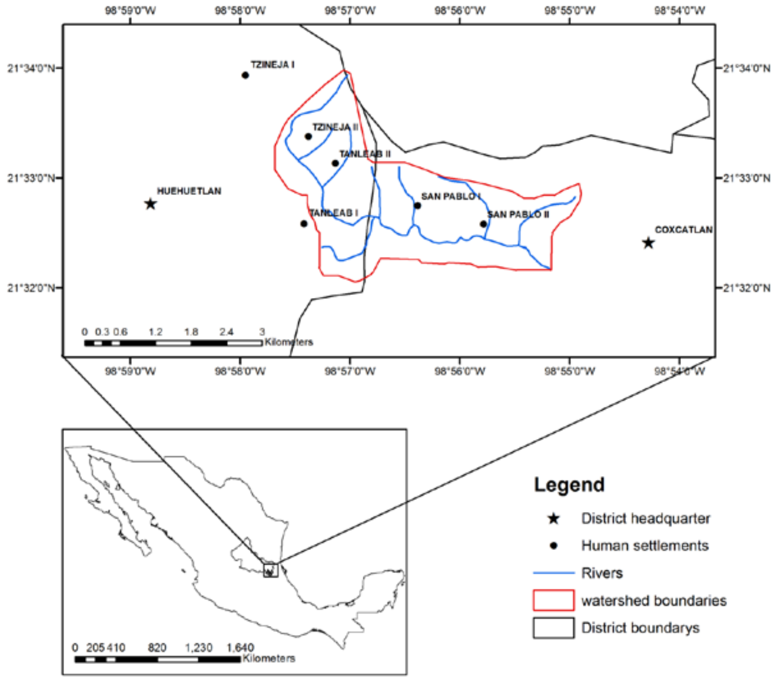

Figure 2.1. Location of Palzoquillo watershed and of settlements Tzineja I and II, Tanleab I and II, San Pablo I y II, in Southern Huasteca, San Luis Potosi, México. Tzineja I and Tanleab I are situated outside the watershed.

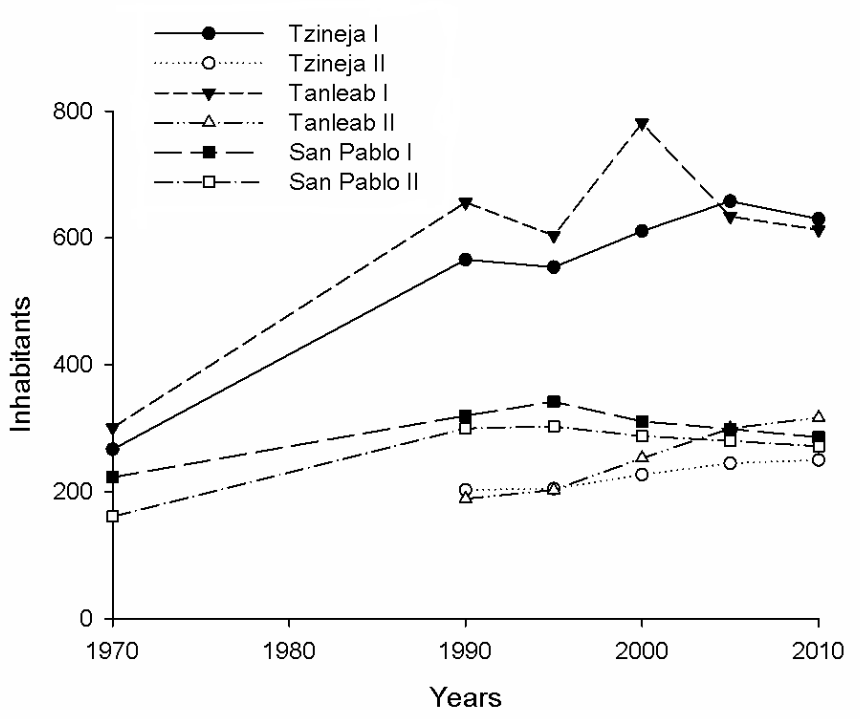

Figure 2.2. Population growth in San Pablo I and II, Tzineja I and II and Tanleab I and II between 1970 and 2010 in Southern Huasteca, San Luis Potosi, Mexico (INEGI 2010).

2.3.2 Data collection and analysis

We used the recently proposed Drylands Development Paradigm (DDP; Reynolds et al., 2007) as analytical framework to systematically examine the sources, interactions and feedbacks of change that characterize the dynamics of the complex social-ecological system in the Palzoquillo watershed. With the five principles (P1-P5) of the DDP (Table 2.1), we first identified a key set of socio-economic and biophysical drivers that explain slow and fast changes in structure, function and adaptability of the social-ecological watershed system. We then explored key features of the different modes of livelihoods and spatial patterns of land use/cover change that emerged as new properties of the watershed under the prevailing conditions of the last four decades. Finally, we analyzed how the interrelatedness between exogenous drivers and local endogenous conditions (including knowledge systems) that shaped livelihood development fed back on landscape transformation and to which degree critical thresholds were crossed.

Table 2.1. Principles of the Drylands Development Paradigm (Reynolds et al. 2007).

	Principles
P1	Human-Environmental systems are coupled, dynamic, and coadapting, so that their structure, function, and interrelationships change over time.
P2	A limited suite of “slow” variables are critical determinants of H-E system dynamics.
P3	Thresholds in key slow variables define different states of H-E systems, often with different controlling processes; thresholds may change over time.
P4	Coupled H-E systems are hierarchical, nested, and networked across multiple scales.
P5	The maintenance of a body of up-to-date LEK is key to functional coadaptation of H-E systems.

a) Socioeconomic and biophysical drivers of land use change at plot scale

In this study, the source of information regarding all decisions on land use at the plot scale was obtained by interviewing farmers (Doorman, 1991; Márquez, 2005; Valdivieso, 2008). 90 family heads were randomly selected in the three communities and asked to reconstruct the history of their plot use (n=120) between 1970 and 2009 and to identify key biophysical and/or socioeconomic reasons for each change. This time span was chosen because i) at the end of the 1960´s the three communities were for the first time officially registered and ii) aerial photographs were available for this period. This information was complemented with information derived from semi-structured interviews applied to key actors at local, regional and national scales. Public sources were also consulted such as the Registro Agrario Nacional (RAN) and the Comisión Nacional del Agua (CONAGUA). We applied discourse analysis to process and interpret the information obtained from the interviews. With this approach, we systematically analyzed conversations and narratives and identified re-occurring themes when comparing interviews (Phillips et al., 2004). This technique allowed us to identify a set of critical socioeconomic and biophysical drivers (DDP P2; Table 2.1) at multiple spatiotemporal scales (DDP P4; Table 2.1).

b) Identification of livelihoods

To the same heads of family structured interviews were applied focusing on socio-economic information related to family structure, age, access to agricultural surface, migration, non agricultural labor, access to subsidies and government programs, and land use and management decisions. To identify different livelihoods, we applied hierarchical cluster analysis using SPSS (version 17.3). With this method, we identified key characteristics (DDP P2; Table 2.1) of individual modes of livelihoods that developed in the watershed landscape. The causes of diversification of livelihoods at the landscape level gave insight on key interactions and feedbacks at the household, community, watershed, and national level (DDP P4; Table 2.1) and on thresholds (DDP P3; Table 2.1) of fundamental properties (DDP P2; Table 2.1) of the social and natural system. With this analysis, we also evaluated how local environmental knowledge (DDP P5; Table 2.1) was incorporated in household decision-making.

c) Land use and cover change at watershed scale

We used aerial photographs of the watershed for the years 1978, 1996 and 2006 (these were the only photographs available for the area). We first created maps of polygons and then compared the extension and change of the eight land use/cover types: 1) citrus orchards, 2) citrus/litchi orchards, 3) litchi orchards, 4) sugar-cane plots, 5) *milpa*, 6) human settlements 7) pastureland and 8) secondary forest. The analysis was performed with the Integrated Land and Water Information System (ILWIS), a Geographical Information System and Remote Sensing software (Version 3.3; ITC, 2005). With this analysis we elucidated the temporal dynamics of the coupled nature and interrelatedness of the human and environmental systems leading to landscape reconfigurations (DDP P1; Table 2.1) and to how strongly exogenous and endogenous drivers influenced land use/cover change (DDP P4; Table 2.1).

2.4 Results

2.4.1 Drivers of land use/cover change at plot scale considering the human-environmental context

Indigenous farmer communities have colonized the Huasteca for over 3000 years (Toledo et al., 2003). Since the Hispanic conquest, farmer communities of the Southern Huasteca have been marginalized to agriculture in the steep slopes of the Sierra Madre Oriental, while the conquerors monopolized large extensions of land in the plains (Aguilar and Flores, 2007). The farmer communities have colonized the watershed for several centuries, but it was only in 1966/1968 when official records of community property were obtained (Registro Agrario Nacional, 2010). Marginalization was accompanied by limited access to land (on average 3 to 4 ha/farmer in 1968); this smallholder regime is one of the main characteristics of this area since the mid 1960s (Registro Agrario Nacional, 2010).

Until the 1970's, agriculture based livelihoods consisted of subsistence farming (*milpa*) together with coffee and sugar-cane as cash crops. Cash crops were subsidized by the Mexican state government in that it intervened in the production, distribution and marketing of the crops. INMECAFE, the National Mexican Institute of Coffee, regulated national coffee prices (Bacon et al., 2008) and the National Commission for Sugarcane national sugar prices (Castillo and Aguirre, 2005). After the mid 1980's, the preservation of this livelihood faced restrictions. With the adoption of the neoliberal economy and in response to emerging global markets, the Mexican government had to re-structure agricultural policies and support domestic and commercial producers to switch to competitive marketable crops. These structural changes affected the Huasteca region as follows: 1) the smallholder regime was accentuated with the introduction of the National Program of Agrarian Certification (Programa de Certificación de Derechos Ejidales y Titulación de Solares Urbanos; PROCEDE) in 1993. This new neoliberal legislation, following World Bank recommendations, gave farmers private property rights (including property title) with the goal to increase farmer's role in decision-making, to enhance their participation in emerging markets and to give them the option to sell their land or to modernize agriculture (Téllez, 1994). Land owners could now a) inherit land to more than one descendent, legally inherit land; and b) keep their land, without necessarily using it in case of temporal out-migration or illness (Braña and Martínez, 2005). This new inheritance process enhanced the smallholder regime in all four communities of the watershed, because of a rapidly growing population (Fig 2.2). However, it was more pronounced in sections I and II of San Pablo, which established in 1966 and 1967 than in sections II of Tanlejab and Tzineja, which were founded in 1985 and 1993. Limited access to land forced a high proportion of the new generations to permanently migrate out of the watershed. The remaining farmers had to divide up their land among their children, which reduced plot size to less than 1.5 ha; barely enough to guarantee life-sustaining income from agricultural production. 2) The sugar cane industry was privatized and between 1988 and 1994 the price of sugarcane dropped substantially (Castillo and Aguirre, 2005). 3) The elimination of INMECAFE in Mexico, the world coffee organization, and the regulation of international coffee markets in 1989 soon caused a drop in the coffee price and the withdrawl of the government subsidy (Bacon et al., 2008). Parallel to the international coffee crisis, a severe frost destroyed 80% of the coffee plantations in the Huasteca region (INIFAP, 1996). 4) The state prompted the creation of private agribusinesses in Northern Mexico, meant to produce garden vegetables for exportation in the 1990's; this offered new opportunities for part time labor. In 2005, the government program, "Seasonal Agricultural Workers in Canada", meant to promote opportunities for wage-labor (Basok, 2003) and temporary migration for farmers to other regions of Mexico, was initiated in the Huasteca (Gomez-Barrera, 2008).

Driven by new global markets, government support programs were restructured at the regional scale to maintain sugar cane production with intermittent government support for infrastructure and to promote commercial agreements with private industries for new crops such as citrus and litchi yet without government investments. In 1988, a private juice factory "Citrofrut" was established in Southern

Huasteca and has since been the nucleus of the citrus market. After the North American Free Trade Agreement (NAFTA) was signed the price of oranges plummeted from 107 USD/ton in 1994 to 25 USD/ton for citrus crops treated with herbicides and to 85 USD/ton for organic oranges in 1998 and it did not recover until present times. Eventually, the litchi program took off in 2000 but the lack of a well established market has limited its success.

2.4.2 Livelihood diversification

Watershed inhabitants responded in different complex ways to the opportunities and restrictions the multitude of exogenous and endogenous drivers presented to them. We identified three different livelihoods, which currently coexist in the watershed (Fig.2.3).

Diversifiers

This group of farmers represents 32% of all households and is generally characterized by an elderly couple over 50 years of age with independent children. Their income consists of sales of citrus, sugar-cane, some litchi and government support, the latter from a family assistance program called “Opportunities” (SEDESOL, 2003). Subsistence crops (*milpa* and shade grown coffee) yield sufficient food for 10 to 11 months a year in these homes. Diversifier farmers have access to 2.5 to 4 ha of land. This comparatively large land surface has allowed the diversification of agricultural activities year-around. This restricts the possibilities of working away from the plots yet allows an important social/cultural institution called “*mano vuelta*” (turning hands) to be conserved. *Mano vuelta* is a collaboration and exchange of labor among farmers during land preparation and crop harvesting. This collaboration compensates for the lack of a young work force in these households and reduces the need to pay day workers (Fig.2.3).

Sugercane producers

This group of farmers comprises 16% of the households and is represented by couples of 40 to 50 years of age with at least one child of reproductive age. Their income consists of the sale of sugar-cane and government support ("Opportunities"). As with Diversifier farmers,, the subsistence crops (*milpa* and shade grown coffee) of sugercane farmers yield food for 6 to 7 months of the year. Sugercane farmers have access to land ranging from 1.5 to 3 ha. Usually sugar-cane is grown on two thirds of the land as a commercial crop and the rest is destined for self-supply. Despite an ongoing crisis in the sugar-cane industry and the fact that this crop is labor intensive, this mode of livelihood has persisted since the 1970s. This is due mainly to: 1) the sugar-cane crop provides adequate income (according to Moctezuma (2006) at least 1 ha of sugar cane is necessary for a family to survive). 2) These households with children, who depend on their father's lands, count with sufficient own work force to maintain this labor-intensive crop. 3) Sugar-cane has received continuous government support through the Ministry of Agriculture (Secretaría de Desarrollo Agropecuario y Recursos Hidráulicos, SEDARH) and the Ministry of Social Development (Secretaría de Desarrollo Social, SEDESOL) to facilitate the purchase of infrastructure for processing sugar-cane (Fig.2.3).

Semi-proletarianized citrus growers

This group is the largest in the watershed and represents 51% of the farmers' households. It is formed by couples aged younger than 40, with children who study or work in nearby cities. Their income is made up of citrus sales, government support ("Opportunities") and temporary wage labor in agribusiness. They have access to small agricultural land of 0.5 to 1.5 ha as a result of a long-term inheritance process. This smallholder regime does not allow sufficient agricultural production and, in addition to the low market prices, is unable to cover the minimum needs of a household. Hence, the option of temporary migration for wage labor in agribusinesses is an important source of income for these households. Wage labor activities are generally time commitments of 5 to 7 months a year outside of the community, which in turn restricts these farmers from growing auto-consumption crops. This has led to the specialization in citrus crops. This type of livelihood does not release land but rather enhances the smallholder regime. While the importance of citrus crops began originally with the orange's attractive market price, at present it is the seasonality of the crops, which requires only 5 months (October to February) of work, and thus allows these farmers to migrate temporally during the rest of the year. Migration has emerged as a highly attractive alternative for younger generations opting for a more consumer-oriented lifestyle with new needs (e.g. increasing demand for modern clothing, food, entertainment, etc.) that cannot be satisfied in the original community setting. Their absence in the community has led to the loss of the *mano vuelta* practice and an increased use of herbicides (86% of the households belonging to this livelihood use herbicides) jeopardizing crop quality for the organic citrus market and compromising its price even further. Also, subsistence crops are only planted on small extensions of land inside the home gardens or they disappeared because of lack of time and/or access to land making this livelihood dependent on purchasing basic food (Fig. 2.3).

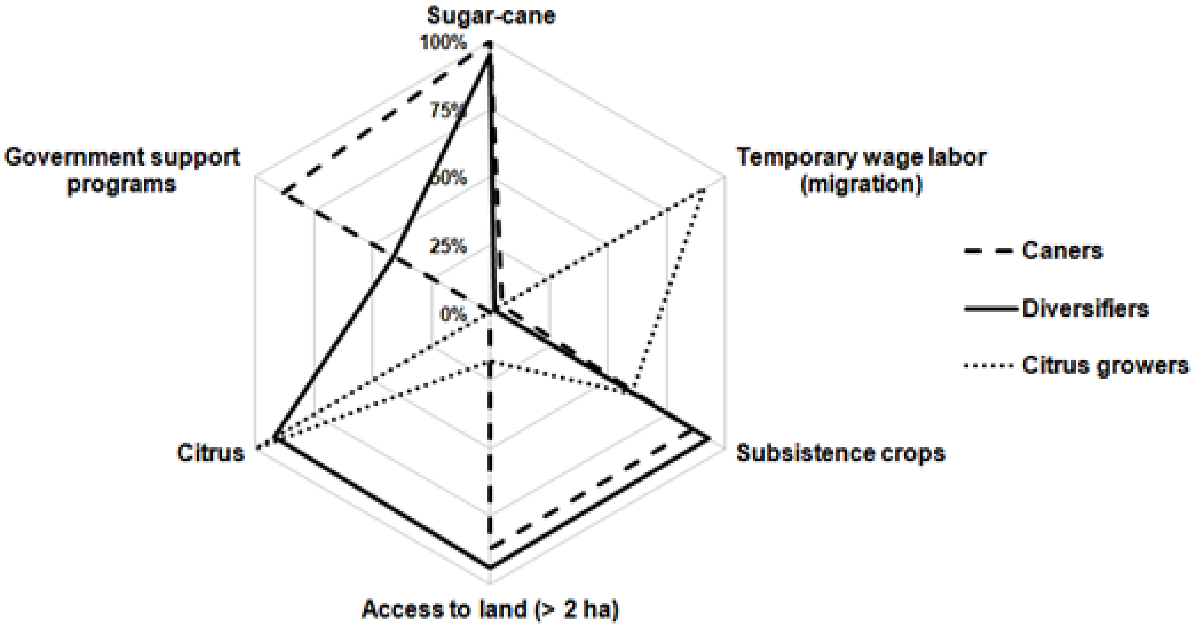

Figure 2.3. Livelihood characteristics of citrus growers, diversifiers and caners in the Palzoquillo watershed, Southern Huasteca, San Luis Potosi, Mexico. Percentage refers to the proportion of peasants in a certain livelihood mode with a certain livelihood

characteristic). For example, of all citrus growers, 100% grow citrus crops, 91% migrate temporarily for wage labor, 60% cultivate subsistence crops within the citrus orchards, and only 18% have access to land > 2 ha; none of them has access to government support programs or grows sugarcane.

2.4.3 Regional land use change

Between 1978 and 2006, the landscape configuration of the watershed changed significantly (Fig. 2.4, Table 2.2). We recognize two periods of transition: 1) the most drastic changes occurred between 1978 and 1996 and affected 418 ha of the total surface area. Large areas of sugar-cane (114 ha), secondary forest (82 ha) and *milpa* (12 ha) were replaced by citrus orchards (167 ha), human settlements (24 ha) and to a lesser degree by pastureland (17 ha). 2) The second transformation, affecting only a total of 175 ha occurred between 1996 and 2006. Sugar-cane dropped by 38 ha, pastureland by 28 ha, *milpa* by 16 ha and secondary forest by 5 ha. The decline in these land cover types favored the spatial expansion of citrus orchards (54 ha), and litchi in monocultures (1.5 ha) and in mixtures with citrus (6 ha). In addition to temporal differences in land use change, spatial differences became also apparent considering the east and the west side of the watershed in 1978 and 2006 (Fig. 2.4, Table 2.2). On the eastern side (San Pablo I y II), human settlements (31 ha) and citrus orchards (158 ha) expanded and litchi appeared as a new land cover type (8 ha). These changes caused the reduction in other land use types such as sugar cane (78 ha), secondary forest (64.3 ha), *milpa* (36 ha) and pastureland (16 ha). On the western side (Tzineja II y Tanleab II), the increase in human settlements (18 ha) and citrus orchards (64 ha) was lower and litchi was not introduced yet. Sugar-cane decreased by 74 ha and to a lesser degree secondary forest (by 23 ha), *milpa* (7 ha) and pastureland (6 ha).

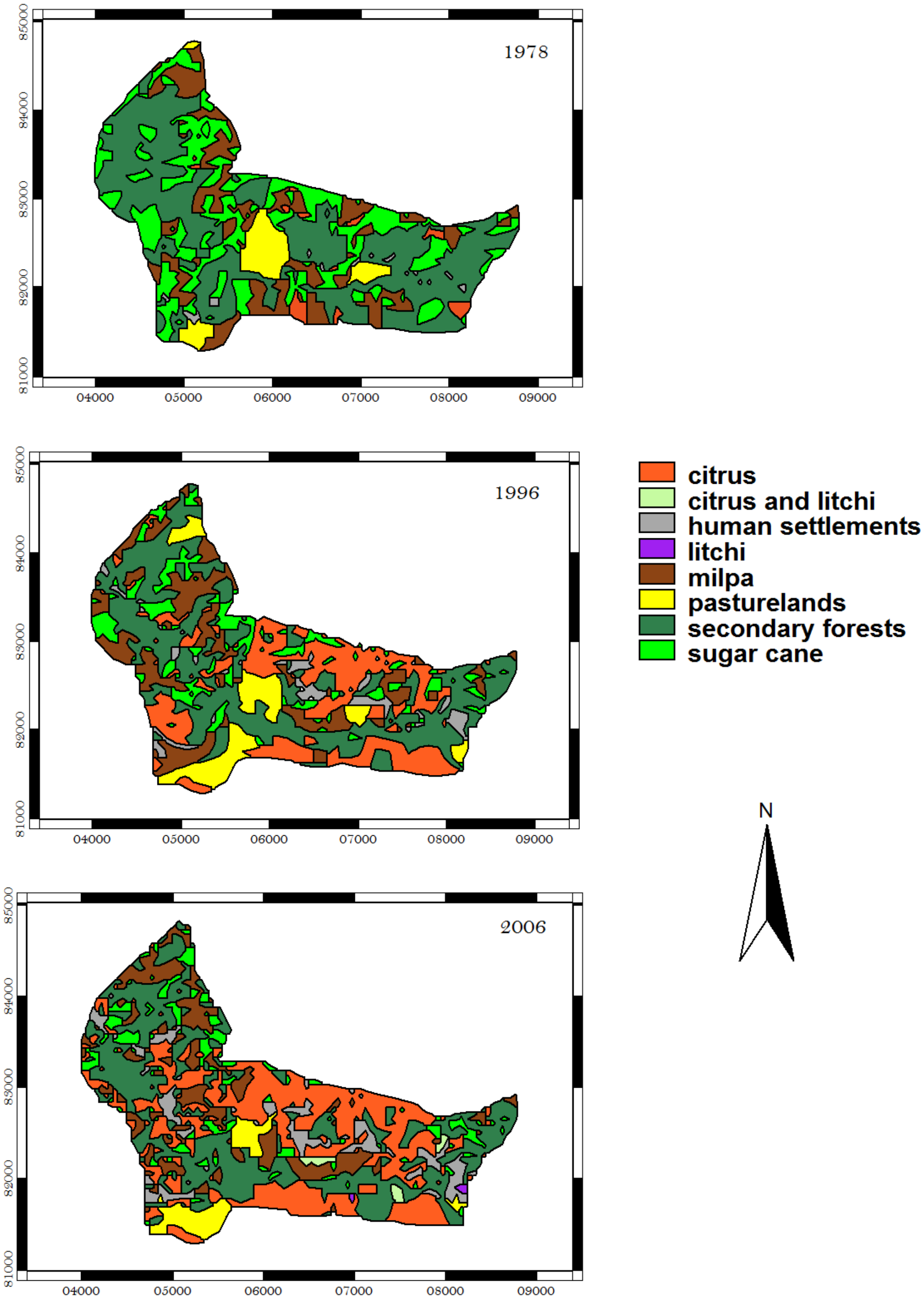

Figure 2.4. Spatial distribution of land cover/use types in the Palzoquillo watershed, in Southern Huasteca, San Luis Potosi, Mexico for the years 1978, 1996 and 2006.

Table 2.2. Total change (hectares) of land cover/use types in the whole watershed area, and on the eastern and western side of the Palzoquillo watershed in Southern Huasteca, San Luis Potosi, Mexico for the years 1978, 1996 and 2006.

	Total change of whole wátershed (ha)			Total change east-side (ha)	Total change west-side (ha)
Land use type	1978 - 1996	1996 - 2006	1978 – 2006	1978 -2006	1978 - 2006
Citrus	167.45	54.33	221.78	157.86	63.92
Citrus/litchi	0	6.37	6.37	6.37	0
Litchi	0	1.5	1.5	1.5	0
Human settlements	23.76	25.46	49.22	31.06	18.16
Milpa	-12.45	-15.96	-28.41	-35.78	7.37
Pastureland	17.59	-28.26	-10.67	-16.61	5.94
Secondary forest	-82.43	-4.79	-87.22	-64.3	-22.92
Sugar cane	-113.92	-38.65	-152.57	-78.56	-74.01

2.5 Discussion

In rural landscapes undergoing regional environmental change, exogenous and endogenous biophysical, socioeconomic and sociopolitical drivers cause continuous unpredictable changes in human-environmental systems thus leading to coupled transformations in land and lives. Our results show an intergeneration livelihood transition towards land use decisions driven by an interaction of diverse, contrasting policies, changing regional and global markets and extreme climatic events and different capacities of farmer groups to respond to them. Hence, this dynamic has created a complex changing landscape, whose underlying causal drivers and dynamic feedbacks were successfully elucidated with the DDP framework.

2.5.1 Integration of livelihood diversification and landscape transformation

In the last decade, three distinct livelihood pathways have developed in the Huasteca watershed, which have transformed the landscape in unique ways. These three livelihoods emerged in response to the many biophysical and socioeconomic drivers, which appeared at multiple spatiotemporal scales (Fig. 2.5). When Mexico switched from being a welfare to a neoliberal state, many public policies disappeared (e.g. government help for coffee production), were restructured (continuous institutional and government support for sugar-cane production was replaced by sporadic government programs, e.g. infrastructure) or newly developed (e.g. prompting wage labor in national and international agribusinesses, reduction of public investment in agricultural sector and enhancement of private industries and trade liberalization) altogether causing a severe crisis in prices of agricultural products (Table 2.3). Changes in these exogenous policies interacted with endogenous drivers such as local land access policy, change in the inheritance process, temporary migration of farmers, and inequity among households to respond to these transitions because of age limitation and/or availability of work force. The dynamic feedback between exogenous and endogenous drivers and overall household responsiveness ultimately determined decision-making processes of different farmer groups.

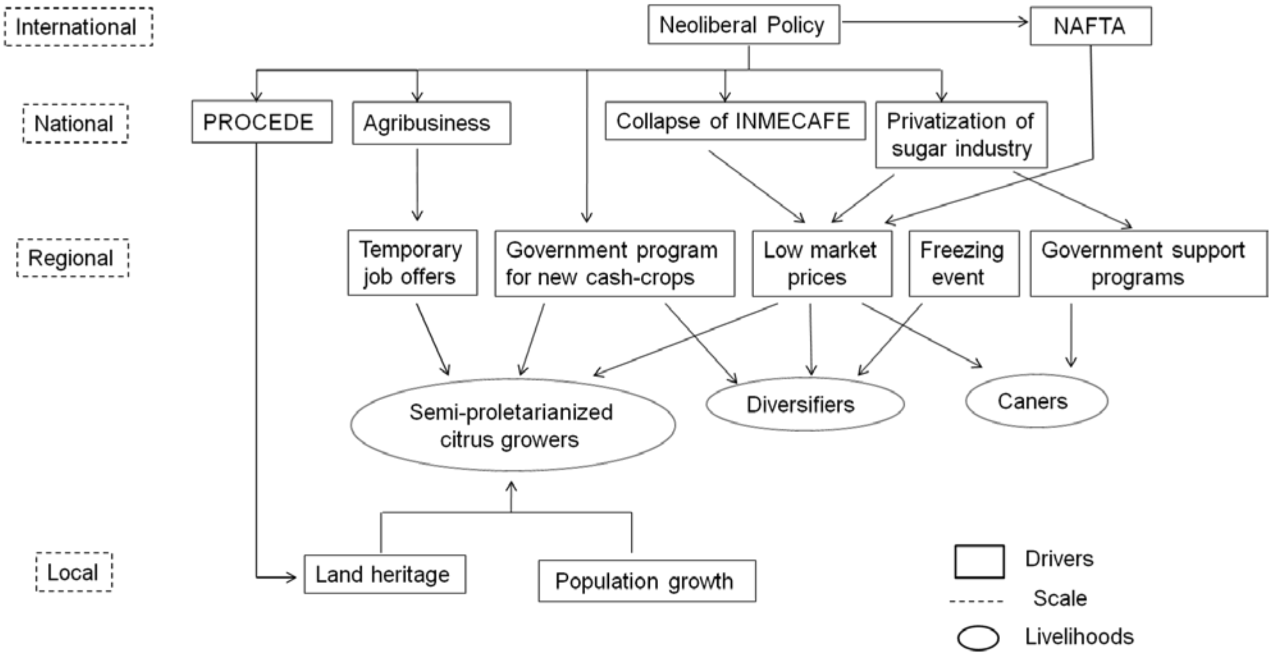

Figure 2.5. Livelihood diversification in citrus growers, diversifiers and caners in response to multiscale drivers (local, regional, national and international) in a tropical watershed in Southern Huasteca, San Luis Potosi, Mexico.

The drivers caused fast, semi-slow or slow changes (according to Reynolds et al., 2007; Table 2.3) in household structure and livelihood mode. However, the changes in key slow variables (DDP P2; Table 2.1), such as loss of access to land, switch in income type by opting for alternative wage-labor, international free trade agreements and neoliberal policies, had the most fundamental impact on livelihood diversification and the associated land use transitions. Restricted land access promoted two consecutive generations of farmers to adopt different livelihood strategies. Access to more land allowed elder farmers not only to diversify and maintain higher crop diversity (slow variable; DDP P2) but also to maintain the traditional *milpa* production system, which is fundamental to enhance soil fertility and food security (slow variable; DDP P2). The youngest households of the watershed had to adopt a new semi-proletarianized livelihood as the threshold of minimum access to land had been crossed (threshold; DDP P3). Adopting this livelihood with temporary wage labor in agribusinesses and specialization in citrus monocultures led to the loss of the *milpa* system, *mano vuelta* and the introduction of pesticides, and thus to an impoverishment of traditional social-cultural institutions, local environmental knowledge, and the ecosystem service of pest regulation at the watershed level (crossing threshold of one key slow variable had positive feedback on crossing thresholds of other biophysical and socio-economic slow variables; DDP P2, P3, P5). Smallholder regime manifested itself differently in the watershed considering the settlement history of the region thus generating temporally and spatially heterogeneous landscape transformations (DDP P4; Table 2.1). On the eastern side of the watershed, San Pablo I and II had less land (327 ha) and a longer history in the watershed and thus a higher population density than the communities to the west, where the second sections of Tzineja and Tanleab alone occupy 348 ha (the total area of the Tzineja and Tanleab communities is 880 ha) (Registro Agrario Nacional, 2010). Lack of land and small extensions of land forced households on the eastern side to a quicker adoption of the semi-proletarianized citrus cultivator livelihood with seasonal migration or to permanent migration. Seasonal migration does not open up land, since migrants do not sell or abandon their land but cultivate it with low-input orange crops. Thus, access to land is highly limited and saturated and an increasing population does actually reinforce the smallholder regime. This explains the predominant regional expansion of citrus orchards in the east of the watershed, until the population in San Pablo reached a peak size of 350 inhabitants beyond which limited access to land no longer permitted profitable citrus production and consequently triggered out-migration of the watershed (Fig. 2.2 and 2.4). On the western side, the lands still support population growth in Tzineja II and Tanleab II (Fig. 2.2) and greater crop diversity (Fig. 2.4). At the temporal scale two distinct mainly policy related drivers caused changes (DDP P4). Between the 1970s and 1980s, the Mexican government responded to the agricultural product crisis with support programs for households to strengthen the primary sector (sugar-cane and new crops). In the

1990s, the expansion of thriving agroindustries created new opportunities for rural households with temporal or part-time income alternatives. However, this relegated the importance of local agriculture and explains why the rate of transition in land use was more pronounced in the 1970s and 1980s than in the 1990s (Table 2.3).

Table 2.3. Chronology of key socioeconomic and biophysical drivers of land use change and livelihood development in the Palzoquillo watershed in Southern Huasteca, San Luis Potosi, Mexico.

Year	Event
before 1970	Minifundism
1980	Government program for orange as an alternative crop
1983 and 1985	New human settlements
1988	Foundation of juice factory CITROFRUT
1988 - 1994	Privatization of sugar industry
1988	Government program for sugar-cane infrastructure
1989	Collapse of INMECAFE
1989	Freezing event killing coffee crop
90s	Expansion of agribusiness in north Mexico
1994	Signing of NAFTA
2000	Government program for litchi as an alternative crop
2005	Seasonal Agricultural Workers Program Mexico-Canada

This diversified watershed-landscape with a variety of land use types need to be seen as a product of survival strategies adopted by farmer families living under precarious social conditions (Steward, 2007; Gómez-Barrera, 2008; García-Barrios et al., 2009). Landscape diversity and land use configuration reflect the accumulated effects of continuously changing and often contrasting public policies; and it is policy reforms that most strongly influence farmers' land use decisions (Madhusudan, 2005). Livelihood modes of the most recent generation of farmers exhibit an increasing tendency towards semi-proletarianization and future generations are expected to follow this tendency. The tendency towards semi-proletarianization of livelihoods repeats itself in several Latin American countries (Bebbington and Batterbury, 2001; Reardon et al., 2001; Janvry and Sadoulet, 2004; Figueroa, 2005; Steward, 2007; Pat et al., 2011) for the following two reasons: 1) land is continually less available (Kay, 2000), and 2) because these countries adopted neoliberal policies to promote economic growth at the end of the 1980s (Gwynne and Kay, 2000). This generated changes in regional economic politics with an increasing focus on markets and the coupling of local agricultural production to the global economy (Gwynne, 2004). Simultaneously, this has strongly increased the demand for temporary agricultural workers (Kay, 2000). Several studies have shown that these socioeconomic drivers have forced small-holders to insert themselves into regional and global markets with high-demand crops (fruit, coffee, cacao) and to alternate their economic activities with wage labor in agrobusinesses or in factories (Rigg and Nattapoolwat, 2001; Trujillo, 2008; Pacheco, 2011). The adoption of this type of livelihood does not lead to land abandonment by households, instead it triggers a reorganization of land use with crops that are maintained for several years and require little agricultural input (Rigg and Nattapoolwat, 2001; Garcia-Barrios et al., 2009). Land use transition tendencies observed in the watershed will lead to an environment that is becoming increasingly vulnerable ecologically, socially and economically, leading to a less resilient watershed-landscape (DDP P1 and P3, Table 1). Ecological vulnerability associated with the specialization in monocultures implies a loss in biodiversity, more land erosion and an overall degradation of fundamental ecosystem services (Vandermeer and Perfecto, 2005; Ferguson, 2007; Krishna and Laksmi, 2010). Along with the long-term history of land use change in the Huasteca, since 1960 average annual precipitation has decreased by 160 mm and annual average temperature has increased by 0.72 ºC (Algara, 2009): additionally pest outbreaks in citrus and coffee plantations occur with greater frequency (Galindo et al., 2009; Olvera, 2010). Social vulnerability is associated with the disintegration of social networks, the loss of community institutions such as *mano vuelta* and the impoverishment of local knowledge systems by abandoning the *milpa* production system. The adoption of wage and monoculture based livelihoods has been leading to the homogenization and trivialization of the environment and is putting the accumulated cultural, social and natural capitals increasingly at risk (Matthews and Selman, 2006). Finally, economic vulnerability is enhanced, because livelihoods depend increasingly on the outside world as in the case of global market fluctuations, job offers and government programs and public policies and rely less on local conditions and decisions.

While the DDP allowed an analysis of system properties that may be critical for management and policy-making (Stafford Smith et al., 2007) and are not readily detected with conventional disciplinary approaches, the five principles did not elucidate livelihood diversification and landscape transformation as emergent properties (but see Assertion 5 of the original Dahlem Desertification Paradigm, Stafford Smith and Reynolds, 2002) of the tropical watershed. Livelihood diversification and landscape transformations are linked human-environmental characteristics (DDP P1) described by human-environmental “compound variables” whose simultaneous analysis allowed new insights in the structure function and feedback of the whole watershed area. For the rural tropical landscape in the Huasteca to remain a long-term multifunctional life-support system for future generations it does not only need to provide multiple ecosystem goods and services but permit livelihood development compatible with the natural and social capitals. The DDP was originally designed to explore the complexity and interrelatedness of factors causing desertification of social-ecological systems in arid, semiarid and sub-humid regions (Reynolds and Stafford Smith 2002). Here, we demonstrate how the DDP can also be applied in humid and subhumid tropical mountains, where it served as an excellent framework to explore potential inherent local to regional impediments, challenges and options for development, and in particular, the complexity and underlying drivers of livelihood development and diversification as a form of local and regional adaptation to new emerging socio-cultural, socioeconomic, socio-political and environmental conditions. The great value of the DDP lies in its flexible nature and thus in its enormous potential to be used in a wide spectrum of social-ecological systems and contexts (Martínez Peña et al. 2012).

2.5.2 Trading market oriented crop production for food sovereignty

Many studies on livelihood diversification in rural communities have focused on shifts in income sources but ignored the analysis of their impacts on subsistence crops. Despite the fact that at the landscape scale the coexistence of three livelihoods has led to crop diversification, this study has shown that at the household level, crop diversity has decreased. Citrus producers and even sugarcane producers opted for specialization in a cash-crop, while reducing or sacrificing subsistence crops. Lacking self-supply of food, these households have become more vulnerable to suffer from food shortages. This phenomenon is not exclusive to this watershed but is wide-spread, especially in Latin American countries (Nussbaumer, 2004; Steward, 2007). Recent studies indicate that global policy and commodity markets induced a decline in subsistence farming (Madhusudan, 2005). In Mexico, food security/sovereignty is increasingly compromised as proletarianized farmer communities produce only a small fraction of the basic grains they consume (Klooster, 2003; Pat et al., 2011). The reduction in cultivation of subsistence crops is a general response to 1) the emerging needs to produce cash-crops in response to global markets, 2) the increasing attraction of wage labor (Appendini et al., 2003), and 3) the lack of access to land (Pat et al., 2011). At the end of the 1990s, the number of corn and bean producers who switched to crop production for the global market was 1.4 million (Figueroa-Pedraza, 2005).

2.5.3 Multi-scale feedback

In several Latin American countries, farmers' decisions and government support programs are immediate top-down responses to economic crisis, such that they are controlled by global markets without simultaneously considering how to conserve social and natural capital and local knowledge and governance (Bryceson et al., 2000). While recognizing that most drivers occur and interact among a range of different scales, many of the regional and local drivers are directly or indirectly triggered by national and international forces. Government assistance programs are primarily short-term and market-oriented and have led to the introduction of new crops (citrus and litchi) driven by global markets *at the cost of* traditional sustainable social structures, local knowledge, and diverse production systems (neoliberal policies mismatch temporal and institutional scales and are fundamentally slow variables including local environmental knowledge; DDP P4, P2 and P5).

It is vital to look for a balance with respect to the strength of impact of drivers, such that government programs should foster the multifunctionality of landscapes, which fulfill economic functions, maintain traditional cultural connections and social structures and allow adapting to change by enhancing local governance in order to maintain food security and the provision of ecosystem services (Ayala-Ortíz and García-Barrios, 2009). Emerging landscape transformation dynamics are complex and yet, their understanding is fundamental for the implementation of management policies. Future landscape transformations must consider the interdependence among the social, cultural, economic and environmental dimensions of a watershed to support future livelihood development in a resilient landscape setting (Matthews and Selman, 2006).

2.6 Conclusion

This research exemplifies the importance of studying the causes and dynamics of transformations of rural landscapes at multiple spatiotemporal scales in the light of current and future environmental change. With the DDP framework, we identified the historical sequence of key socioeconomic and biophysical drivers that controlled the structural and functional transformation of the watershed landscape, and in turn gave rise to the development of diverse livelihoods and associated land use change patterns.

Livelihoods and land use types are heterogeneously distributed in the watershed. We have shown how the mosaic of a rural landscape in the Southern Huasteca in Mexico has been historically re-organized and how and why different yet simplified agricultural ecosystems have predominated. The current landscape configuration is the result of a combination of local drivers such as smallholder regime and local population growth, regional drivers such as public policies, and national/international drivers such as neoliberal policies and tendencies of global markets. These drivers seem to be generic drivers in tropical regions of Mexico and Latin America. In the current watershed landscape, three livelihoods emerged independently from each other primarily driven by access to land, access to a work force, the functioning of social networks, and the mobility to include distant wage-labor activities – together leading to rapid landscape fragmentation and disintegration. Most recent and young generations have undergone a transition in livelihood type, which is headed towards specialization and proletarianization at the cost of crop diversification. Under the current scenario, rural landscapes will become more vulnerable economically, socially and environmentally.

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Chapter 3

Linking livelihoods and land through ecosystem service interactions in a tropical landscape in Southern Huasteca, México.

3.1 Abstract

Land use targeted towards maximizing a single provisioning ecosystem service often causes declines in supporting and regulating ecosystem services at the cost of livelihood diversification, ecosystem resilience and human well-being. To make more informed holistic land use decisions, recent studies have called for thorough understanding underlying complex socio-environmental relationships controlling the status and long-term availability of different ecosystem service types. We applied the ecosystem services bundle framework in a rural landscape in tropical Mexico. We examined the relationships among multiple ecosystem service types characterizing orange plantations, traditional sugarcane plantings, *milpa* – corn production system, and secondary forests. We then explored how certain livelihoods and their land use systems influence landscape function in a watershed in tropical Mexico. To explore farmer livelihoods and associated land use types in a landscape context, we interviewed citrus farmers, sugarcane producers and diversifiers about their land use and management practices. We then examined 15 variables characterizing fundamental soil and hydrological functions, crop production and important cultural aspects corresponding to supporting, regulating, provisioning and cultural services of each land use type. To evaluate if current land use practices cause trade-offs (negative relationships) or synergies (positive relationships) among provisioning and supporting and/or regulating ecosystem services and how this may feedback on livelihood development and landscape function, we conducted Pearson correlation analysis considering all ecosystem services variables. To further examine how livelihood diversification is linked to landscape multifunctionality, we developed maps of the spatial distribution of these ecosystem services and ecosystem service bundles for each land use/cover type. Results showed a landscape level tradeoff between provisioning and almost all supporting, regulating and cultural ecosystem services. The spatial heterogeneity of landscape function is coupled to the heterogenous distribution of ecosystem service types and the interactions between ecosystem service types. Drivers of these interactions are themselves complex interactions between dynamic socio-economic, socio-cultural, socio-political and biophysical factors influencing livelihood development and diversification. Hence, ecosystem management aimed at stewarding ecosystem services requires multicausal analysis and integrated knowledge of the origin of heterogeneity of tropical landscapes to increase long-term multifunctionality of rural landscapes and human well-being.

Keywords: ecosystem service, ecosystem service bundles, synergy, tradeoff, livelihood, landscape

3.2 Introduction

Human wellbeing depends on the functional and structural attributes of earth's natural systems to provide ecosystem services (Daily, 1997; Mainka et al. 2005; Nelson et al. 2009). Land use change has serious environmental impacts on ecosystem services, particularly in the tropics (Koellner et al. 2008). It has become a great challenge to manage ecosystems so future generations can equally benefit from ecosystem services as society today, such that the flow of ecosystem services is sustainable (Chapin 2009). The Millennium Ecosystem Assessment (2005) distinguishes between four categories of ecosystem services: 1) provisioning services, such as food, fiber, fresh water, and forest products; 2) regulating services, which regulate climate, disturbance regimes, pest and disease outbreak, water quality/quantity and erosion; 3) cultural services, which deliver recreational, aesthetic, and spiritual benefits; and allow cultural identity; and 4) supporting services, such as soil formation, carbon, nutrient and water cycling and maintenance of biological diversity (MEA 2005, Chapin 2009). In many tropical regions of the developing world, land use and management policies are targeted towards maximizing the production of provisioning services such as crops, livestock and timbe at the unintended or often overseen cost of declines of many supporting services. However, it is the supporting services that are ultimately the fundamental ecological processes that control long-term ecosystem structure and function (Farber et al. 2006, Raudsepp-Hearne et al. 2010a). In many tropical regions, rural small holder farmers develop their lilvelihoods on steep degradation prone terrain. Thus, to guarantee long-term sustainable production of low-input crops and natural resources is it essential to know the condition and availability of the supporting and regulating ecosystem services and how land use type and management influence these service types (Pretty 2006, Hellin 2006).

Land use and management priorities often overlook the multifunctionality of landscapes particularly in rural mountainous areas (See chapter 2). Ecosystems produce multiple ecosystem services simultaneously, thus when managing for a particular good or service other goods and services may interact in complex dynamic ways (Bennett et al. 2009). Interactions among ecosystem services occur when multiple services respond to the same driver of change or when interactions among the services themselves cause changes in one service to alter the provision of another (Raudsepp-Hearne et al. 2010b). There are two types of interactions among ecosystem services. Tradeoffs occur, when the provision of one service is enhanced at the cost of another service; synergies arise when multiple ecosystem services are enhanced simultaneously. For example, afforestation of grasslands enhances carbon stocks, helps control groundwater recharge but reduces stream flow and soil quality (salinize and acidity) (Jackson et al. 2005). Drivers of synergy and tradeoff most often are socioeconomic and respond to production needs (fertilizer use, land use change), management (forest land clearing, maintaining forest patches) or restoration practices (wolf reintroduction, wetland rehabilitation) (Bennett et al., 2009). Hence, the dynamics of ecosystem service interactions is a key characteristic of social-ecological systems.

Although the ecosystem services concept is widely applied, the dynamics and interactions of how multiple ecosystem services are simultaneously affected by land use remain poorly understood (Kremen 2005, Naidoo et al. 2008). However, understanding these dynamics and interactions is particularly important for maintaining resilient human-environmental systems and for improving and maintaining multifunctional landscapes (MEA 2005, Carpenter et al. 2009). In response to this call, the concept of ecosystem service bundles has recently been proposed (Raudsepp-Hearne et al. 2010b).

Ecosystem service bundle refers to the need to consider the size, number and condition of all ecosystem service types provided by certain ecosystems or land use or cover types. The purpose of this approach is to come to understand how and why certain ecosystem service types may be related with each other and how management practices focused on a certain service type may enhance or impair other ecosystem service types. The study of ecosystem service bundles in a certain region requires an in-depth analysis of the nature and causes of the interrelatedness and feedbacks among ecosystem service types in landscape, i.e. human-environment context. Once we understand the composition and dynamics of ecosystem service bundles for specific land use and cover types, we can enhance and maintain landscape multifunctionality and human wellbeing with appropriate adaptive ecosystem management (Lovell et al., 2010). Hence, it is essential to understand how external drivers of ecosystem change, such as land use change, may alter the availability and interaction of multiple ecosystem services in space and time (Bennett et al 2009), as livelihood development and diversification are tightly coupled to landscape function.

Livelihood diversification influences the spatial distribution of land use at landscape scale resulting in different production systems and management. This diversification directly influences the provisioning ecosystem services and indirectly the supporting and regulating services causing ecosystem service tradeoffs and synergies. Current ecosystem service distribution and availability in tropical landscapes are the result of land use and land cover legacies associated with various coevolving livelihoods. Hence, a spatio-temperal assessment of land use change and livelihood development offers a new social-ecological framework that includes the feedback of farmers' decision-making on ecosystem service supply and the dynamics of landscape multifunctionality.

The central question of this study was how/why do different land use/management types supporting different livelihoods influence the dynamics and interactions of multiple ecosystem services in a rural mountainous landscape in tropical Southern Huasteca in San Luis Potosi, Mexico. To answer this question we 1) examined the current availability and status of the supporting, regulating, cultural and provisioning ecosystem services considering citrus plantations, sugarcane plantings, *milpa* systems and secondary forests; 2) designed and compared ecosystem services bundles for the four land use types; 3) explored the spatial distribution of ecosystem services at the watershed scale; and 4) identified tradeoffs and synergies between ecosystem service categories. We highlight the importance of landscape multifunctionality when taking land use decisions and developing integrated landscape management.

3.3 Methods

3.3.1 Study site

Biophysical context

The study area was located in the Southern Huasteca east of the Sierra Madre Oriental in the east of the state of San Luis Potosí, Mexico. It is a densely populated region (95 inhabitants per km^2), where indigenous groups live in politically, economically and environmentally marginal conditions (CONAPO 2005). The predominant climate is sub-humid with rains between July and September (García 1973), with an average annual temperature of 23-25ºC and average annual rainfall of 2072±900 mm (average of 40 years). Over the past 20 years, regional precipitation shows a decreasing tendency (Fig. 3.1) (CONAGUA, 2011). The original vegetation is médium semi-deciduous perennial tropical moist forests (Rzedoswki, 1966; Puig, 1991)Current natural vegetation are fragments of secondary forests product of the succession processes acting after the abandonment of land cultivation or grazing, when these areas are not disturbed again, may tend to the original state (CONAFOR, 2010).

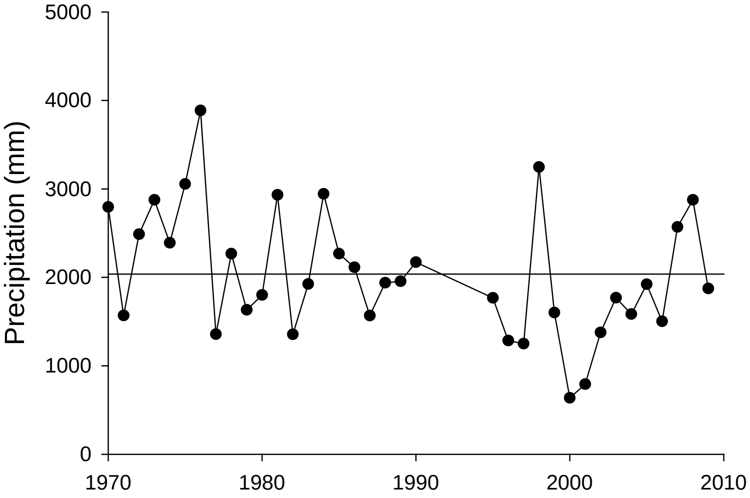

Figure 3.1. Annual precipitation (mm) between 1970 to 2010 in Tancanhuitz station. Horizontal line is the long-term mean considering 40 years of precipitation.

Soils are classified as Rendzina and Litosol (Algara 2009). Two soil horizons define the soil profile, a shallow A horizon with relative high organic matter content and the lower B horizon with heavy clays and low concentration of organic matter (locally called "coy"). The two horizons have a heterogeneous distribution of macro- and micronutrients considering different land use types (Table 3.1). Topography is characterized by hillsides with steep slopes which are highly vulnerable to degradation, soil erosion and loss of productivity (INIFAP 1996).

Table 3.1. Soil chemical characteristics of each land use type in the watershed Palzoquillo, San Luis Potosí, México (n = 10)

	Micronutrients				Macronutrients			
Land use type	Soil Fe (cmol kg-1)	Soil Mn (cmol kg-1)	Soil Cu (cmol kg-1)	Soil Zn (cmol kg-1)	Soil K+ (cmol kg-1)	Soil Mg2+ (cmol kg-1)	Soil Na+ (cmol kg-1)	Soil Ca2+ (cmol kg-1)
Milpa	0.41±0.03	0.47±0.01	0.33±0.02	0.67±0.09	1.40±0.54	2.22±1.02	1.63±0.55	12.42±1.10
Citrus	0.22±0.01	0.52±0.02	0.37±0.04	0.60±0.05	1.22±0.81	1.70±0.74	1.01±0.62	11.14±2.35
Sugar-cane	0.50±0.05	0.71±0.04	0.21±0.02	0.51±0.08	0.85±0.22	0.96±0.11	0.94±0.24	6.36±0.86
S. Forest	0.96±.0.04	0.83±0.02	0.30±0.05	0.72±0.12	1.71±0.73	1.13±0.31	1.29±0.53	8.65±1.23

Socio-economic context

Our study site was the Palzoquillo watershed (774 ha area) (Fig. 3.2). The Palzoquillo watershed is located between the municipalities of Huehuetlan and Coxcatlan (latitude 21º 33' N; longitude 95º 58' W). The elevation gradient ranges from 160 to 500 m a. s. l. Over the last 40 years, 90% of primary tropical forest was transformed to underdeveloped and subsistence agriculture (Dirzo and Miranda 1991, Reyes et al. 2008). This site is representative for the larger regional complexity and dynamics of landscape heterogeneity caused by land use change and livelihood diversification over the last 40 years. The watershed is inhabited by three indigenous farmer communities (between 230 to 320 inhabitants) (INEGI 2010): 1) San Pablo I and II, 2) Tanleab II and 3) Tzinejá II all with a high level of exclusion (CONAPO 2005) and their principal activity is agricultural production. The landscape matrix is a mixture of: 1) citrus orchards, 2) sugarcane plantings for piloncillo production (traditional brown sugar), 3) *milpa;* a traditional policulture (corn, bean and squash) farming system for subsistence, 4) secondary forests to cultivate shade grown coffee and locally 5) pastureland. The current landscape configuration carries the legacy of a 40 year history of livelihood development and transformation (Chapter 2). Currently three livelihoods coexist in the watershed: 1) Diversifiers; these are farmers of the elder generation with access to 2.5 to 4 ha of land. This comparatively large land surface has allowed diversification of agricultural activities year-around. Their lands are divided in citrus orchards, sugar-cane, *milpa* and secondary forest. 2) Sugarcane producers constitute the elder generation; they have access to land ranging from 1.5 to 3 ha. Usually they grow sugarcane in two thirds of their land and the rest functions as *milpa*; only 47% of these farmers have plots covered by secondary forest. 3) Semi-proletarianized citrus growers form the younger generation with small agricultural land of 0.5 to 1.5 ha. Many sugarcane and coffee farmers switched to citrus production thereby abandoning sugarcane and coffee production.

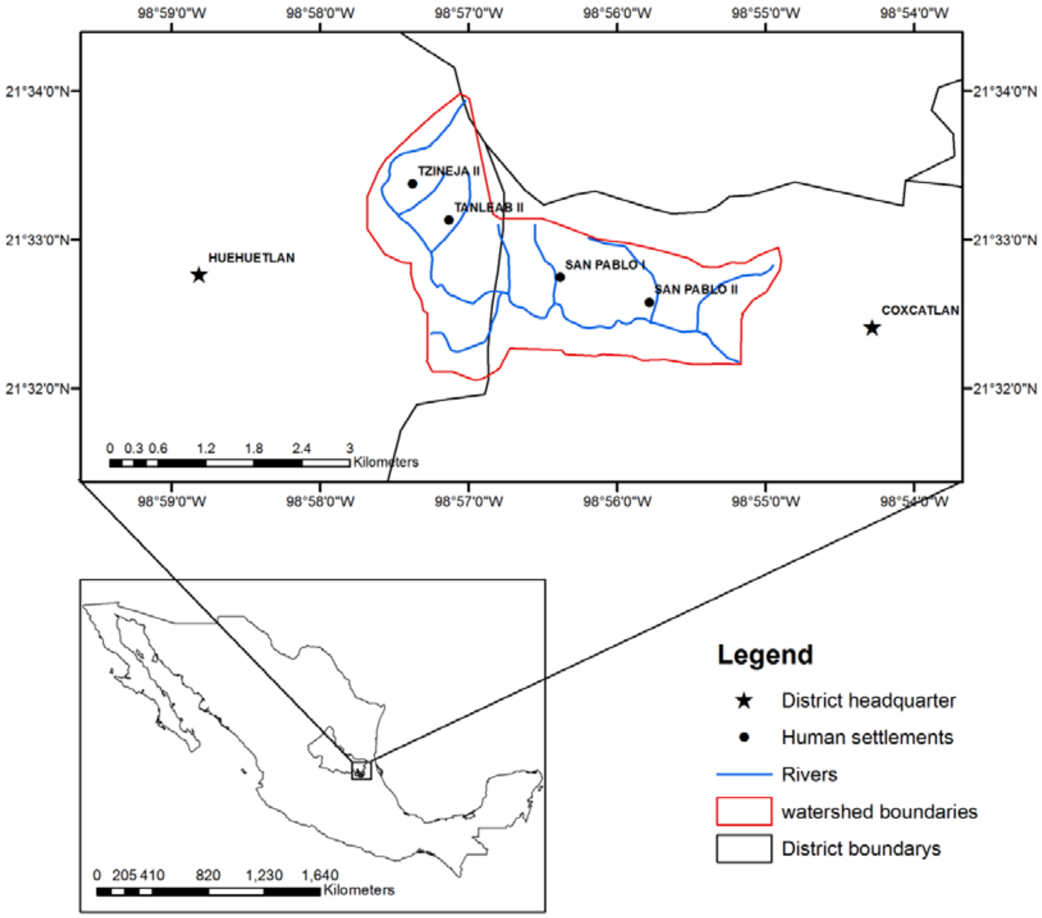

Figure 3.2. Palzoquillo watershed in the Huasteca Sur situated between the municipalities Huehuetlan and Coxcatlan, San Luis Potosi, Mexico.

3.3.2 Specific methods

3.3.2.1 Current status of ecosystem services in different land use types

Field sampling

a) Provisioning services

We randomly selected 90 landowners and applied structured interviews to learn about land use type and the products obtained from the different land use types, for selling and/or subsistence (Appendix 1). We also consulted the,Information

Service for Agrifoods and Fisheries (Servicio de información Agroalimentaría y Pesquera) (SIAP, 2011), a public information system to obtain data on crop production (corn, sugarcane, coffee and orange) for the last 10 years.

b) Cultural services

In same 90 interviews (Appendix 1) we asked about traditional land use management and the products obtained for traditional religious practices from the different land use types

c) Supporting services

To describe the supporting services we examined soil organic carbon (SOC), soil total nitrogen (N), soil phosphorus, soil organic matter (SOM), nitrogen mineralization rate, and soil texture in each land use type (Table 3.2). For soil sampling, we randomly selected 10 plots of each land use type and within each plot we extracted one composite sample consisting of 5 subsamples. We extracted soil with a soil auger (5 cm diameter) at two soil depths (0-15 cm and 15-30 cm). Soil samples were taken in the vegetation free interspaces. Composite soil samples were collected in labeled plastic bags and stored in coolers for transportation to the Laboratory, where samples were kept in the refrigerator until processing. Soil sampling took place in July of 2009.

To characterize soil fertility, we measured in-situ soil N mineralization rates in each of the 10 plots. In April 2010, we inserted a set of 9 soil cores enclosed in PVC sleeves (15cm X 6.4cm) in vegetation-free interspaces in each plot. PVC sleeves were loosely capped with perforated plastic bags to minimize soil moisture changes but not gas exchange. Cores were allowed to incubate in situ for four (after July, 2010 rainy season), eight (after december, 2010 winter season) and twelve (after April 2011summer season) month. At each sampling date we extracted three cores starting (Fig. 3.3). Adjacent 3 cores are taken to provide an estimate of initial nitrate and ammonium levels. At the end of the incubation period the field-incubate cores were removed and put in potassium chloride solution (KCl) where samples were kept in the refrigerator until analyzed accumulated nitrate and ammonium. We determined the rate of net nitrogen mineralization using the difference between final and initial levels of total inorganic N (ammonium + nitrate). Data in results was presented in percent using as a 100% the secondary forest data.

Figure 3.3. Soil cores enclosed in PVC sleeves (15 cm x 6.4cm) after four months of field incubation in Secondary forest plot in Palzoquillo watershed

d) Regulating services

To describe the regulating services we measured soil bulk density as a surrogate of soil structure / soil compaction, depth of A horizon, surface runoff, sediment retention, soil fertility loss, soil infiltration potential, soil water retention/humidity (Table 3.2). We used the same soil composite samples to determine soil bulk density. To determine the long-term effect of soil erosion on soil profile characteristics, we measured soil depth of the A horizon using 3 excavated soil profiles in each plot.

To determine ecohydological processes associated with the four land-use types we established surface runoff plots (2 m x 3 m x 20 cm) in 8 plots of each land use type. We established the runoff plots parallel to the slope in four subwatersheds on the south-exposed side of the watershed. In each land use type four plots were established on slopes with 10% – 25% inclination and another four plots on slopes with 26% – 40% inclination. Slopes were measured with a clinometer. To collect runoff water, we connected the surface plots with hoses (4 inches diameter) to 200 liter collection tanks, which were positioned downhill of the surface-runoff plots, so water flow could follow gravity (for a detailed description of the procedure see Williams and Buckhouse (1991) (Fig. 3.4). Runoff was measured after each rain event during 17 months between October 2009 and February 2011. The size of each rainfall event was recorded in five pluviometers positioned at 1.5 m height at strategic points along the watershed (Fig. 3.4). Precipitation was monitored for 17 months from October 2009 to February 2011 covering 7 summer and 10 winter months.

Figure 3.4. Surface run-off plots, 200 liter collection tanks connected to run-off plots and pluviometer

To determine annual soil and soil fertility loss associated with soil erosion, we collected and weighed soil sediments that accumulated in the collection tanks each month during a year and calculate annual monthly average. In order to refer to sediment retention as a regulating service, we converted annual monthly soil loss into monthly sediment retention rate by reporting the inverse of the erosion rate (soil erosion rate/1). To quantify gross soil fertility loss, we determined organic carbon and total N in same sediments and total dissolved organic carbon (DOC) in water samples of the run-off collection tanks each month during one year and calculated annual average fertility loss.

Water infiltration rate was determined with a single-ring infiltrometer following the method described in Herrick et al. (2005) in March 2010 in dry soil. To determine soil water retention capacity of soils, we measured soil humidity at two soil depths (15 cm and 30 cm) with the Time Domain Reflectometer method using a MiniTrace (Soilmoisture Equipment Corp). We took measurements every 4 weeks from October 2009 to October 2010 and calculated the annual average. Data in results was presented in percent using as a 100% the secondary forest data for reference.

Table 3.2. Provisioning, cultural, regulating and supporting ecosystem services (n=15) used for the analysis of identifyng tradeoffs and synergies between different ecosystem service types and of ecosystem service bundles for four land use/cover types in the Palzoquillo watershed, San Luis Potosi.

Provisioning services	**Cultural services**	**Regulating services**	**Supporting services**
Crop production (10 year average) • Orange • Sugarcane • Corn • Shadow coffee	Traditional products for religious practice	Depth of A horizon	Soil organic carbon (SOC)
Extra products associated with each land use type	• Secondary forest: camedor palm	Soil infiltration potential	Soil total nitrogen
• Secondary forest: fuel/construction wood, leaves for roofs, medicinal plants, freshwater	• Milpa: corn stalks, cempazuchitl flowers, cabs	Soil water retention /humidity	Soil phosphorus
• *Milpa*: food supplies squash, bean, tomato, chili, huitlacoche		Soil structure / Compaction	Soil organic matter (SOM)
• Citrus orchards: fuel Wood		Sediment retention	Soil N mineralization rate
• Sugarcane: Leaves for roofing		Surface runoff	Soil texture

Laboratory analysis

In November 2009, composite soil samples were oven-dried at 70 ºC for 72 hours and sieved (< 2 mm) for all physical and chemical analyses. Roots and rocks were separated and calculate de volume. Soil samples were returned in labeled plastic bags until analysis.

For soil textural analysis, we used the Bouyoucos hydrometer method (Van Reeuwijk, 1993). The following fractions were determined using 60 g of soil: sand, silt and clay. To determine soil organic matter (SOM) we applied the calcinations method (600 ºC, 2 hours) (Storer, 1984). Soil exchangeable mineral nutrient (K^+, $Ca_2{}^+$, $Mg_2{}^+$ and Na+) concentration were determined by dissolving 0.8g soil in 1N CH_3COONH_4 solution for 1 hr. Soil micro elements ($Cu_2{}^+$, $Fe_2{}^+$, $Mn_2{}^+$, and $Zn_2{}^+$) were determined using 9 g soil and 0.005M DTPA as extractable solution for 2 hrs. Both exchangeable and micro elements were determined with ICP-Mass Spectrometry (modified from Chapman, 1965; Cheng and Evett, 1990). Extractable P was analyzed with the Bray and Kurtz method using 0.03N NH4F and 0.025N HCl as extractable solution (Olsen and Sommers, 1982). To determine the level of soil compaction we determined soil bulk density (g/cm^3) as a surrogate for soil structure; we divided dry soil weight / core volume. Core volume was corrected using the volume of rock separated previously (Blake and Hartge, 1986). Soil organic C and total N (for soil and sediment samples) were determined by combustion with the Elemental Analyzer (Costech, modelo 1016) after inorganic C was removed by fumigating soil subsamples with HCl for 12 hrs (Midwood and Boutton, 1998). Total dissolved organic carbon (DOC) in runoff water samples was determined using a Total Organic Carbon analyzer (TOC-VCSN, SHIMADZU). For determining soil N mineralization rate, we extracted soil samples, sieved samples in the field and fixed the rate of N mineralization by scooping 10 g of soil in a 2M potassium chloride solution (KCl) (Robertson et al., 1999). From the filtered soil extracts we determined ammonium concentration by indophenols blue method (Keeney and Nelson, 1982) and nitrite and nitrate concentration by reduction of nitrate by vanadium (III) combined with the detection by the acidic Griess reaction (Miranda et al., 2001).

Statistical analysis

For soil organic carbon (SOC), soil total nitrogen, soil phosphorus, soil organic matter (SOM), soil compaction we used a general linear model of analysis of variance (ANOVA) with two factors, land use types with four levels (Secondary forest, Citrus orchards, *milpa* and Sugarcane) and soil depth nested within in land use with two levels (0-15cm y 15-30cm). Each land use – soil depth combination was repeated 20 times (N = 2 x 10 = 20). For depth of A horizon, soil infiltration potential, surface runoff, soil fertility loss and sediment retention we applied a one way analysis of variance with land use type as a single factor with four levels (Secondary forest, Citrus orchards, *milpa* and Sugarcane); each combination was repeated 10 times (N = 10) for the former three variables and 8 times (N=8) for the latter two variables. For soil inorganic nitrogen mineralization rate, we use a general linear model for analysis of variance (ANOVA) with two factors, land use type with four levels (Secondary forest, Citrus orchards, *milpa* and Sugarcane) and time with four levels (initial, four months, seven months and ten months); each combination was repeated 120 (N = 4 X 3 X 10)= 120). For soil water retention/humidity we use a general linear model for analysis of variance (ANOVA) with 3 factors; land use type with four levels (Secondary forest, Citrus orchards, *milpa* and Sugarcane) soil depth nested with land use with two levels (0-15cm y 15-30cm) and time in 12 levels (months during a year) each combination was repeated 1192 (N= 8 X 2 X 12 = 192). For soil texture, we used a general linear model for analysis of variance (ANOVA) with two factors land use type with four levels (Secondary forest, Citrus orchards, *milpa* and Sugarcane) and soil fractions three levels (sand, clay and silt), each combination was repeated 10 (N = 10 X 4 X 3 = 120). We use a multiple comparison Tukey test and as alternative use multiple comparison Scheffe’s test. All analysis was performance with SAS v8.02.

3.3.2.2 Determination of tradeoffs, synergies and ecosystem services bundles

We identified patterns of tradeoffs and synergies between each pair of 15 ecosystem service types (Table 3.2) with Pearson correlation analysis (SAS v8.02). Negative values were considered tradeoffs and positive values synergies; we distinguished between high significant correlations, $P<0.001$ (indicated as ***), moderate correlations $P < 0.01$ (indicated as **) and weakly correlated $P < 0.05$

(indicated as *) (Appendix 2). The identification of ecosystem services bundle was determined with a Principal component analysis (Minitab 15) using the same 15 ecosystem service types (Table 3.2) and four land use types. Ecosystem services bundles are presented in a flower diagram performance in R (x64 2.11.1), considering highest values in each ecosystem services as a complete petal with value of 1

3.3.2.3 Spatial distribution of ecosystem services

We mapped the range of seven key ecosystem service types of the watershed landscape considering the spatial distribution of different land use types using aerial photographs of 2006 (most recent form area). This analysis was performed with ArcView GIS 3.2. We used data obtained in laboratory and field analysis. Unknown category corresponded to roads, human settlements and pastureland.

3.4 Results

3.4.1 Ecosystem service characteristics of four land use types in the Palzoquillo watershed

Human well-being and livelihoods in this tropical landscape depend directly on a variety of different provisioning and cultural goods and services and on many supporting and regulating services that control the structure and functioning of secondary forest fragments, sugarcane plantings, *milpa* subsistence systems, and citrus orchards.

a) Provisioning services and land use management

Citrus orchards produce 7.1 ± 0.31 t $ha^{-1}yr^{-1}$ (10 year average) (SIAP, 2011) of orange and mandarin fruits mainly for regional markets. Citrus plantations also provide fuel wood. Management is a traditional practice, where the herbaceous vegetation is removed throughout the year with a traditional tool (huingaro), and the top 10 cm soil is tilled manually. Vegetation residues are removed to facilitate crop harvesting. However, many farmers (mostly semi-proletarianized citrus growers) have replaced this practice by herbicide (organophosphate) application. In addition, most citrus orchards have to apply pesticides (organophosphates) to control fruit fly; this is an imposed subsidized government program.

Sugarcane plots produce 3.6 ± 0.52 t $ha^{-1}yr^{-1}$ (10 year average) (SIAP, 2011) of sugar for piloncillo production (traditional brown sugar) for regional markets and subsistence. Sugarcane farmers use sugarcane leaves as roofing material. During manual land preparation, they leave any plant residues on soil surface.

Milpa systems offer a diverse set of annual subsistence crops; they produce on average 0.8 ± 0.25 t $ha^{-1}yr^{-1}$ (10 year average) of corn (SIAP, 2011). Also *Milpa* produce beans, squash, tomato, chili and *huitlacoche* (corn fungus) for subsistence and occasionally other foods are intercropped such as chili, papaya and banana. This land use type is fundamental to maintain farmer's food security. *Milpa* system is maintained by traditional slash-and-burn practices; after 5-7 years cultivation is interrupted by a 2-10 years resting period allowing the regeneration of secondary forests. Traditional land preparation is manually done using huingaros (traditional tool) to remove herbaceous vegetation and tilling the top 10 cm of soil, the vegetation residues are maintained on the soil surface. However, this practice has been replaced by herbicides (organophosphate) use principally by Semi-proletarianized citrus growers but less than citrus orchards.

Secondary forests used in this study are characterized by vegetation of at least 15 years or more (up to 50 years) which support subsistence coffee production 0.7 ± 0.44 t $ha\text{-}^{1}yr^{-1}$ (10 year average), roofing material (leaves), fuelwood (2.1 kg/day/household), construction wood material, the most commun are Teca (*Tectona grandis Linn F.*), Melina (*Gmelina arbórea* Roxb)., Frijolillo (*Cojoba arborea* (L.), Britton & Rose, Cedro Rosado (*Cedrella odorata L.*) and Palo Rosa (*Tabebuia rosae Bertol. DC.*). These forests also provide medicinal plants for example: *Anoda cristata L.* for fever, *Guazuma ulmifolia Lam*. for headache, *Tabebuia rosae Bertol. DC.* for diabetes and *Cedrella odorata L.* for stomach pain. Secondary forest fragments provide freshwater for drinking and household use; i.e. inside 14 forest fragments of the total watershed area there are surface wells with open access to all community members. In the past 10, community members observed a clear decline in the water level of surface wells, particularly in the hottest months (March to June).

The main watershed river is used for cloth washing and bathing; but water flow has greatly decreased over the past 30 years and currently occurs only during 8 months of the year. In former times when river carried water throughout the year, waters were used for fishing, which greatly improved farmer's diets.

b) Cultural services

Secondary forests and *Milpa* provide goods used for the day of the dead (November 1); during this traditional religious festivity, which dates back to pre-hispanic times, it is common to set up altars in memory of families and friends in people's homes and in public places. For these altars, community members extract camedor palm (*Camaedorea elegans*) from secondary forest and corn stalks, cobs, cepazuchitl flowers as ornaments and corn to prepare *tamales* (traditional food) from *Milpa*. Also, Milpa is an ancient policulture system that provides many cultural services such as cultural identity and local environmental knowledge (Alcorn and Toledo, 2000).

c) Supporting services

Considering the watershed was originally covered by primary forest and for many centuries by secondary forest we used secondary forest values as reference or baseline data. We found that SOC content dropped in sugarcane by 12% and 7%, *milpa* by 15% and 12%, and in citrus orchards by 23% and 22%, for 0-15 cm and 15-30 cm soil depth, respectively (Fig. 3.5) (Table 1, Appendix 2). Total soil nitrogen dropped in sugar-cane and *milpa* 20% and 12% and in citrus orchards

31% and 24% for 0-5 cm and 15-30 cm soil depth, respectively (Fig. 3.5) (Table 2, Appendix 2).

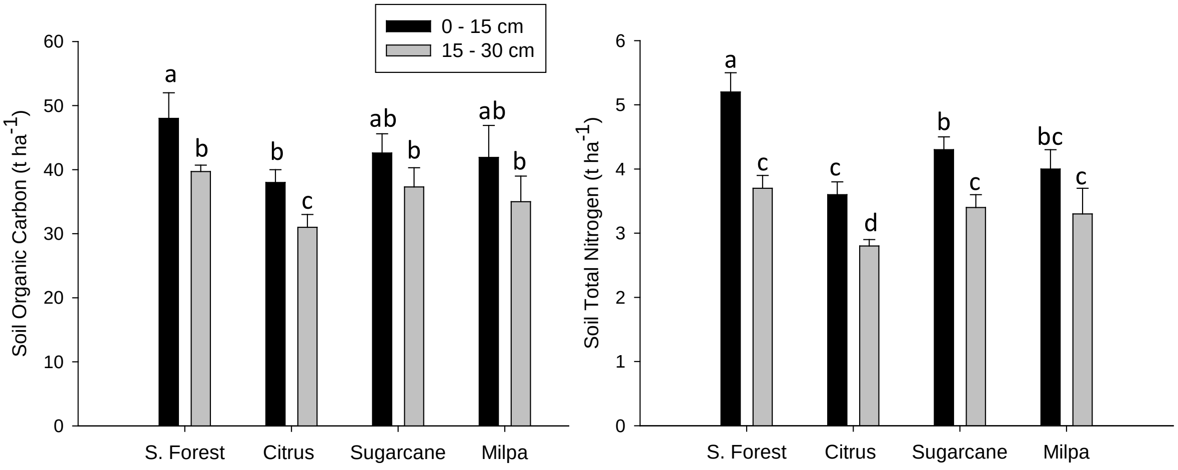

Figure 3.5. Soil organic carbon (t ha^{-1}) (left) and total soil nitrogen (t ha^{-1}) (right) content for secondary forest, citrus, sugarcane, and *milpa* systems. The bars indicate average values (± 1SE, n=10) and different letters on bars indicate statistical difference at $P<0.05$.

Net N mineralization was higher in rainy season in four land use types and lower in summer season. Secondary forest presented the highest values in all seasons followed by *milpa*, sugarcane and citrus orchards the, latter one exhibiting the loweste values in all seasons (Table 3.3) (Table 3, Appendix 2).

Table 3.3. Seasonal net N-mineralization (µg g^{-1} mol^{-1}±1SE) at different sites (2010-2011) by PVC sleeves method.

Land use	Rainy	Winter	Summer	Annual mean
Secondary Forest	37.7±0.5a	24.6±2.2b	11.8±2.1d	24.7±7.5b
Sugarcane	16.4±0.8c	9.2±1.7d	4.7±0.1e	10.1±3.4
Milpa	31.9±1.0ab	17.3±2.2c	8.2±1.3d	19.1±6.9c
Citrus	20.3±3.8b	2.9±0.4e	0.6±0.1f	7.9±6.2d

For SOM, in comparison to secondary forests, sugarcane lost 8% and 3%, *milpa* 11% and 4% for 0-15 cm and 15-30 cm soil depth, respectively, while in citrus orchards around 28% at both soil depth (Fig. 3.6) (Table 4, Appendix 2).

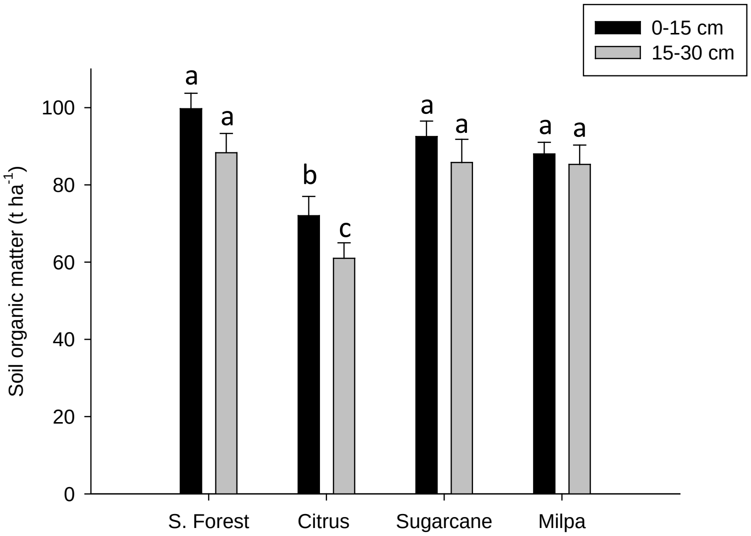

Figure 3.6. Soil organic matter (t/ha^{-1}) content for four land use types in the Palzoquilla watershed. Bars indicate average values (± 1SE, n=10) and different letters above bars indicate statistical difference at $P<0.05$.

Soil phosphorus increased in citrus orchards by 287% and 200%, in *milpa* by 137% and 60% and sugarcane 25% and 20% for 0-15 cm and 15-30 cm soil depth, respectively (Table 3.4) (Table 5, Appendix 2).

Table 3.4. Soil supporting and regulating services associated with management and land use types in Palzoquillo watershed. Different letters in rows within a column indicate statistical difference at $P<0.05$.

Land use type	Soil depth (cm)	Soil phosphorus (t ha^{-1})	Soil infiltration rate (mm h^{-1})	Soil humidity average (%)	Sediment retention (t ha^{-1}yr^{-1})
S. Forest	0-15	0.81±0.04c	595±32a	37.6±1.3a	13.1±3.24a
	15-30	0.53±0.07d		34.1±1.0b	
Citrus	0-15	3.17±0.3a	403±22c	25.8±1.2c	1±0.63d
	15-30	1.51±0.2b		27.1±1.1c	
Sugarcane	0-15	1.01±0.2c	528±24b	34.3±1.4b	8.3±2.01b
	15-30	0.62±0.05d		31.0±1.5b	
Milpa	0-15	1.93±0.3b	483±31b	31.5±1.3b	3±0.85c
	15-30	0.80±0.1c		30.2±1.2b	

Land use types greatly influenced soil texture. Citrus orchards exhibited the highest content of clay (40%) content at both soil depth, *milpa* systems had two well-defined horizons; the A horizon had an equal mixture of silt and sand and the B-horizon an equal mixture of clay and silt. Secondary forest and sugarcane had high contents of silt, were rich in organic matter and had low clay content in both soil depths (Table 3.5) (Table 6, Appendix 2).

Table 3.5. Soil texture in different land use types in Palzoquillo watershed. Different letters between rows within a column indicate statistical difference at $P<0.05$.

Land use	Soil depth (cm)	sand (%)	clay (%)	silt (%)
Citrus	0-15	21±0.51e	40±.021b	38±0.15c
	15-30	24±0.43e	44±0.35b	32±0.24d
Milpa	0-15	45±0.38b	17±0.11f	38±0.32c
	15-30	25±0.21e	38±0.23c	36±0.19c
Sugarcane	0-15	37±0.26c	9±0.10g	54±0.27a
	15-30	33±0.30d	15±0.22f	52±0.14a
S. Forest	0-15	29±0.21d	27±0.30d	43±0.21b
	15-30	30±0.12d	28±0.16d	42±0.26b

a) Regulating services

Soil depth of the A horizon was 34% 28% and 13% lower in citrus orchards, *milpa* and Sugarcane, respectively than in secondary forest (Fig. 3.7) (Table 7, Appendix 2).

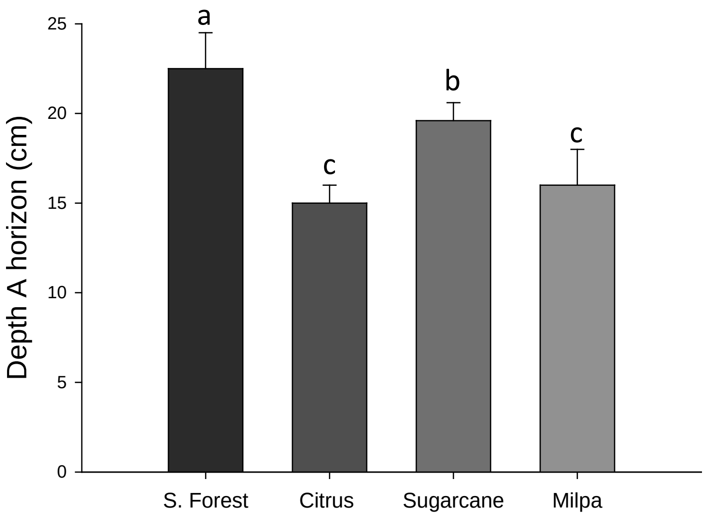

Figure 3.7. Depth of A horizon for different land use types. Bars indicate average values (± 1SE, n=10) and different letters above bars indicate statistical difference at $P<0.05$.

Soil bulk density (soil compaction) was significantly higher in citrus orchards at both soil depths compared to other crops and secondary forest (Fig. 3.8) (Table 8, Appendix 2).

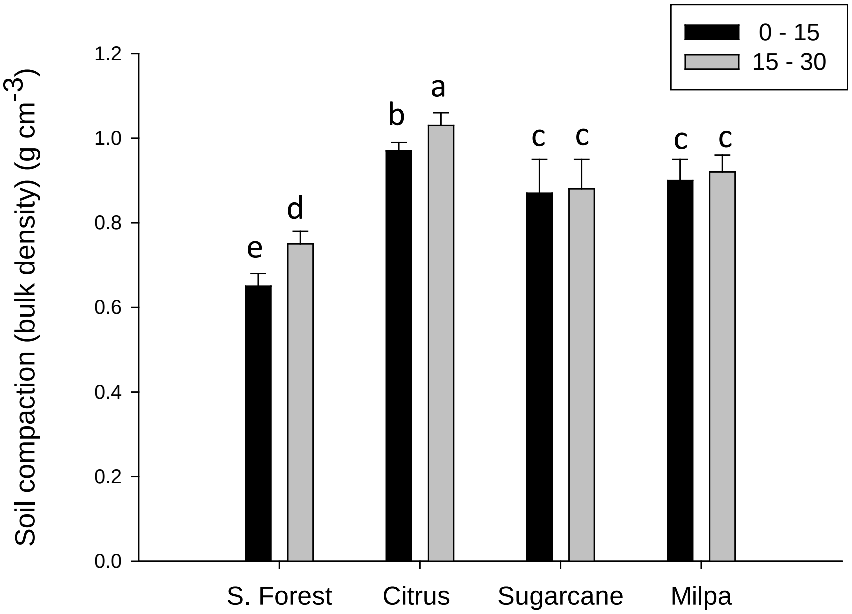

Figure 3.8. Soil bulk density (g cm^{-3}) (soil compaction) in four different land use types. Bars indicate average values (± 1SE, n=10) and different letters among values in a column indicate statistical difference at $P<0.05$.

Water infiltration rate dropped by 33% in citrus orchards, 11% in sugarcane and 19% in *milpa* compared to secondary forests (Table 3.4) (Table 9, Appendix 2). Average annual soil humidity dropped in sugarcane around 9%, in *milpa* 15% and in citrus orchards 26% in both soil depths (Table 3.4). Soil humidity dynamics is different among land use types; in sugarcane and secondary forest values are higher and constant in the year with small fluctuations compared with *milpa* and citrus orchards with lower values and stronger fluctuations in the year (Fig. 3.9) (Table 10, Appendix 2).

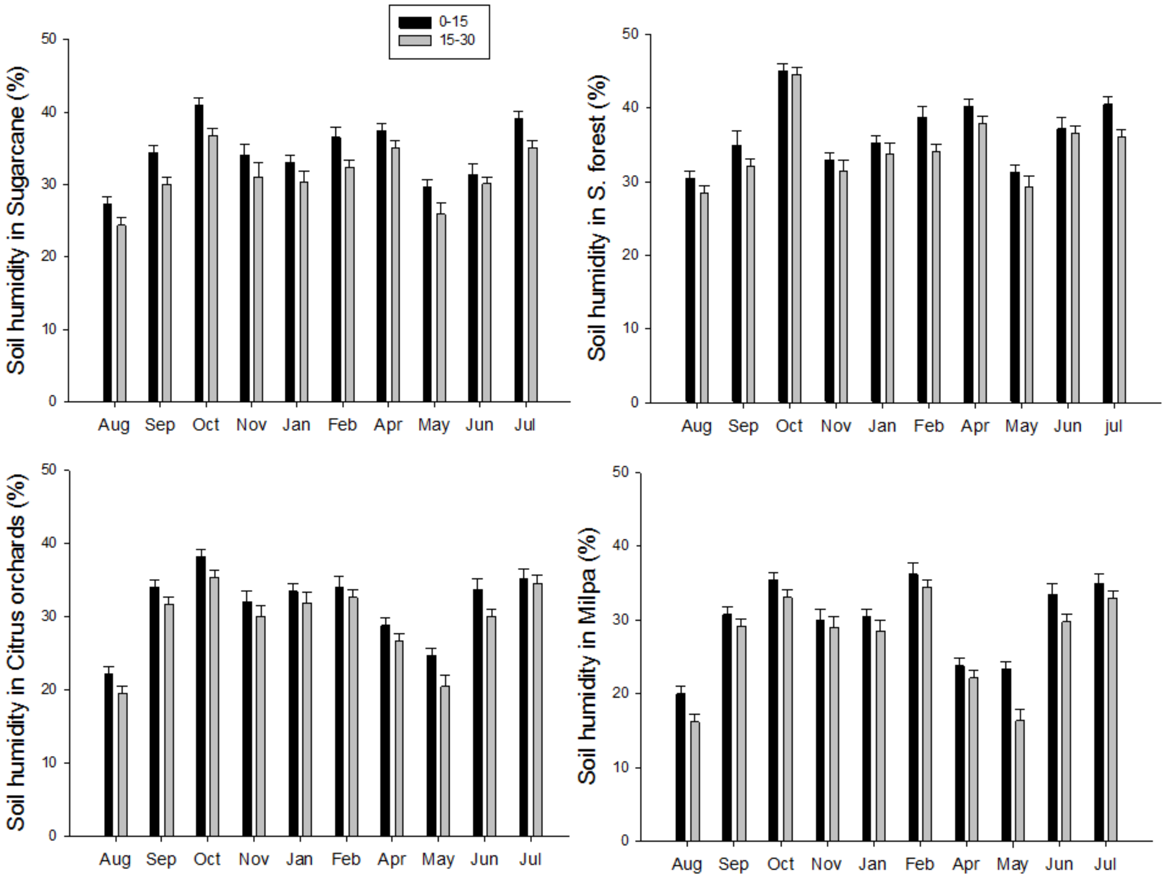

Figura 3.9. Monthly soil humidity measures taken in four land use types at two soil depth (0-15 cm, 15-30 cm) between August 2009 and July 2010.

Total annual precipitation was 2306.08 mm. Annual surface runoff was similar in secondary forest and sugarcane, followed by *milpa* and was highest in citrus orchards (Fig. 3.10) (Table 11, Appendix 2). At very high precipitation and run-off events (June 2010 – Sept 2010), run-off was higher in sugarcane than secondary forests and the difference in run-off between *milpa* and citrus was more pronounced than at lower precipitation events.

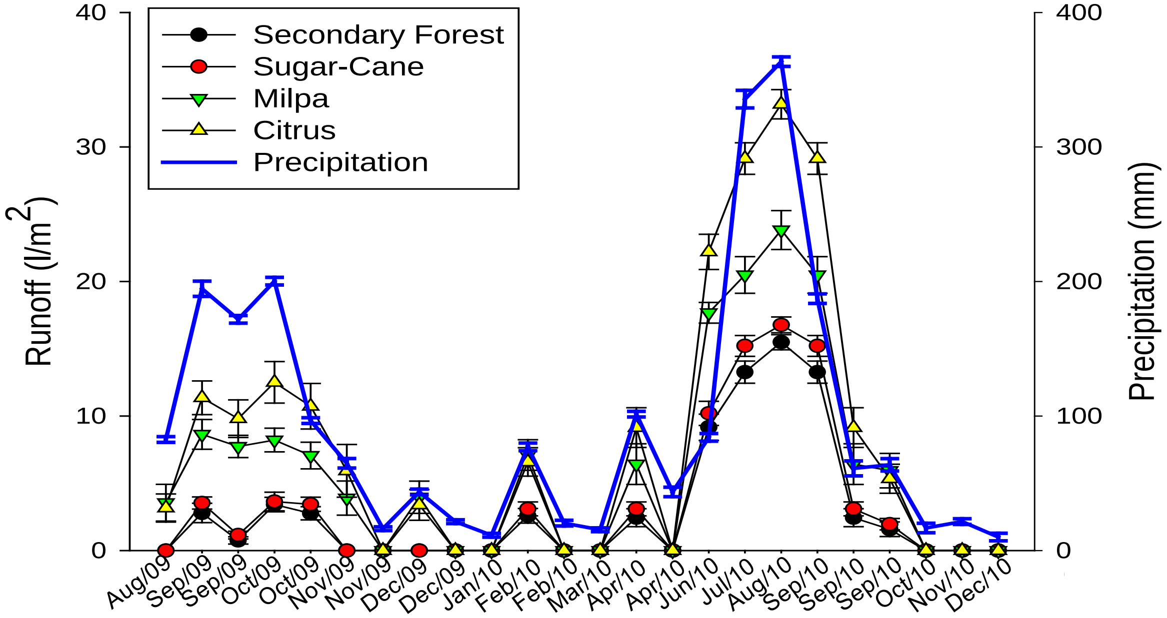

Figure 3.10. Average monthly volume (l m^{-3}) of surface runoff in different land use types (± 1SE, n=8) compared to monthly precipitation between August 2009 and December 2010.

Sediment retention (erosion rate/1) decreased in citrus orchards by 91%, in *milpa* by 75% and in sugarcane by 36% compared to secondary forests (Table 3.4) (Table 12, Appendix 2). Total C loss in surface runoff was significantly higher in citrus orchards (170%) and *milpa* (178%), while sugarcane only lost 38% compared to secondary forest (Fig. 3.11) (Table 13, Appendix 2).

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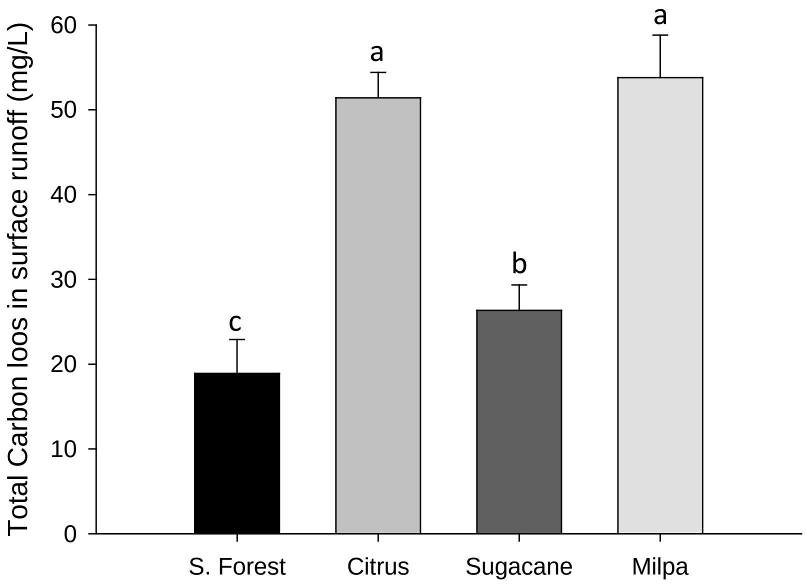

Figure 3.11. Total carbon loss (mg/l) in surface runoff in different land use types. Bars indicate average value (± 1SE, n=8), different letters on bars indicate statistical difference at $P<0.05$.

3.4.2 Interactions between ecosystem service types and categories

Of the 105 possible pairs of ecosystem service interactions in the Palzoquillo landscape, 99 pairs were significantly correlated: 49 of them were highly correlated ($P<0.001$), 32 moderately correlated ($P<0.01$), and 18 weakly correlated ($P<0.05$). Of these correlations, 44 were tradeoffs (negative correlations) and 55 were synergies (positive correlations) (Table 3.6) (Table 14, Appendix 2). Crop production showed synergies with soil compaction, P concentration and surface runoff, however, exhibited strongest tradeoffs with all other services. This means higher crop production came at a cost of regulating services (depth of A horizon, soil infiltration potential, soil water retention/humidity, sediment retention) and supporting services (SOC, soil total N, SOM, soil inorganic nitrogen, soil texture). On the other hand, we recognize that the production of additional and traditional products for religious practice enhanced synergies with regulating services (soil infiltration potential, soil water retention/humidity, soil structure compaction, sediment retention) and supporting services (SOC, soil total N, SOM, soil inorganic nitrogen, soil texture). These results showed the multifuncionality at landscape level, except for soil compaction, P concentration and surface runoff, all regulating, supporting and cultural service types presented synergies among them.

crop productivity	-0.79***	-0.55***	-0.43**	-0.57***	-0.70***	-0.71***	-0.27	0.68***	-0.88***	-0.71***	0.42**	-0.45**	-0.92***	0.49**
	Extra products	0.89***	0.47**	0.65***	0.59***	0.67***	0.26	-0.66***	0.90***	0.7***	-0.33*	0.46**	0.94***	-0.31*
		Soil texture	0.46**	0.55***	0.46**	0.54***	0.44**	-0.38*	0.73***	0.48**	-0.45**	0.71***	0.76***	-0.47**
			SOC	0.45**	0.48**	0.49**	0.50***	-0.50***	0.36*	0.46**	-0.18	0.45**	0.43**	-0.16
				Total N	0.69***	0.66***	0.45**	-0.65***	0.49**	0.64***	-0.34*	0.59***	0.57**	-0.40*
					SOM	0.78***	0.40*	-0.83***	0.49**	0.79***	-0.42**	0.59***	0.89***	-0.49**
						Infiltration	0.61***	-0.86***	0.49**	0.88***	-0.55**	0.76***	0.49**	-0.45**
							A Horizon	-0.60***	0.1	0.55***	-0.34*	0.7***	0.22	-0.33*
								P	-0.67***	-0.85***	-0.39*	0.64***	-0.5**	0.40*
									Products for religius	0.46**	-0.33*	0.4*	0.98***	-0.43*
										Soil humidity	-0.43*	0.71***	0.56**	-0.35*
											Compactation soil	-0.63***	-0.40*	0.54***
												Sediment retention	0.52**	-0.65***
													S.Inorganic N	-0.40*
														Surface runoff

Table 3.6. Correlations (r^2) between key ecosystem service types at the landscape scale. Red signifies negative correlation, and blue signifies positive correlations. The intensity of shading refes to the three significant levels (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$)

3.4.3. Ecosystem Service Bundles.

Results of the principal component analysis showed that 15 ecosystem service variables could be explained by principal component 1 (Fig. 3.12) (Table 15, Appendix 2), this component explained 59% of variance, the remaining principal components explained less than 15% of the remaining variance. Principal component 1 suggests a gradient of impact with respect to land use type. Orange plantations with the highest crop production had the lowest availability of regulating, supporting and cultural services. Diversified sugarcane and *milpa* crops, which provided additional and traditional products, however with a lower cash crop production, had a higher number of supporting and regulating services.

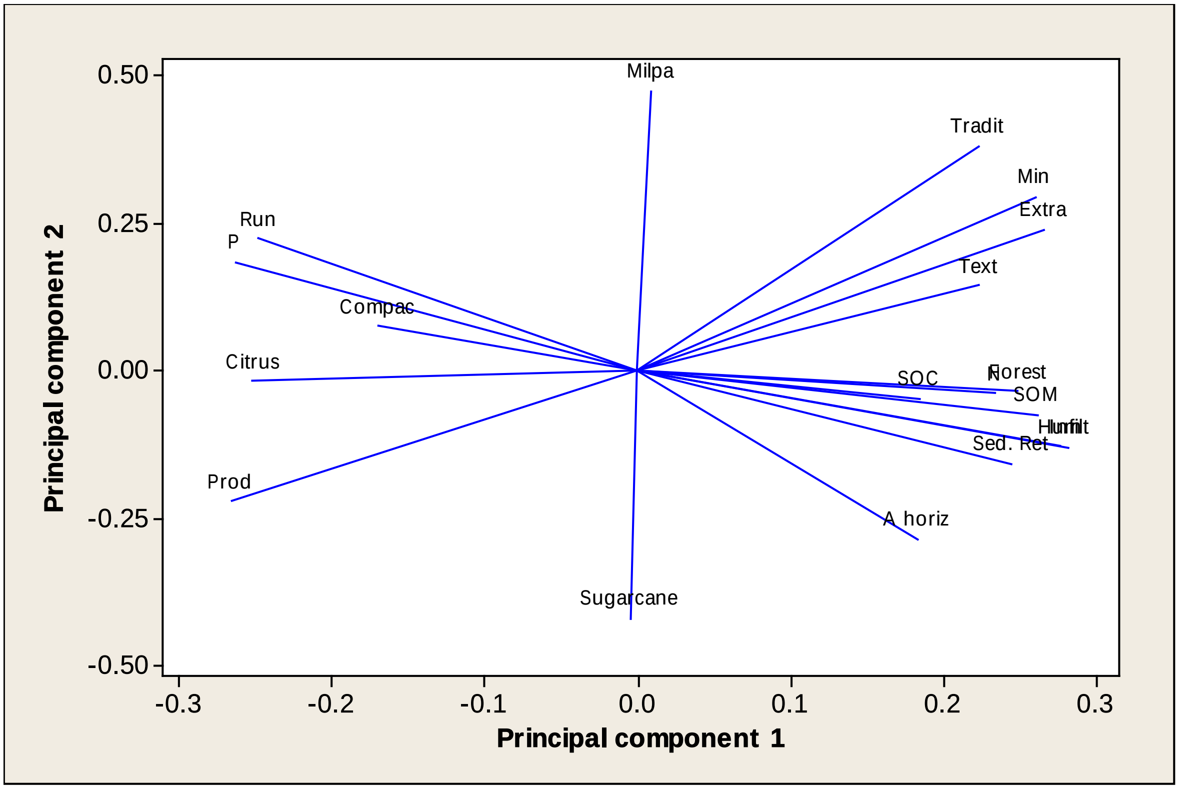

Figure 3.12. Principal component analysis, principal component 1 explained 59% of variation of ecosystem services and principal component 2 explained only 15% (Appendix 2).

Based on these analyses we determined ecosystem services bundles for each land use type recognize four types in watershed.

Citrus ecosystem service bundle type characterized by high synergies between crop productivity, soil phosphorus and soil compaction, and high tradeoffs with extra products, traditional products for religious practice, soil texture, total nitrogen, SOM, soil inorganic nitrogen, soil infiltration, soil humidity, depth of A horizon and moderate tradeoffs with sediment retention and SOC. This ecosystem service bundle only maximizes the production of a single provisioning service for markets (orange) thereby affecting all other ecosystem services categories (Fig. 3.13).

Sugarcane ecosystem service bundle is characterized by high synergies between soil humidity, soil infiltration, depth of A horizon, sediment retention and SOM, moderate synergies with soil compactation, soil texture and SOC and weak synergies with total nitrogen, soil inorganic nitrogen and crop production. It presents tradeoffs with soil P, extra products and traditional products for religious practices. Despite of providing provisioning services for markets (sugarcane), this bundle represents strong conservation of regulating services, while only slight maintains of supporting services but no cultural services (Fig. 3.13).

Milpa ecosystem service bundle type characterized by strong synergies between extra products, traditional products for religious practice, soil texture and soil inorganic nitrogen, moderate synergies with total nitrogen, SOM, infiltration, soil humidity, depth of A horizon, and weak synergies with SOC and sediment retention and tradeoff with crop production (corn), soil P and soil compaction. This bundle maintains extra products for food security and cultural services, not only for traditional religious practices but also for conserving environmental local knowledge, identity. Supporting and regulating ecosystem services are moderately conserved (Fig. 3.13).

Secondary forest ecosystem service bundle is characterized by high synergies between depth of A, soil infiltration, soil humidity, soil compaction, sediment retention, SOC, soil total nitrogen, soil P, SOM, soil inorganic nitrogen, soil texture and extra products, moderate synergies with traditional products for religious practice and tradeoffs with crop productivity (coffee), phosphorus and soil compaction (Fig. 3.13).

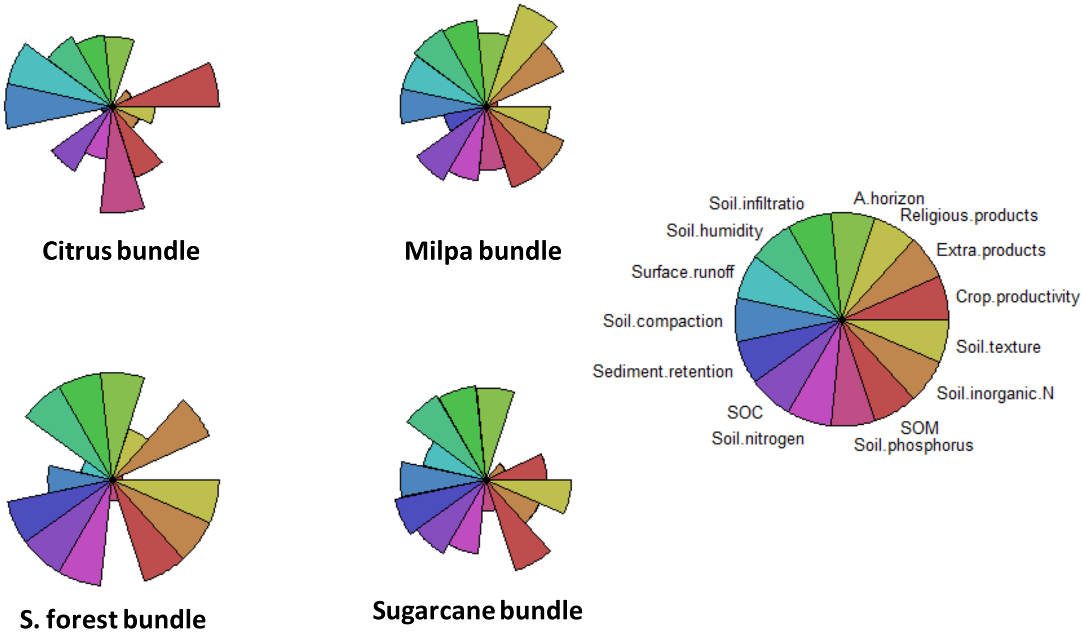

Figure 3.13. Ecosystem service bundle types represent the average values of ecosystem services.

3.4.4 Spatial distribution of Ecosystem Service

The spatial distribution of key ecosystem services in the Palzoquillo landscape showed a similar gradient (Fig. 3.14). We can distinguish areas with high values in crop production and soil P but low values in other ecosystem services and areas with high extra products and traditional products that enhance the supporting and regulating services. These areas correspond to different land use type.

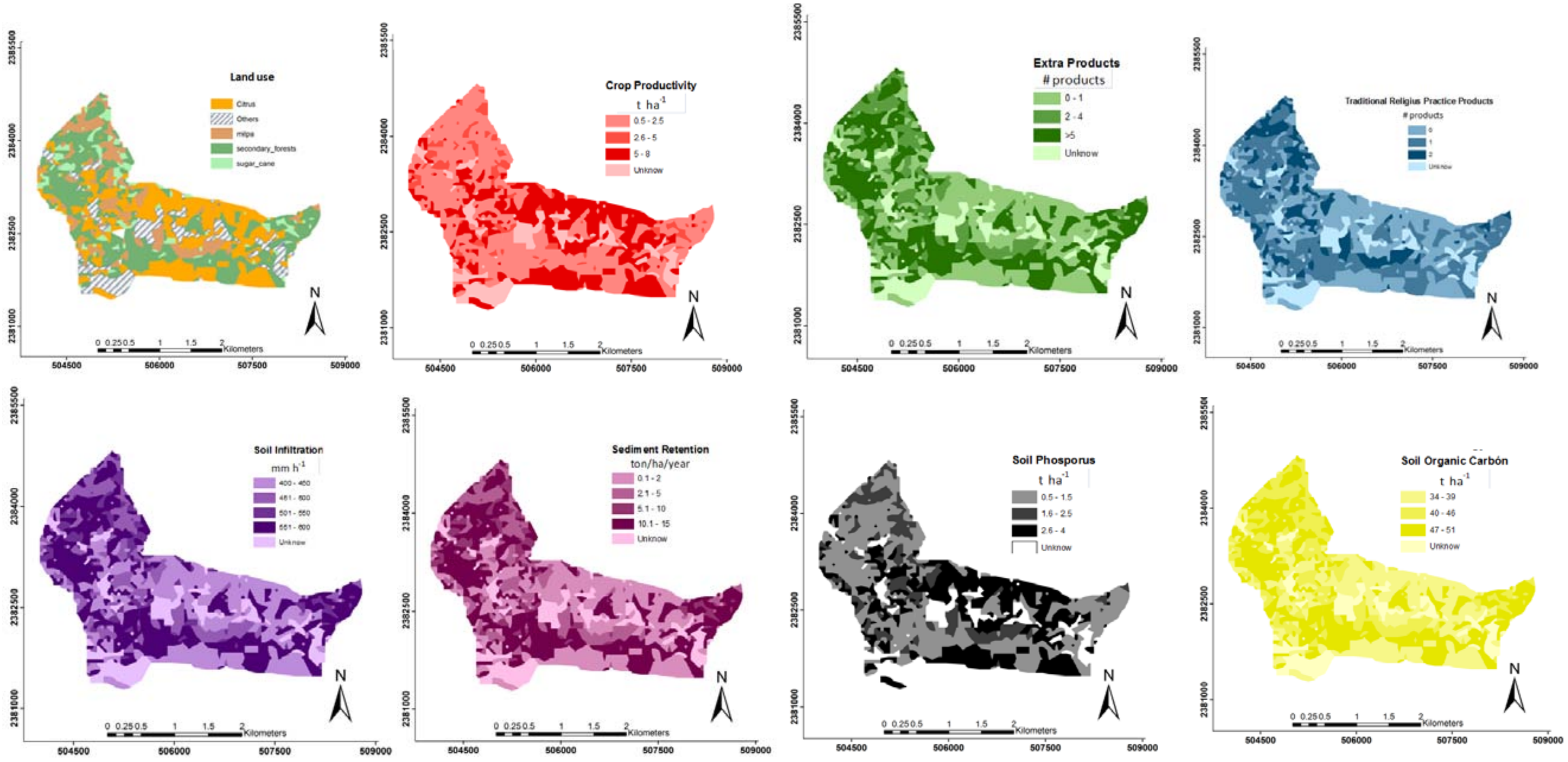

Figure. 3.14. Spatial distribution of land use and key ecosystem services: crop productivity, extra products, traditional religious practice products, soil infiltration, sediment retention, soil phosphorus and soil organic carbon in watershed Palzoquillo.

3.5 Discussion

This research is the first in Mexico that examines the interaction of a large set of supporting, regulating, cultural and provisioning ecosystem services in a rural tropical watershed landscape in the Huastecea in San Luis Potosi. This watershed is characterized by a long legacy of landscape transformation in response to multiple external and internal drivers shaping the development and continuous adaptation of livelihoods in response to socio-environmental conditions. This study contributes to an emerging necessity to understand multiple ecosystem service interactions at local scales (Hu et al. 2007, Turner et al. 2007) to contribute to better informed decision-making on adaptive land management as a fundamental asset sustainable development in a directionally changing global environment (Koellner et al., 2008). Most studies on ecosystem service bundles have been conducted at the municipality or country level (Nelson et al., 2009), where intervention occurs at higher governance levels. Our research focused on ecosystem service dynamics at the local scale associated with four land use types typical for the region. We chose this scale, as the household level constitutes the smallest unit of decision-making. Thus, this research may fill an important gap in our knowledge on the composition, dynamics and heterogeneity of interaction types among multiple ecosystem service associated with land use type and management practices. Our study had two goals: 1) to inform farmers on synergies and trade-offs of their farming practices with respect to regulating, supporting and cultural ecosystem services and how feedbacks of changes in these latter services may feedback on livelihood adaptation. 2) to respond to the recently established Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (UNEP 2012) whose functions it is among others to contribute to policy-relevant research on biodiversity and ecosystem services and in particular to better integrate research, monitoring, assessment, policy development and capacity building in the science-policy process from the local to global scale (Perrings et al. 2012). Our study is highly representative for decision-making processes on land use and management and livelihood development in rural landscapes in Latin America.

In tropical ecosystems, increasing land use change will have a large influence on important ecosystem services (Metzger et al., 2006). Our results show that of 15 key ecosystem services four land use type specific ecosystem service bundles were identified corresponding to citrus plantations for cash crop production, sugarcane plantings for traditional piloncillo production, *milpa* systems for corn subsistence and secondary forests. This suggests that albeit of land use legacies and larger-scale landscape transformations, current land use practices have left their “fingerprint” on regulating, supporting and cultural ecosystem service in response to orange, sugar, corn and wood production. This suggests that social-ecological properties such as livelihoods may not only contribute to local plot heterogeneity but also to the multifunctionality at the landscape scale as a function of the specific characteristics and dynamics of ecosystem service bundles. Each land use type provides a particular ecosystem services bundle as a result of decision-making processes and interactions among three currently coexisting livelihoods in the watershed.

Diversifiers used to be the livelihood that was most abundant in the watershed landscape and thus contributed the most to land use diversity (sugarcane, *milpa*, secondary forests), because this elder generation had greatest access to land (Chapter 2). However, this feature is highly dynamic. For instance, the youngest generation, with very limited access to land as a consequence of smallholder inheritance regulations, has adopted a semi-proletarianized livelihood dedicating agricultural activities to citrus production. Therefore, with an increase in this citrus production based livelihood citrus orchards spread in watershed while the other three land use types decrease (Chapter 2). Citrus orchards are the land use type that is producing the economically most valuable provisioning service (orange, mandarin, grapefruit) at the enormous cost of most of the regulating and supporting services and with an increment in soil phosphorus and soil compaction. High phosphorus concentration in citrus orchards soils is the result of excessive use of organophosphate pesticides for pest control (fruit fly) and herbicide use because of lack of time for agricultural work. These are programs subsidized by the government to facilitate the production of monocultures crops destined for regional markets (Chapter 2). High soil compaction came at the cost of giving up traditional practices, where the herbaceous vegetation had been removed with a traditional tool (huingaro) and the top soil was slightly tilled. This seemed a necessary practice because of the high clay content and low organic matter these soils compact easily and thus enhance run-off. With the adoption of semi-proletarianized citrus growers livelihood, local environmental knowledge as well as with identity and socio-cultural ties to the traditional *milpa* production system disappeared and had severe consequence on key supporting and regulating ecosystem services (Fig. 3.12).

When scaling at the landscape scale, fundamental supporting and regulating ecosystem services in large extension of the watershed (236.78 ha) occupied by citrus orchards induced a drop in provisioning services, when considering both cash-crops and extra products for self supply. Citrus orchards cover increase 222 ha in last 30 years. The citrus land use is becoming less resilient, because it do not have the capacity to recover from extreme climate events such as drought. In 2011, a severe drought event in souther Huasteca caused a decrease in citrus crop yield by 10,000 ton when compared to the previous years with 90,000 ton. Also, the crop had poor quality (little juice and level of acidity) because of water scarcity and it was predicted that by 2012 this loss in crop quantity and quality could not be recovered (Pulso, 2012). This high vulnerability to external biophysical drivers (climate, pests and diseases) associated with overextraction of provisioning services is a consequence of a clear tradeoff with the regulating services. This phenomenon is common in poor rural communities and results in a poverty trap because their crop productivity drop and are ecological and socio-economical vulnerable for extreme internal and external events (Sudmeier-Rieux et al., 2006; Persson et al., 2010).

Identifying areas where the provision of ecosystem services is low or high considering desired ecosystem services can be used to discover areas that seem to be particularly ineffective or effective at producing desired ecosystem services (Raudsepp-Hearne et al., 2010). The farmers perceived as desirable ecosystem services water in surface wells, fuel wood and staple food, these services pronounce secondary forest and *milpa* as principal areas for conservation

When considering the spatial distribution of ecosystem services in the watershed, what becomes apparent is that of all state factors (geology, climate, biota, topography) from which one could predict the distribution of supporting and regulating ecosystem services, disturbance type, i.e. land use that overrides any natural gradients in soil humidity, soil depth, accumulation of SOM, soil texture associated with the pronounced topography of this watershed. This does not come as a surprise as this watershed has been appropriated by people for many centuries if not milenia (Toledo et al., 2003).

The watershed is divided into large areas where different ecosystem services dominate in that they are spatially clustered. However, since most provisioning services exhibit tradeoffs with the other ecosystem services, the area of clusters of supporting and regulating services is relatively small. This small areas provide fundamental services for all farmers in the watershed, even though semi-proletarianized citrus growers only have citrus orchards and sacrifice other land use types such as sugarcane producers or diversifiers that maintain the functionality of the whole watershed ecosystem. In this context, the citrus growers adopt a free-rider strategy according to game theory, in that they maximize financial gain with the smallest investment (Ostrom 2000). Orange production was introduced in middle of 1970s hence, after 40 years of land conversion, plots formerly cultivated by sugarcane (207 ha in 1978) or secondary forest (360 ha in 1978) have lost most of their supporting and regulating services. Regulating and supporting ecosystem services appear to play a critical role in sustaining local livelihoods and providing capacity for recovery and regeneration following natural disasters or social shocks (Bennett et al., 2009). When farmers' decisions are based solely on market returns and when access to land is limited land use patterns emerge that are low in the provision of regulating, supporting and cultural services. This tendency is repeated in many countries (Nelson et al. 2009) suggesting that homogenization of landscapes by single land use types may reduce the provision of regulating and supporting ecosystem services and thus the multifunctionality of landscapes. This suggests that citrus production is not sustainable and overall offers less possibilities for future land use changes compared to the other three land use types. Areas on the landscape with higher values for regulating, supporting and cultural services maintain more options for the future, both for agriculture and other land use types, because any alternative land use type underlies the production of the fundamental sustaining types of services (Carpenter et al. 2009). Secondary forest, *milpa* and sugarcane represent ecosystem service hotspots that should be the focus of management and conservation (Egoh et al. 2008). Conserving a high diversity of land use/cover types promotes heterogeneous landscape and enhance multifunctionality in rural landscapes (Taylor et al., 2010).

Examining ecosystem service bundles emphasizes the linked nature of ecosystem services in response to land use and management. Hence, for land management the consideration of multiple tradeoffs and synergies among ecosystem service types involved should be encouraged in land management decisions (Rodriguez et al., 2006; Kareiva et al., 2007).

Our study is distinct from previous studies in that in addition to a spatially explicit analysis of different ecosystem service types with reference to the condition (state of degradation) and interaction type we linked livelihood development and diversification to these ecosystem service bundles. This approach allows us to predict on potential impacts of land use types on the resilience and sustainability of rural landscapes as fundamental life-support system for a large population. We consider this approach promising as it addresses complex issues of social-ecological systems both from a scientific analytical perspective but also from a managament and development perspective. The inclusion of ecosystem services and livelihood analysis in management planning has great potential to enhance not only benefit from economy but also natural and social capital (Chapin, 2009; Brondizio, 2009).

3.6 Conclusion

Our analyses of ecosystem service assessment, distribution and ecosystem services bundles revealed that social-ecological systems produce ecosystem services in complex patterns in accordance with where humans desire specific ecosystem services, where it is possible to produce them, and how they will interact.

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4. Conclusions

The current rural landscape in Southern Huasteca is the result of 3000 years of socio-environmental interactions which have shaped landscapes and livelihoods under substantially changing climatic, social, ecological, political conditions. Our study site Palzoquillo lies in the center of the mountainous Huasteca Potosina and as a rural marginalized landscape it is highly representative for the socio-environmental conditions and dynamics of the larger tropical region of the Huasteca, of Mexico and Latinamerica. In this case study, we were interested in exploring the underlying root causes of the dynamics of what seems a highly adaptive social-ecological system. Approaching the analysis in an integrative and holistic manner, we examined these dynamics considering the Palzoquillo watershed as a complex system. Hence, we analyzed a variety of external, internal, biophysical, social, economic, political and cultural drivers, and how they have influenced decision making of critical stakeholders, most importantly of the farmers who worked on and lived from their lands for centuries. Choice of land use type, crop types, and management all play fundamental roles in the development of livelihoods and in cross-scale feedbacks of these land use practices on the goods and services these agroecosystems and livelihood diversification.

Analyzing this variety of factors allowed us to elucidate the sources and dynamics of the multifunctionality of landscapes at multiple spatiotemporal scales. We applied plot scale analyses of the historical trajectory of landcover/use. We then scaled plot scale information to the landscape scale, which emerged as a highly fragmented heterogeneous system. The spatial distribution of landuse and cover types is the product of livelihood characteristics including age class, access to land, inheritance rules and human choice.

Our research showed that one key emergent property of socio-ecological complex systems is livelihood diversification (Chapter 2) and ecosystem services interaction dynamics (Chapter 3). Understanding these properties is fundamental for future proposals of adaptive integrative management and governance of rural social-ecological systems

Using a watershed setting in Southern Huasteca as case study and the Drylands Development Paradigm (DDP; Reynolds et al. 2007) as general conceptual model, we identified the historical sequence of key socioeconomic and biophysical drivers that controlled the structural and functional transformation of the watershed landscape, and in turn gave rise to livelihood diversification and associated land use change patterns and ecosystem services dynamics. We demonstrated that in Mexican rural landscapes simplified agriculture ecosystems have predominated in response to market trends, neoliberal policies, population growth, migration, and smallholder regime that are generic drivers in tropical regions of Mexico and Latin America. This agricultural restructuration led to changes in ecosystem service dynamics sacrificing supporting, regulating and cultural services for single-resource provisioning services following market demands. Under this scenario, watershed landscapes will become less resilient and more vulnerable in the face of new socio-economic, political and biophysical events.

APPENDIX 1

Interviews

1) Structure Interviews

Date_________________________. Municipality_______________________.

Community ___________________. Family head name _________________.

Age _______. Number of inhabitants in household _____. What is your relationship and their age?____.

How many members depend on you financially?________________________.

Do you migrate temporary? a) yes b) not How long?_________________.

Do you make some non-farm labor? a) yes b) not Wath? ______________.

Do you receive some government support for household?________________.

What government programs support your crops?_______________________.

How many plots do you have?__________.

For each plot:

Plot #	Plot Size (Ha)	Land use	How long this use

Management:

Land use	Clean methods*	Times a year and what months for harverst	Other inputs*

*Clean methods = a) herbicides b) Traditional method (guingaro)
*Other inputs = a) Fertilizer b) Insecticide c) Both d) others

How many people clean and harvest in your plots? ____________________.

What kind of people? a) family b) same community peasants
c)wage-labor peasants (jornaleros)

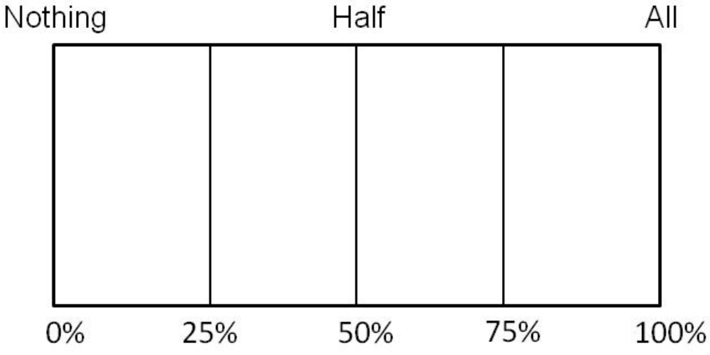
Productivity:

Land use	Products obtained	Sell/subsistence/tradition	Price

Where do you sell your products?____________________________________.

How months at year you count with self food production?_________________.

Fill in the box with blue color depending on how much help agricultural production incomes in your familiar economy. The other incomes fill in red color.



Why use water from surface wells? ________________________________. and how long does the water? ____.

Why use water from main watershed river? ___________________________. and how long does the water? ____.

2) Semi-structure Interview for drivers defined

The peasants recognized and mark each own plot (included sold and bought plots) in a printed aerial photograph from 2006 (90cm x 65cm). We asked to owners to reconstruct the land use history of their marked plots between 1970 to 2009 period using this semi-structure interview as a guide.

For each plot:

1.- Currently land use:

2.- How long is this land use?

3.- What land uses/crops had before?

4.- Why you decided change to this land use/crop?

5.- How was the market during the land use change? (Who bought the products? at what price? Etc)

6.- Do you received some government help or incentive for this land use change?

7.- Why not other land use/crop?

8.- If don't change, why keep this land use?

9.- Do you think change (or keep) was a good decision? Why?

10.- What benefits obtained?

12.- Do you are thinking in a new land use change? What land use? Why?

13.- If sold or bought plots, how many plots? what were the reasons? What crop was in this plots?

Note: These questions were repeated if more than 1 land use change occurred in the plots

APPENDIX 2

Statistic Tables

Table 1. ANOVA of soil organic carbon testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and soil depth (0 – 15cm and 15 – 30cm) nested within land use.

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	179.90	3	12.79	6.86	0.0004
Soil depth (land use)	171.08	7	10.75	9.23	<0.0001

Table 2. ANOVA of soil total Nitrogen testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and soil depth (0 – 15cm and 15 – 30cm) nested within land use

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	5.48	3	18.56	10.68	<0.0001
Soil depth (Land use)	5.13	7	13.49	18.94	<0.0001

Table 3. ANOVA of Nitrogen mineralization rate the effects of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and date (zero, four, eight and twelve months).

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	185.40	3	6.3	29.25	0.0024
Date	210.61	2	7.5	16.85	<0.0001
Land use*Date	199.11	3	5.4	13.09	<0.0001

Table 4. ANOVA of soil organic matter testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and soil depth (0 – 15cm and 15 – 30cm) nested within land use

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	2220.96	3	7.4	56.05	<0.0001
Soil depth (Land use)	1140.39	7	5.7	48.54	<0.0001

Table 5. ANOVA of soil phosphorus testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and soil depth (0 – 15cm and 15 – 30cm) nested within land use

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	25.81	3	25.80	160.35	<0.0001
Soil depth (Land use)	11.60	7	22.05	98.59	<0.0001

Table 6. ANOVA of soil texture testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane), fraction (sand, silt, clay) and soil depth (0 – 15cm and 15 – 30cm) nested within land use.

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	1910.03	1	12.71	61.79	0.0001
Soil depth (Land use)	26.68	3	11.15	18.22	0.0085
Fractions	2958.46	3	10.60	95.71	0.0001
Land use * Fractions	92.09	3	13.14	2.98	0.0379
Soil depth (Land use) * Fractions	26.57	3	14.26	1481.4	0.0001

Table 7. ANOVA of depth of A horizon testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane).

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	66.16	3	10.57	17.78	<0.0001

Table 8. ANOVA of soil compaction / soil bulk density testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and soil depth (0 – 15cm and 15 – 30cm) nested within land use.

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	102617.51	3	6.3	30.25	<0.0001
Soil depth (Land use)	47601.04	7	6.22	14.74	<0.0001

Table 9. ANOVA of soil infiltration testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and soil depth (0 – 15cm and 15 – 30cm) nested within land use.

Test of fixed effects **Source of variation**	**Mean Square**	**DF**	**CV**	**F**	***P***
Land use	64918.20	3	5.02	101.90	<0.0001

Table 10. ANOVA of soil humidity testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane) and soil depth (0 – 15cm and 15 – 30cm) and date (twelve months).

Test of fixed effects **Source of variation**	**Mean S quare**	**DF**	**CV**	**F**	**P**
Land use	1910.03	1	28.25	61.79	0.0001

Profundity	2958.46	3		95.71	0.0001
Date	2211.12	3		56.05	<.0001
Land use * Date	3056.68	3		84.99	0.0001
Land use * profundity	92.09	3		2.98	0.0379
Land use * profundity * date	11.80	3		97.60	<.0001

Table 11. ANOVA of surface runoff testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane).

Test of fixed effects	**Mean Square**	**DF**	**CV**	**F**	***P***
Source of variation					
Land use	224.82	3	42.41	339.14	0.0001

Table 12. ANOVA of sediment retention testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane).

Test of fixed effects	**Mean Square**	**DF**	**CV**	**F**	***P***
Source of variation					
Land use	376.31	3	55.97	64.37	<0.0001

Table 13. ANOVA of carbon loss testing the effect of land use (Secondary forest, Citrus orchards, Milpa, Sugarcane).

Test of fixed effects	**Mean Square**	**DF**	**CV**	**F**	***P***
Source of variation					
Land use	2603.30	3	18.77	53.51	<0.0001

Table 14. R2 of Pearson Correlations between 14 ecosystem services

crop productivit	0.0001	0.0002	0.0046	0.0001	0.0001	0.0001	0.0865	0.0001	0.0001	<0.0001	0.0427	0.0031	<0.0001	0.0032
	Extra products	0.0001	0.0017	0.0001	0.0001	0.0001	0.0962	0.0001	0.0001	<0.0001	0.0353	0.0024	<0.0001	0.0059
		Soil texture	0.0036	0.0001	0.0012	0.0001	0.0011	0.0362	0.0001	0.0016	0.0032	<0.0001	<0.0001	0.0091
			SOC	0.0031	0.0015	0.0013	0.0009	0.0008	0.0199	0.0023	0.255	0.0030	0.01	0.5228
				Total N	0.0001	0.0001	0.0032	0.0001	0.0012	<0.0001	0.0302	<0.0001	<0.0001	0.0104
					SOM	0.0001	0.0105	0.0001	0.0013	<0.0001	0.0057	<0.0001	<0.0001	0.0031
						Infiltration	0.0001	0.0001	0.0012	<0.0001	0.0002	<0.0001	<0.0001	0.0038
							A Horizon	0.0001	0.5228	0.0002	0.0318	<0.0001	0.1623	0.0055
								P	<0.0001	<0.0001	0.126	<0.0001	0.0009	0.0105
									Products for religius	0.0023	0.0362	0.0089	<0.0001	0.0102
										Soil humidity	0.0055	<0.0001	0.0008	0.0056
											Compactation soil	<0.0001	0.0102	0.0001
												Sediment retention	0.0006	<0.0001
													S.Inorganic N	0.0103
														Surface runoff

Table 15. Eigenvalues of the corretation matrix by Principal Components analysis.

	Eigenvalue	Difference	Proportion	Cumulative
1	9.58186379	7.14856378	0.5989	0.5989
2	2.43330002	1.21312454	0.1521	0.7509
3	1.22017547	0.35176199	0.0763	0.8272
4	0.86841348	0.35524082	0.0543	0.8815
5	0.51317266	0.05726061	0.0321	0.9136
6	0.45591205	0.16098621	0.0285	0.9421
7	0.29492584	0.11120739	0.0184	0.9605
8	0.18371846	0.05796421	0.0115	0.9720
9	0.12575424	0.01893149	0.0079	0.9798
10	0.10682276	0.00926293	0.0067	0.9865
11	0.09755983	0.01810325	0.0061	0.9926
12	0.07945658	0.05312510	0.0050	0.9976
13	0.02633148	0.01373815	0.0016	0.9992
14	0.01259333	0.01259333	0.0008	1.0000
15	0.00000000	0.00000000	0.0000	1.0000
16	0.00000000		0.0000	1.0000