Abstract

Tropical deforestation through agricultural expansion is an important driver of a number of environmental and social problems. In developing countries, the individuals at the centre of these problems are often smallholders who manage less than 5 hectares of land. Collectively, the decisions of approximately 65 million smallholders worldwide contribute significantly to the processes of global climate change, local environmental change, and a variety of social problems relating to food security, poverty, urban growth, and, at times, armed conflict and genocide. This thesis, above all, argues that to mitigate these global environmental and social problems, we must take a bottom-up approach that focuses on farm-level decisions. In this way, it is possible to devise better national and regional-level policy interventions that specifically target local problems.

To explore this farm-level approach, this thesis integrates three key theoretical frameworks. First, a resilience framework is adopted to help explain the relationship between farm-level decisions, disturbances, and feedbacks that can negatively impact the integrity of farming systems. The resilience approach also helps to explain how systems can change over time without losing their identity, or change completely into a new type of system. Second, a land change science approach is adopted to help explain the relationship between land cover change and the underlying human dimension. Third, an agroecological approach is adopted to view farms and farming communities as complex systems that include both environmental and social variables.

As a case study, a group of Mestizo and Mennonite farming communities in Northern Belize were investigated using a methodology that integrates a land cover change assessment and a farm practice survey. The 700 km² study area was evaluated using a LANDSAT time-series dating from 1980 to 2010. Land cover change statistics showed that different patterns of deforestation and land use occurred within the study area, including agricultural expansion through deforestation, reforestation through cropland abandonment, and conversion from one type of production to another (e.g. cropland to pasture). This suggests that different types of farm-level decisions were being made, but farm-level data were required. To investigate these farm-level decisions, 145 farmers were interviewed concerning land appropriation, crop production, livestock production, and household and labour organization. This farm-level information helped to identify several types of farms in the study area with very different land use practices. In short, although previous studies
identified 3 or 4 types of farms in Northern Belize, this thesis demonstrates that many more types likely operate within the study area, a fact that helps explain the complex land cover change patterns observed in the remote sensing data.

By integrating land cover and farm survey data, this thesis evaluates how farm resilience relates to environmental change in Northern Belize by identifying specific patterns relating to agricultural expansion through tropical deforestation and agricultural intensification through the adoption or increased use of agricultural technologies. Based on these results, this thesis proposes areas where policies can be formed and implemented to mitigate the potential negative effects of agricultural development in areas experiencing high rates of tropical deforestation and intensification.
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For Natalie
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1 INTRODUCTION

Tropical forests represent a third of world's forested area and are an essential part of the biosphere. However, since the end of World War II, the area of tropical forests has declined by over 550 million hectares (Horrigan et al. 2002). If this rate of loss continues, tropical forests could disappear completely in as little as sixty to eighty years (Adedire 2002). In addition to the irrevocable damage this loss would cause for the long term survival of our species, tropical deforestation has numerous local and immediate environmental and social impacts that include land degradation, loss of biodiversity, water contamination, increased incidence of vector-borne diseases, and social conflict.

At the global scale, tropical deforestation is a major driver of climate change since it is responsible for approximately 20 percent of global greenhouse gas emissions (IPCC 2013). Hence, there is a growing need to understand the local-scale causes of tropical deforestation in order to slow or reverse these impacts through effective policy interventions. Although researchers now recognize multiple causes of tropical deforestation (see, for example, Geist & Lambin 2002), agricultural expansion remains one of the primary drivers, especially in Latin America (Hosonuma et al. 2012). Given this reality, the relationship between tropical deforestation, agricultural development, and global food security is an issue that requires significant research attention.

The United Nations' Food and Agricultural Association (FAO) recently estimated that the global population will reach 9.3 billion people by 2050. Although population growth is only one of many pressures on food systems, it is a major contributor to the growing need to increase agricultural production to meet future food and fibre requirements (FAO 2003; FAO 2006). Since the Green Revolution of the 1960s, production increases were achieved through the adoption of intensive agricultural technologies, such as synthetic fertilizer, conventional tillage, new methods of irrigation, genetically modified (GM) crops, and pesticides. Future agricultural intensification is likely to increase in developing countries where 80 percent of the crop production increases by 2050 will be achieved by the
widespread introduction of these same agricultural technologies (FAO 2003). While the food requirement needs can be met through these means, it is likely that the gains will cause significant environmental and social impacts (Matson et al. 1997; for a review of impacts, see Foley et al. 2005; Horrigan et al. 2002). Hence, researchers, governments, and non-governmental organizations (NGO) alike are confronted with the question of whether the consequences of deforestation and agricultural intensification represent an acceptable trade-off to improve the prospects for future global food security.

The pressing global environmental and social issues that underlie the question of food security profoundly impact on a diverse group of smallholders, mostly from developing countries, whose agricultural production is a key component of global food security. Research has revealed that smallholders vary with respect to their land use practices and associated environmental impacts and vulnerability to disturbances (see, for example, Brondízio & Moran 2012; IFAD 2013; Rudel et al. 2005). However, the dynamics and precise nature of these relationships, especially at the local-scale, require further investigation (see, for example, Morton 2007). For example, land cover change patterns in Latin America are complex because they result from the decisions made by a highly diverse range of smallholders, composing more than 65 million people and over 400 different indigenous groups (Altieri 1992; Altieri & Toledo 2011; UNEP 2007).

In particular, research in the frontier regions of the Amazon suggests that different land cover change patterns relate to the use of a variety of land use strategies (see, for example Brondízio et al. 2002; McCracken et al. 2002; Carmona & Nahuelhueal 2012). This diversity results largely from the human dimension that underlies deforestation and agricultural change, such that land use and land cover change are affected to varying degrees by combinations of demographic characteristics, ethnic diversity, the prevailing land regime, land appropriation, the types of production (e.g., polyculture, monoculture, livestock production etc.), the intensity of production (e.g. use of agrochemicals, irrigation, mechanization), and the destination of agricultural produce (Geist & Lambin 2006; Lambin et al. 2001). To address the relationships between these factors and the process of tropical deforestation and agricultural intensification in the quest for food security and economic development, it is necessary to evaluate the underlying human dimension and, specifically, the decision-making capacity and processes of local farmers (DeFries et al. 2004).

Since the early 1990s, various research groups have investigated the human dimension of environmental change, namely the Global Lands Project (GLP), The International
Human-Biosphere Programme (IHDP), and the National Research Center (NRC) in the United States (for a review, see Moran 2010). This research has recognized the complex relationship between the human dimension and environmental change, termed the coupled human-environment system or the social-ecological system (SES). With advances in computer technology over the last twenty years, and more recent increases in the amount and resolution of remote sensing data available to meet research needs, there is a steadily increasing volume of research that examines the complex relationship between land cover change and social, economic, cultural, and political processes (see, for example NRC 1992; NRC 1998; Geist & Lambin 2006; Lambin et al. 2001; Turner et al. 2007). In fact, by 2005, the GLP published a science plan that was intended to help guide future research (GLP 2005). From this plan, a multidisciplinary research area, labelled Land Change Science (LCS), was formalized to integrate human geography, ecology, environmental studies, geospatial sciences, statistics, and other disciplines to investigate the complex relationships between land cover change and the human dimension (Turner et al. 2007).

This thesis builds upon the LCS research approach and addresses issues that relate to agricultural and environmental change. It contributes to this research agenda by investigating the temporal and spatial relationships between farm-level decisions, agricultural change, and the process of land cover change. This is achieved by adopting a resilience thinking approach, as formalized by the Resilience Alliance (2010).

Resilience thinking describes the ability of a system (e.g. a farm, an ecosystem, etc.) to manage various types of disturbances through a process of adaptation and/or transformation in such a way that the system is able to maintain essentially the same function and qualities over time (Folke et al. 2010). In this context, a disturbance is anything that the system must manage in order to maintain its structure and function (e.g. a hurricane, market fluctuation, land degradation). The approach of resilience thinking provides a suitable framework to investigate the decision-making processes of individual smallholders that individually and collectively result in land cover change patterns, most notably deforestation within tropical regions. Farmers in these areas can respond to disturbances by either changing their environment through deforestation, changing their agricultural practices through intensification, or by changing aspects of their household characteristics, such as through rural-to-urban immigration or livelihood diversification. Thus, in order to understand global environmental and social issues like deforestation and food security, it is necessary to evaluate the decision-making processes of smallholders. The use of resilience thinking is
Specifically, this thesis examines farm resilience in Belize, a small, tropical nation in Central America. Belize is characterized by thousands of smallholders, a growing agricultural sector, and a high rate of tropical deforestation. In the past 50 years, Belize has experienced increasing deforestation and agricultural intensification as its agricultural sector has grown consistently since the 1970s (Day 2003; IICA 1995). As of 2010, Belize was still 60 percent forested with several types of tropical forests (Cherrington et al. 2010), yet pressure for land is likely to increase as the population is expected to grow from 331,000 in 2013 to over 700,000 by 2050. This trend is especially important since the rural population has grown on par with the urban population, making it distinct in Latin America (Statistical Institute of Belize 2011). Since a quarter of Belize's gross domestic product (GDP) is based on agricultural production (Martin & Manzano 2010), and with an annual forest loss of about -0.7 percent, it is likely that agricultural expansion and intensification will continue to have a deleterious effect on various terrestrial and aquatic ecosystems (Government of Belize 2008).

Hence, the decision-making processes of over 11,000 smallholders regarding agricultural expansion and/or intensification is key to understanding and addressing tropical deforestation in Belize. Despite several government agricultural policies and environmental assessments and conservation efforts, the relationships in Belize between smallholders, agricultural development, and tropical deforestation is still poorly understood. This need is a primary motivation for examining the human dimension of land cover change in Belize.

1.1 RESEARCH QUESTIONS AND OBJECTIVES

This thesis has three principal goals. The first is to evaluate how farm-level decisions relate to environmental change in Northern Belize by evaluating land cover change patterns. The second goal is to classify farms in the study area based on a number of social and environmental variables, and evaluate their distribution in relation to major environmental change patterns. Lastly, the third goal is to propose areas where policies can intervene to mitigate the potential negative effects of agricultural development in areas experiencing high rates of tropical deforestation and intensification.

Achieving these goals necessitates the integration of two primary lines of evidence, namely a top-down land cover change assessment and a bottom-up farm-level evaluation of
environmental and agricultural change within the study area. By taking this integrative approach, the following three questions are addressed relating to the study area:

1. What are the different patterns of land cover change over time?
2. Have certain types of farms had a greater or lesser environmental impact, as demonstrated by higher or lower rates of agricultural expansion and/or intensification?
3. How can future policy interventions help mitigate the negative environmental impacts of agricultural expansion and intensification, while also improving the livelihood of farmers, supporting conservation initiatives, and protecting national food security?

These research questions are addressed using an LCS approach that incorporates a resilience framework (Resilience Alliance 2010) and concepts derived from agroecology (Altieri & Toledo 2011; Francis et al. 2003; Gliessman 2013; Wezel et al. 2011). There are three main phases to this multidisciplinary assessment. The first phase is a temporal and spatial assessment of land cover change that is aggregated to the landscape and zone levels, such that the study area is divided into four zones. This analysis provides a broad perspective on the major processes of agricultural expansion, change, and intensification in the study area among its Mestizo and Mennonite communities. The second phase uses farm-level data to classify farms and examine how each class demonstrates varying levels of environmental impacts. This approach builds upon resilience thinking to evaluate how farms respond to disturbances by expanding, abandoning, or changing agricultural practices. In this context, agricultural expansion and intensification are seen as two principal responses to disturbances (i.e. choices made at the farm-level). When both lines of evidence are integrated, it is possible to identify how different compositions of farms within an area produce different environmental impacts. As a closing discussion, the third phase includes an environmental policy discussion that incorporates the preceding results to propose policies that target the various sources of environmental concerns. Within these phases, the following specific objectives are examined:

1. To evaluate farm resilience at the landscape level by evaluating proxy indicators derived from land cover change data;
2. To evaluate how different types of farms demonstrate resilience to environmental and anthropogenic disturbances;
3. To identify the relationship between environmental change and the types of farms within different zones within the study area.
4. To review areas where policy interventions could help mitigate negative environmental impacts associated with agricultural change.

By identifying the specific types of farms and related activities that contribute most to
environmental change in Belize, it is possible to design policy interventions that avoid specific destructive activities in favour of more sustainable practices. The first objective is addressed in Chapter 4, the second and third objectives are addressed in Chapter 5, and the last objective is addressed in Chapter 6. The following sections specify how each of these objectives are addressed in these chapters.

1.1.1 Land cover change and farm resilience

In order to address the first objective, a LANDSAT time-series dating from 1980 to 2010 is used to evaluate land cover change patterns. Additional datasets for the study area, such as land suitability indicators and ecological features, are also used in this assessment.

A geographic information system (GIS) database is developed to integrate the associated data in order to evaluate farm resilience at the landscape-scale and for the Mestizo and Mennonites communities. This is achieved by classifying the LANDSAT time-series into eight land cover classes, then conducting post-classification image comparison and pixel trajectory analysis to produce landscape- and community-scale statistics on net land cover change (e.g. percent forest change over time) and pixel-scale trajectories (e.g. the proportion of pixels that change over time from forest to cropland and then to pasture). The statistics derived from these techniques are then used to quantify deforestation, reforestation, and the conversion of agricultural land from one type of land use class to another (e.g. cropland to pasture).

The land cover change statistics provide insights into farm resilience by revealing how the study area as a whole and each individual zone has changed over time as a response to the numerous environmental and social disturbances that are identified. Additional insights are gained from a farm-level assessment that helps to explain the relationship between farm-level and landscape-level land change responses.

1.1.2 Farm typologies and farm resilience

The second objective is addressed by using the results from a farm practice survey in the study area to evaluate farm resilience. Specifically, the question of how individual farms have responded to disturbances through expansion, intensification, or by making other changes to the farm system is evaluated (e.g. income diversification).

A total of 145 farms were surveyed in two different communities to evaluate the four main properties of farm systems, namely the cropping system(s), the pastoral system(s),
household organization, and land appropriation. Multivariate analysis is used to classify farms and evaluate how each farm type has responded to disturbances. On-farm deforestation is used to evaluate agricultural expansion, while a number of variables are used to evaluate agricultural intensification including tillage, fertilizer application, use of pesticides, and irrigation practices. Sustainable intensification strategies are also considered, such as crop rotation and fallowing. Lastly, other responses, such as income diversification and household emigration, are also considered for each farm type. Thus, the second objective is addressed using farm-level data, and the results help to explain landscape-, community-, and farm-scale changes.

1.1.3 Farm resilience and environmental change

To address the third objective, land cover change and farm survey data are integrated using a multivariate statistical approach. Insights are gained by observing the distribution of different farm types throughout the study area in relation to empirically defined land cover change patterns. From this, it is possible to identify the types of farms, defined by a set of empirical properties, that have experienced the most severe environmental impacts through agricultural expansion and/or intensification. Hence, by relating major land cover change processes with farm-level decisions, it is possible to review more critically existing environmental and agricultural policies in Belize.

1.1.4 Farm resilience and policy interventions

To address the fourth objective, the land change patterns and the farm composition profiles of each zone are considered from a policy perspective. Through a comprehensive review of recent agricultural policies in Belize, insight is gained concerning the role that policies play in the process of environmental and agricultural change. Specifically, policies relating to livestock production, sugarcane production, and domestic crop production are considered, and based on the enhanced understanding of farm resilience and environmental change in the study area, suggestions are made for future policy interventions.

1.2 THESIS STRUCTURE

The second chapter presents the theoretical framework, that is derived from LCS and resilience thinking, for the thesis. LCS is first reviewed by discussing deforestation and agricultural intensification. This is followed by a thorough discussion of farm resilience, which considers the structure of farm systems and various components of the resilience
framework (e.g. the disturbance regime, the response diversity, and feedback mechanisms).

Chapter 3 reviews background information on farm resilience in Latin America and the Caribbean (LAC) in general and in Belize in particular. The first part of the chapter discusses agricultural expansion and intensification, drawing contrasts between historical, economic, and agricultural developments within the LAC region. Belizean farm resilience is then evaluated, which provides essential background for the empirical analysis in the remainder of the thesis.

Chapter 4 presents the methodology and results of the land change assessment within the study area. The results are presented at the landscape scale followed by a closer examination of four zones. Proxy indicators of farm resilience are derived from the remote sensing assessment, and contrasts are observed between each zone. Land cover change statistics are statistics for the entire study area and for each of the four zones are used to identify major trends relating the possible responses to disturbances.

Chapter 5 presents the multivariate analysis of the farm survey results. A total of 143 farms are classified into 6 groups based on household demographics and land appropriation. The resulting groups are further evaluated and compared based on household organization, land use change, crop systems, and pasture systems. These analyses serve to identify the different land use strategies of different types of farms.

Chapter 6 integrates the land changes assessment and farm survey data to identify the potential environmental impacts of different types of farms. After considering current policy strategies in Belize, issues relating to the environmental and social impact of livestock, sugarcane, and domestic crop production are considered. Lastly, policy recommendations are made based on the research findings and related research in other parts of Latin America.

The final chapter concludes the thesis by reviewing its main findings relative to the thesis objectives. Its contribution to research on farm resilience is assessed, and its contributions to knowledge on agricultural and environmental change in Belize are reviewed. Finally, directions for future research are presented.
2 LAND CHANGE SCIENCE AND FARM RESILIENCE

This chapter reviews literature on the application of resilience thinking in land change science to evaluate the role that farms play in the processes of deforestation and agricultural intensification. The chapter presents reviews the objectives of land change science and the concept of social-ecological resilience and places them into a conceptual framework that comprises the foundation of the thesis. The discussion considers key concepts in resilience thinking and each component of the resilience framework, namely the organization of the farm system, the disturbance regime, the response diversity, and how actions taken at the farm level may modify the farm and feed back into the local disturbance regime. Through this discussion, the notion is supported that deforestation and agricultural intensification are local processes driven by a diverse group of farmers who each respond through adaptive management to a variety of local, regional, and global biophysical and social disturbances. This proposed framework comprises the foundation for the analysis that follows in subsequent chapters.

2.1 LAND CHANGE SCIENCE AND ENVIRONMENTAL CHANGE

Environmental change is a common consequence of agricultural development, be it through the loss of biodiversity, through deforestation, or the modification of soil and water quality though unsustainable agricultural intensification. With the global human population estimated to reach 9.3 billion people by 2050, food and fibre production is expected to increase by both expanding the current agricultural area and intensifying agricultural production through mechanization, irrigation, agrochemical applications, and, perhaps, through the adoption of more sustainable practices (i.e. sustainable intensification). Since the processes of deforestation to expand the agricultural area and agricultural intensification raise a number of potential environmental and human health concerns, it is crucial to understand the relationships between farm-level and regional environmental change. Research developments in land change science (LCS) have provided considerable insights
into these processes. This section discusses the aims and objectives of LCS as an overarching framework for this thesis.

2.1.1 Land change science

LCS is an integral part of a broader research agenda that focuses on the human dimension of global environmental change. In essence, LCS “joins the human, environmental, and geographical information-remote sensing sciences in an interdisciplinary effort” (Turner et al. 2007) to improve the understanding of land change by examining environmental changes that result from social-ecological systems (also known as coupled human-environment systems). Prior to the late 1980s, research on global environmental change rarely included explicit reference to the human dimension. Rather, efforts were firmly rooted in Earth Sciences and instead sought to document the extent, rate, and impact of biophysical changes on the planet's surface (Moran 2005, 2010). By not considering fully the human dimension of change, little was understood about the causes of deforestation and agricultural intensification, especially at the local level. Hence, a new, integrated approach was required to investigate the role that social-ecological systems, coupled systems with human and ecological dimensions, play in the process of environmental change.

To accommodate this change in LCS thinking in the 1990s, the International Human Dimensions Programme (IHDP) was formed as part of the International Geosphere-Biosphere Programme (IGBP) and a preliminary Science Plan to promote the study of the human dimension of environmental change was published (Turner et al. 1995). Several initial and basic questions were posed in this document, namely:

1. How has land cover been changed by human use over the past 300 years?
2. What are the major human causes of land use change in different spatial (and temporal) contexts?
3. How will global environmental changes affect land use and land cover?

The first decade following the publication of the IGBP Science Plan saw the publication of numerous studies addressing these questions, and the scope of research in this field of study was further expanded in the current century.

The IHDP Science Plan clarified the distinction between the terms “land cover” and “land use”. Land cover was formally defined as “the biophysical state of the Earth's surface and immediate subsurface,” and therefore land cover change refers specifically to changes in these surface and subsurface biophysical properties (Turner et al. 1995, p.20). On the other hand, land use, an integral part of human dimension research, was defined as both “the
manner in which the biophysical attributes of the land are manipulated and the intent underlying the manipulation – the purpose for which the land is used” (Turner et al. 1995, p.20). For example, cropland is a land cover class, whereas agriculture is a form of land use defined specifically by farm practices (e.g. tillage, agrochemical inputs, fallow cycles, and crop rotation).

Land cover can be evaluated using remote sensing techniques, whereas land use is determined largely through direct survey of specific areas, such as farms. Following Turner et al. (2007), the term “land change” is an integrated term that refers to processes that involve both land cover and land use change, such as agricultural expansion which may involve clearing forest (land cover change) and establishing crop production (land use change). By looking at both land cover and land use change, researcher gain important insight into the decision making process that underlies environmental change.

In 2005, the IHDP initiated the Global Land Project (GLP), which included a team of international researchers from both the natural and social sciences. Their revised Science Plan established the research objectives and main themes to be addressed within the following decade (GLP 2005). The main objectives of the plan were:

...to identify the agents, structures and nature of change in coupled human-environment systems on land, and to quantify their effects on the coupled system; to assess how the provision of ecosystem services is affected by the changes in above; and to identify the character and dynamics of vulnerable and sustainable coupled human-environment systems to interacting perturbations, including climate change (GLP 2005, p.1).

The most pressing themes to be addressed in the plan were identified as the dynamics of land systems, the consequences of land system change, and the integrated analysis and modelling of the two for the purpose of achieving land sustainability. The third theme in particular called for researchers to:

integrate the dynamic interactions of human and environment subsystems in order to assess vulnerability, resilience and adaptation towards sustainable land systems, and specifically aims to provide this understanding in ways that are meaningful to decision making and policy. (GLP 2005, p.38, emphasis added).

The goal of the GLP, therefore, was to develop better methods and analytical techniques to evaluate the vulnerability of land systems, including both land cover and land use dimensions. However, since remote sensing can only identify broad scale land cover change patterns and only hint at potential land use changes, it has became increasingly necessary to
examine land change processes from a bottom-up perspective that involves analysis of land use. To achieve this required a fresh perspective that also considers the human dimension, and this is a research area that also developed significantly since the 1990s within LCS.

2.1.2 The human dimension of environmental change

In their effort to support the IHDP initiative, The National Research Council (NRC) and the Social Science Research Council (SSRC) in the United States developed a parallel program to investigate the human dimensions of environmental change (NRC 1992; NRC 1994; NRC 1999; NRC 2001). Their first publication on the subject (NRC 1992) established a research agenda that was expanded in later years to have an explicit focus on the need to understand land change because it was recognized that the majority of environmental change is driven by human action (NRC 1994). Further research broadened the definition of the “human dimension” to encompass not only individuals, but also institutions, organizations, and governments. With this broad definition, their 1999 publication, “Global Environmental Change: Research Pathways for the Next Decade”, outlined key research imperatives to address the human dimension in environmental change, notably “improving the integration of human dimensions research with other global change research” (NRC 1999). In 2001, land change was identified as one of the key research areas at the NRC (NRC 2001).

The 2006, the IGBP edited volume, “Land-use and land-cover change: local processes and global impacts”, was the first comprehensive volume published to promote local level research to understand better global environmental change. This contribution promoted ground-based analysis because it recognized that the massive land cover change that occurred over the previous century, especially in areas like the Amazon basin, would probably not occur at the same rate in the 21st Century. Instead, the authors expected that significant agricultural intensification would likely occur alongside limited deforestation in many areas. To address the growing concerns with agricultural intensification, it is essential to analyse land modifications that are not observable in remotely sensed data, such as selective logging and changes in agricultural production (Lambin et al. 2006). Hence, as with the study of deforestation, evaluating land use intensification must include ground-based survey, farm practice surveys, and the integration of survey results with geospatial analysis of land cover change patterns, land systems, and ecosystem properties.

The last two decades of land change research have established land change science
(LCS) as a legitimate field of applied research in its own right. By taking a spatial approach, focus is placed upon the outcomes of land change, notably the concepts of vulnerability, resilience, or sustainability (Turner et al. 2007). Thus, LCS proposes an integrated approach that can be used to address the main processes that lie at the centre of this thesis, namely the role that farms and farmers play in deforestation, agricultural intensification, and the resultant environmental and human consequences that may occur. In short, an approach that considers the human dimension of land change offers considerable insight into the broader processes of environmental change that can be observed and analysed using remote sensing technologies.

To exemplify the benefits and complexity of a human dimensions approach, the following section reviews literature on the current understanding of agricultural change, specifically as it relates to the causes of deforestation and agricultural intensification.

2.1.3 The human dimensions of agricultural change

A central theme in LCS is the process of agricultural change. This is a complex land change process that includes the interactions of both biophysical and human dimensions. Deforestation and the adoption of conventional agricultural intensification techniques by farmers are perhaps the most prominent examples of land change associated with agricultural change. After the exponential expansion of agricultural production since the Green Revolution of the 1960s, agricultural land covers roughly 33 percent of Earth's land area (FAOSTAT 2014). However, within this global agricultural landscape are “hidden landscape changes”, according to Rice (2003), that include “the socioeconomic and/or cultural changes that accompany physical landscape transformations.”

This hidden landscape refers to the complexities of the human dimension that drive and shape agricultural change. To understand better the complexity of agricultural change, this section considers briefly four crucial aspects relating to the human dimension of agricultural landscapes, namely the causes of agricultural change, the relationships between the composition of tropical agricultural landscapes and farmer agency, and the environmental and human impacts of agricultural change.

2.1.3.i Theorizing agricultural change

Prior to the emergence of LCS and its explicit focus on the human dimension of environmental change, agricultural change was largely explained as a result of single causes that were viewed either to promote or limit agricultural production (Turner II & Ali 1996).
For Malthus, a 19th Century economist, the level of technology determined the level of cropping intensity. The Malthusian line of thinking continues to the present day with neo-Malthusians theorizing various limiting factors of economic growth. The Malthusian and neo-Malthusian perspectives, however, are flawed because they both disregard the ability of people to direct change.

During the Green Revolution of the 1960s, new concepts developed that viewed social evolution and agricultural change from a completely different perspective. Boserup (1965) proposed an anti-Malthusian thesis that intensification and agricultural change are induced primarily by population pressure. Instead of acting as limit to agricultural growth, Boserup observed through a case study approach that population pressure was not a limiting factor to agricultural change, but rather it contributed to innovation. Subsequently, other studies have proposed factors such as economic and social pressures, market incentives, and cultural traditions as factors inducing agricultural change (see, for example, Stone 2001; Turner II & Ali 1996). However, it was not until the work of LCS researchers that all these factors were combined into a more holistic view of agricultural change.

In terms of investigating the underlying causes of deforestation, which is a major component of agricultural change, early studies of tropical deforestation were driven primarily by the Malthusian belief that population growth was the primary causal agent. However, recent cross-cultural research has revealed a much more complex series of underlying causes (Sydenstricker-Neto 2012). For example, Geist and Lambin and conducted a meta-analysis of 152 sub-national case studies on tropical deforestation, and found that the causes of deforestation are more numerous, complex, and rarely reducible to univariate factors (Geist & Lambin 2002; Lambin et al. 2001). In other words, when a farmer chooses to clear a patch of forest to expand his/her agricultural area, that decision is influenced by a variety of factors, not just population pressure, technology, or economic factors.

Within the LCS framework, the causes of deforestation can be viewed as proximate or underlying. Proximate causes of deforestation are the immediate triggers, and the underlying causes operate above the local or household scale, according to Lambin et al. (2003). The underlying causes of deforestation can include demographic, economic, technological, policy, institutional, and cultural factors (Lambin et al. 2001) and they interact with at least three categories of proximate causes, namely agricultural expansion, wood extraction, and infrastructure extension. Other causes can also include land characteristics, biophysical
drivers, and social triggers. Although there are many exogenous factors that can contribute to deforestation, the decision to clear land ultimately rests with the farmers. Therefore, to understand the underlying causes of deforestation it is essential to understand how the decision process of farmers are constrained by multiple local, regional, national and global factors.

Similarly, the causes of agricultural intensification are also more numerous than previously conceived. Keys and McConnell (2005) conducted a meta-analysis of case studies (n=91) to examine the causes of agricultural change and intensification. They defined agricultural intensification as “a complex process that includes the slowing or halting of agricultural expansion, increasing inputs to production, and increasing outputs per input” (Keys & McConnell 2005, p.322). Six broad categories of causal factors were identified relating to agricultural intensification. These included biophysical factors, demographic factors, market influences, institutional factors, government and non-government influences, and the property regime (Keys & McConnell 2005). Hence, as with deforestation, Keys and McConnell (2005) also observed that agricultural intensification is a multi-causal process that is rarely reducible to a single factor, such as population growth. Thus, since individual farmers make decisions to intensify their land use practices based on a variety of social, economic, environmental, and demographic factors, it is crucial to understand the local, national, and regional contexts which which agriculture changes.

2.1.3.ii Agricultural landscapes and human agency

Another important aspect of agricultural change is the relationship between human agency and the composition of agricultural landscapes. In this context, human agency refers to the capacity of people to make decisions regarding a land use strategy. An example of agency is the decision either to expand or intensify agricultural production. For example, it was once thought that farmers increased agricultural production by either intensifying or expanding their agricultural area, principally through deforestation. Consequently, intensification was viewed as a way of sparing nature by minimizing deforestation (Matson & Vitousek 2006). However, Rudel et al. (2009) examined global FAO data relating to land use and found that “agricultural intensification was not generally accompanied by decline or stasis in cropland area at a national scale...” (Rudel et al. 2009, p.20675). In short, farmers make various decisions and there is no evidence to suggest that certain causes elicit a predictable response. This prompts the question of how does human agency shape agricultural landscapes.
As a result of human agency, agricultural landscapes tend to be a complex mosaic of different cropping and livestock systems. Rice (2003) explains that tropical agricultural landscapes are notably complex since they include subsistence cropping, agroforestry systems, various traditional agricultural export cropping systems (e.g. sugar cane, coffee, cacao), irrigated areas, and areas producing non-traditional agricultural exports (e.g. fruits, vegetables, flowers, seeds). Thus, since the complexity of agricultural landscapes logically results from human agency, it is necessary to consider the human dimension of agricultural change more rigorously.

2.1.3.iii Consequences of agricultural change

Agricultural change is associated with numerous environmental and social consequences, which are discussed further in this chapter. Environmental consequences of agricultural change can include soil and water contamination, soil degradation, greenhouse gas emissions, and a general decline in biodiversity (Tscharntke et al. 2012; Hazell & Wood 2008). The social consequences of agricultural change can include the spread of disease (e.g. malaria), poisoning due to agrochemicals, conflict, poverty, and a variety of economic changes (Hazell & Wood 2008). Such consequences of change are notably acute in developing countries that may not have the resources to manage change in an effective manner. It is therefore important to recognize that evaluating the human dimension of agricultural change requires an assessment of not only the cause-effect relationships that result in new forms of agricultural production, but also of how people manage and mitigate a range of social and environmental consequences.

In summary, the human dimension of agricultural change includes three important elements, namely multiple causes and subsequent effects, a complex relationship between the agricultural landscape and human agency, and a series of environmental and social consequences. As a conceptual research framework, LCS encourages researchers to consider agricultural change as a holistic process that includes both environmental and social change. However, to put these ideas into practice requires a multidisciplinary approach that can be easily operationalized with data. Resilience thinking provides one such approach to evaluate agricultural change.

2.2 RESILIENCE THINKING

The fundamental concepts of resilience thinking have been used widely to evaluate land
change (see, for example, MacLeod & Moller 2006). This section introduces the basic concepts underlying resilience thinking that support the assessment framework used in this thesis. Specifically, this section introduces the concepts of the social-ecological system and social-ecological resilience and demonstrates how they have been used to evaluate farm resilience. Finally, a proposed operationalization of farm resilience is presented in the final subsection for application in the evaluation of the study area.

2.2.1 Social-ecological systems

In recognizing the complex human-environment interactions that underlie the processes of environmental change, researchers currently examine various types of social-ecological systems (Moran 2010). Also termed a coupled human-environment system, a social-ecological system is “an integrated system of ecosystems and human society with reciprocal feedback and interdependence” (Folke et al. 2010, p.22). This concept hinges on the ideas that pristine, untouched nature does not exist since it is unimaginable to conceive of a natural ecosystem without a social component, and vice versa (Berkes et al. 2000; Denevan 1992).

This definition of a social-ecological system, therefore, includes ecosystems that may otherwise be considered “natural”, such as reefs, forests, and wetlands, and social systems such as political, economic, social, and cultural organization. Thus, the social-ecological system concept integrates human dimension research with ecological research in order to present a more holistic view of human-environment interactions and change. Resilience thinking has adopted and further developed this concept in order to evaluate a range of important human-environment interactions, such as the study of urban wetlands (Li et al. 2013) and home gardens (Reyes-García et al. 2014).

2.2.2 Defining social-ecological resilience

Since Holling (1973) first defined ecosystem resilience in his seminal paper, the concept has been used widely to evaluate social-ecological systems (see, for example, Berkes et al. 2003; Walker et al. 2004; Folke 2006; Folke et al. 2010). In fact, it has become a central concept in risk/hazard assessments (Mavhura et al. 2013), political ecology (Peterson 2000), and, most recently, agroecosystem assessments (Eakin & Luers 2006; Fletcher et al. 2006; Cabell & Oelofse 2012). Based on Holling’s conceptualization, Folke et al. (2010, p.22) define social-ecological resilience as:

The capacity of a system to absorb disturbance and reorganize while undergoing
change so as to still retain essentially the same function, structure and feedbacks, and therefore identity, that is, the capacity to change in order to maintain the same identity.

Hence, resilience thinking is essentially a way to evaluate how a system responds to, adapts to, is transformed by, and/or absorbs a variety of disturbances over time without losing its identity. Unlike the concept of sustainability, resilience can either be desirable or undesirable since undesirable systems, such as dictatorships, can also demonstrate resilience. In other words, a resilient system manages disturbances in such a way that it is able to perform the same functions without changing its identity. Whether that identity is perceived positively or negatively is entirely subjective. Conversely, a system that is forced to change significantly is said to be vulnerable to one or more disturbance since it is unable to maintain its identity.

To operationalize this definition, resilience thinking is conceptualized through the Resilience Alliance (www.resalliance.org) as an applied science that utilizes a framework approach to facilitate the assessment of social-ecological systems. Hence, as a framework, resilience thinking is not a set of theories or testable hypotheses but rather it is likened to a heuristic, which is a tool to facilitate problem solving and exploratory learning to evaluate complex change patterns. It is, ultimately, a way of thinking about systems that encourages researchers to ask and answer new and innovative questions.

When applied to social-ecological systems, a resilience framework recognizes a number of important system properties. An early study by Levin et al. (1998) recognized that social systems are “non-linear and adaptive, exhibiting complex and far-from-equilibrium dynamics” (p224). In the context of resilience thinking, the notion of complex adaptive social systems places considerable emphasis on how individuals, groups, and communities manage social, political, economic, and environmental disturbances (Adger 2000). This focus led to S. Carpenter et al.’s (2001, p.776) three properties of social-ecological resilience, namely:

(a) the amount of change the system can undergo (and implicitly, therefore, the amount of extrinsic force the system can sustain) and still remain within the same domain of attraction (that is, retain the same controls on structure and function); (b) the degree to which the system is capable of self-organization (versus lack of organization, or organization forced by external factors); and (c) the degree to which the system can build the capacity to learn and adapt.

These three properties require some elaboration since they relate to a variety of other
important concepts that are central to resilience thinking and the manner in which the concept is used in this thesis.

The first property refers to the general definition of resilience provided in the previous section that emphasizes the ability of a system to retain its identify in the face of change. Terms like “latitude”, “resistance”, and “precariousness” are frequently used to describe a system's theoretical position within a domain of attraction. A domain of attraction is theoretical domain in which every combination of system variables is possible without losing the system's identity. For example, Figure 2.1 shows that a system can exist at any position (e.g. 1 to 4) within the first domain of attraction, labelled A. However, when it crosses a threshold at position 5, a process referred to as a regime shift moves it into another domain of attraction (labelled B) where it loses its previous identity as it becomes a different type of system (Folke et al. 2010; Walker et al. 2004). Political revolutions exemplify such a regime shift as a political system can pass from one domain of attraction, such as a dictatorship, to another domain of attraction, such as a democratic state. Thus, resilience thinking is equally concerned with the amount of change a social-ecological system can undergo before it crosses a threshold from one domain of attraction to another.

![Figure 2.1: Domains of attraction and regime shifts.](image)

The second property of resilient social-ecological systems is self-organization. This refers to the ability of a system to manage autonomously disturbances in order to stay within its current domain of attraction. Self-organization builds upon agency theory, which considers the capacity of individuals to act freely within an otherwise structured world (see, for example, Bourdieu 1977). Self-organization also incorporates the idea that feedbacks from the social-ecological system can directly or indirectly strengthen or weaken its
resilience (S. Carpenter et al. 2001). For example, a commonly discussed problem today is the process of globalization that often erodes the autonomy of national economies and local producers, thus limiting their ability to self-organize (see, for example, Hecht 2010). A system that is unable to address disturbances on its own without external support is less resilient than one that is able to manage disturbances independently. However, feedbacks from a resilient social-ecological system are more likely to strengthen, rather than erode, its resilience. Thus, self-organization plays an integral role in a system's ability to manage disturbances and maintain its resilience over time.

The third property of resilient social-ecological systems refers to the capacity to learn and adapt, which is the manner in which social-ecological systems self-organize over time. This property relates to four important and interrelated properties, namely adaptability, transformability, the overall concept of change that includes the metaphor of the adaptive cycle, and cross-scale interactions. Adaptability refers to changes made by individuals that strengthen or build resilience (Folke 2006), whereas transformability refers to “the capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable” (Walker et al. 2004). These two choices, to adapt or transform the system, are fundamentally made by individuals within social-ecological systems. Hence, agency plays an important role in adaptive or transformative responses, but these processes are also framed within an overarching concept in resilience thinking of change, which requires additional discussion.

Despite the existence of several contrasting theories on social and biological change, no theories exist to adequately explain social-ecological change (for a review, see Moran 2010). Instead, resilience thinking provides an innovative framework that is particularly relevant to understanding change within social-ecological systems. Resilience thinking conceptualizes change as a cycle that includes four phases, namely (i) the phases of growth or expansion when the systems begins to learn about disturbances, (ii) a conservation phase when the system experiences a period of stability, (iii) to a reorganization phase when the system must adapt to new disturbances, and finally (iv) a release phase when the system either collapses or transforms into another domain of attraction (Resilience Alliance 2010; Walker & Salt 2006; Walker et al. 2004).

Systems can progress through each phase, or jump across different phases, but Walker et al. (2004, p6) explain that the first two phases are slow and flexible while the last two phases are periods when “resources become increasingly locked up”. In other words, when
social-ecological systems first emerge, they are characterized by a period of learning and adaptation with minimal restrictions. However, agency is eventually limited as restrictions are imposed over time. For example, colonizers may deforest an area for a number of years before land becomes scarce and/or policies are imposed to limit further expansion. Thus, as Folk (2006) explains, there are both rapid and gradual periods of change within resilient social-ecological systems, and researchers must be able to identify these different types of change in order to understand fully self-organization.

Besides agency, resilient thinking also considers how cross-scale interactions (i.e. panarchies) can effect social-ecological systems. The term panarchy refers to the cross-scale interactions between other higher and lower systems, such as economic markets, global climate change, and local environmental conditions (Cabell & Oelofse 2012; Darnhofer et al. 2010; Gunderson & Holling 2002; Walker et al. 2004). Essentially, changes at other scales can impact or influence the adaptation or transformation response. For example, a lower global price for a certain commodity may make it unprofitable to produce on a small scale, thus forcing smallholders to adopt new forms of agricultural production. Hence, it is important to consider cross-scale interactions in order to understand how systems operate both independently and in conjunction with other systems. Thus, when considering how social-ecological systems adapt and learn, it is important to consider adaptability, transformability, the metaphor of the adaptive cycle, and cross-scale interactions.

The three main properties associated with resilient social-ecological systems have been investigated in a variety of contexts, including coastal communities (Adger 2000), cities and urban growth (Collier et al. 2013), food systems (Fraser 2006; Fraser et al. 2005), tourism development (Ruiz-Ballesteros 2011), marine conservation (Jones et al. 2013), coastal planning (Lloyd et al. 2013), wetland conservation (Li et al. 2013), and forest management (Rist & Moen 2013). An underlying theme in many studies is the concept of adaptive governance which empowers front-line decision-makers, be it individuals, communities, or other groups, whose self-organization is seen as a key to achieving social-ecological resilience (Folke et al. 2005; Dietz et al. 2003). Those who study social-ecological resilience champion the processes of experimentation, learning, and change within communities in order to build and strengthen resilience. These concepts have been applied to understand better the farm-level organization and resilience.
2.2.3 Farm resilience

Farms are a specific type of social-ecological system that have attracted much resilience research in the last decade (see, for example, Jackson et al. 2011; Milestad & Darnhofer 2003). Farms contain various ecosystems, such as forests, wetlands, natural grasslands, cropland, and pastures, and various social subsystems, such as the households, land tenure systems, and cross-scale economic, political, and cultural relationships. Due to this structural, functional, and ecological diversity, farms are exposed to and must adapt to a wide variety of biophysical and social disturbances in order to build and strengthen their resilience over time (see, for example, Apeldoorn, van D.F. et al. 2011; Darnhofer 2010). Hence, farm systems neatly demonstrate S. Carpenter et al.'s (2001) three properties of resilient social-ecological systems discussed in the previous section, namely farmers have the ability to change aspects of the farm system without losing its identity, to self-organize, and the ability to learn and adapt over time. To further examine how farm resilience is strengthened through different forms of adaptive management, the following discussion considers case studies that investigate farm-level adaptive management in general, farm resilience to natural disasters and the effects of climate change, and research on resilient farming communities.

2.2.3.i Farm-level adaptive management

Current research on farm resilience stresses the deep interconnection between farm management practices and resilience, although researchers take several different approaches to explore this perspective. One body of research takes a bottom-up perspective in which farm resilience can be strengthened manage a variety of disturbances by adopting or enhancing certain adaptive management practices. This bottom-up perspective views farmers as the primary source of resilience, since it is observed that farm-level decisions ultimately address disturbances over the short and long term. Consider, for example, the intricacies of pasture management. In this context, Ran et al. (2013) observed that certain pasture management practices can have a deleterious effect on ecosystem functions, namely causing drought by reducing the amount of soil organic matter which decreases a pasture's water-holding capacity. This negative feedbacks can be changed by simply modifying these practices, thus eliminating or at least minimizing the disturbance. Similarly, Rodriguez et al. (2011) found that farms in Australia that have a “plastic farm management strategy” can adapt to variable access to resources and environmental conditions and therefore demonstrate higher resilience over time. Hence, these farms are more likely to be resilient.
when farmers demonstrate the ability to change in order to address new and pre-existing disturbances.

The idea that farms can self-organize to strengthen their resilience is also supported by a number of studies that examine diversification of on- and off-farm activities and agricultural knowledge (see, for example, Darnhofer et al. 2010; Tittonell 2013). Lin (2011), for example, found that on-farm diversification of agricultural activities was an important source of resilience since it increases biodiversity and suppresses pests, disease, and other disturbances that relate to long-term climatic change and short-term climatic variability. Likewise, diversification of agricultural knowledge by integrating traditional and scientific knowledge may also strengthen farm resilience. In this context, Reyes-Garcia et al. (2014) found that the continual evolution of traditional knowledge alongside the adoption of modern scientific knowledge contributed significantly to the self-organization of farms in the Iberian Peninsula. Such bottom-up approaches suggest that farm resilience can be strengthened through the use of adaptive management techniques that embrace diversification while minimizing negative feedbacks that can otherwise challenge long-term sustainability.

In contrast, other studies have investigated how farm resilience can be strengthened with top-down extension initiatives that target specific disturbances (e.g. pests, drought). This approach grew out of discontent with agricultural policies that emphasized stability and efficiency of farms over strengthening their adaptive capacity (see, for example, Berardi et al. 2011). This approach also takes a more holistic view of adaptive management by recognizing multiple sources of farm resilience that may exist beyond the farm. In other words, farmers may occasionally require or benefit from assistance from above, such as through government intervention policies. For example, Hunt et al. (2012) found that a major source of farm resilience was extension services that targeted pests and promoted knowledge among Australia's sugarcane growers. This study recognized the value of five capital asset sets that supported farm resilience, namely produced, human, natural, institutional, and social capital. This approach suggests that adaptive management and farm resilience is strengthened by supporting and developing a number of capital assets.

Another research approach suggests that adaptive management is best strengthened by promoting bottom-up, farm-level adaptive responses alongside top-down interventions (see, for example, Kenny 2011). Building upon this notion is a study by Nicholas and Durham (2012) which examined how the resilience of winegrowers in California was strengthened
by implementing both farm-level adaptive management techniques as well as broader, collective responses. Taking such a two-pronged approach was an effective way to reduce vulnerability to a variety of disturbances. Similarly, Hammond et al. (2013) adopted the concept of social-ecological resilience to examine farm disturbances, adaptive strategies, and national-level policies that strengthened farm autonomy. Significantly, the participants in this study identified multiple subsystems that supported or influenced farm resilience, including the biophysical system, climate, and personal attributes (e.g. the farmers' cultural identity). Participants also identified thresholds where current activities would be untenable. Adaptive strategies included lowering external inputs, the ability to perform multiple tasks (e.g. mechanic), strategic planning, and governmental support that promotes self-organization (e.g. infrastructure improvement).

These adaptive management strategies are summarized by Darnhofer (2010, p.214) as four ways in which family farms can strengthen their resilience, namely:

1. learning to live with change and uncertainty,
2. nurturing diversity in its various forms,
3. combining different types of knowledge and learning and
4. creating opportunity for self-organization and cross-scale linkages.

Thus, this integrated approach suggests that strengthening farm resilience requires promoting farm-level adaptive management aided by cross-scale interactions, notably top-down support from government investment or through collective organization. Above all, however, it remains clear that external support must always supplement or enhance the self-organization of farms.

2.2.3.ii Disaster and climate change resilience

A number of studies apply the concept of adaptive management to examine farm resilience in response to natural disasters and the effects of global climate change. Research has shown that farm resilience to natural disasters, such as droughts, can be evaluated using a number of socio-economic indicators relating to land, labour, capital, agricultural technology, and infrastructure (Simelton et al. 2009). Similarly, Lawes and Kingwell (2012) evaluated the business strategies of 123 Australian farms using a number of quantitative variables and found that factors such as farm income diversity, area of farm cropped, and yields were associated with farm resilience to droughts. Using a similar approach that examines adaptive management strategies, Rockström (2003) found that a simple and cheap water harvesting system that could potentially help farmers manage droughts. The key to these and other disaster resilience studies is that the researchers took a holistic view of farms.
by considering not just cropping and pasture management, but also livelihood diversification, capital, traditional knowledge, and a range of other socio-economic indicators. Thus, by examining specific disturbances and the adaptive responses that they elicit from farmers, disaster resilience helps to identify the precise source(s) of farm resilience.

As with disaster resilience, there is considerable research on farm resilience to climate-related disturbances (e.g. changes in precipitation rates and patterns). It is widely recognized that industries which rely heavily on ecosystem services, such as farming, will be significantly impacted most severely by climate change, thus necessitating continual adaptation to maintain resilience (Marshall 2010; Reidsma et al. 2010).

There are two approaches to the evaluation of farm resilience to the effects of climate change. The first approach evaluates farm vulnerability to climate change by using a variety of quantitative techniques, which often include simulation modelling (see, for example, Rivington et al. 2007; Jackson et al. 2011). These simulation results are often provided to farmers to help guide better decisions to address the effects of climate change. For example, Reid (2009) describes the use of an integrated property planning tool that supplies information relating to soil moisture. This information is used to enable farmers to better target the adaptive response and therefore minimize farm-level vulnerability to droughts caused by climate change.

The second approach takes a bottom-up perspective by evaluating farm-level adaptation strategies to climate change (see, for example, Reidsma et al. 2010; Bryan et al. 2013). This approach is important since, as Reidsma et al. (2010) observed, the impacts of climate change rarely considers the adaptive ability of farmers. In other words, farmers may demonstrate resilience by changing aspects of their farm system to address specific climate-related changes. Thus, farm variability in terms of its total area, crop/livestock diversification, and livelihood diversification contribute greatly to their adaptive response capacity, such that access to capital, energy, new technology, and other factors will facilitate positive and effective responses.

The research on farm resilience to climate change, as with natural disasters, supports the view that farm adaptive management practices are likely the key to strengthening farm resilience. These disaster and climate resilience studies highlight the importance to study the whole farm system by considering both biophysical and social subsystems. Thus, a holistic
view of adaptive management is necessary to understand farm resilience to disaster, climate-induced, and other disturbances.

2.2.3.iii Resilience of farming communities

Researchers have also studied the resilience of entire farming communities. Such studies typically evaluate how agricultural communities collectively respond to specific disturbances, such as natural disasters, globalization, climate change, and policy changes (see, for example, Schwarz et al. 2011; Frazier et al. 2013). By recognizing that rural communities play an integral role in international trade, economic development, and food security, the overarching goal of community resilience studies is to support policy initiatives that strive to strengthen community, and therefore, farm resilience.

As with farm-level resilience studies, community resilience often takes a holistic approach by considering biophysical and social factors that strengthen and/or disturb community resilience. Barnes (2009), for example, adopted a resilience framework to qualitatively evaluate the resilience of the Mexican ejido land tenure system to specific shocks, namely changes in land policy and legal reforms. Similarly, Wilson (2012; 2013) also discussed socio-economic disturbances and observes that certain types of communities lose resilience by losing their ability to self-organize as they are incorporated into globalized pathways of decision-making (e.g. international agricultural policies).

Socio-economic disturbances are further studied by Gu et al. (2012) who qualitatively examined the resilience of a rural Chinese agricultural community to changing economic conditions caused by tourism development. Research has also highlighted a variety of important structural and functional characteristics that strengthen community resilience. For example, McManus et al.’s (2012) multivariate analysis highlighted the importance of the local economy, environment, and community spirit to strengthen the resilience of farming communities in rural Australia. These studies all have highlighted the fact that a diverse set of biophysical and social factors can strengthen community resilience to an equally diverse set of biophysical and social disturbances.

In summary, the various perspectives on farm resilience confirm the view that farms, like other social-ecological systems, demonstrate three essential properties, namely they can change without losing their identity, they are self-organized, and they have the ability to learn and adapt over time. Furthermore, farm resilience is strengthened by a number of factors, including the ingenuity of farmers, intervention or extension of services via cross-
Figure 2.2: The components of adaptive management.
scale interactions (i.e. panarchy), and through farm diversification. Several studies champion a “whole farm” approach, since adaptation strategies likely include adjustments to both agricultural and non-agricultural activities. Building on this perspective, it is possible to build a holistic approach to assessing farm resilience by investigating not simply how farmers adapt and manage to a specific disturbance, but by considering how farm resilience is maintained by responding to a variety of disturbances over time. This requires an operationalization of the concept of resilience that takes a truly holistic perspective of farms, disturbances, responses, and feedbacks. The following subsection considers how such a holistic perspective of farm resilience can be applied to the study of agricultural change.

2.2.4 Operationalizing a holistic approach to farm resilience

Although a number of researchers have evaluated how farms respond to specific disturbances, such as droughts, very few studies operationalize the “whole farm” or holistic approach to evaluate how farms respond in a variety of ways to multiple disturbances. Fundamentally, operationalizing social-ecological resilience entails, as S. Carpenter et al. (2001) first suggested, that researchers evaluate the “resilience of what to what” (e.g. resilience of farms to drought). When this concept has been applied to farms, both qualitative (Cabell & Oelofse 2012) and quantitative (MacLeod & Moller 2006) methods have been used to examine how farmers adapt to specific disturbances. However, by focusing on single disturbances and a limited number of associated responses, researchers have overlooked other important aspects of the adaptive management process. Instead of focusing on a limited number of disturbances and responses, a holistic approach to farm resilience needs to address the following questions:

1. What are the structures and functions, and therefore identities of the farms being evaluated?
2. What disturbances affect a particular type of farm, and how much disturbance can it absorb without losing its identity?
3. How do different types of farms respond to disturbances through adaptation and/or transformation over time?
4. What are the positive and negative feedbacks associated with farm adaptive management?
5. How do farms relate via cross-scale interactions to the rest of society, and how do such interactions influence them?

Hence, the key to operationalizing farm resilience is to consider the entire adaptive
management process, as shown in Figure 2.2. There are three main parts to the adaptive
management process in Figure 2.2, namely the farm's identity, the disturbance regime that
impact the farm, and how the farmer responds to such disturbances (i.e. its response
diversity). In addition to these three main parts, the adaptive management process affects all
components and includes cross-scale interactions that influence disturbances and responses,
and social and biophysical feedbacks that may be triggered by specific responses.

As shown in Figure 2.2, the farm includes four main subsystems, namely land
resources, the pastoral system(s) (if any), the cropping system(s) (if any), and the household
unit, which is the centre of decision-making that influences all other subsystems. The
household is also the primary source of labour, tradition, knowledge, belief, and capital.
How ecosystems are managed, how land is appropriated, how and what kind of crops are
produced, and how pastures and livestock are managed are all farm household decisions,
However, these can also be influenced by the outside world. Taken together, the structure
and function of the farm's subsystems are collectively referred to as its identity, and through
this identity the types of disturbances that affect the farm and how farmers responds to them
can be understood. Farm identity is further examined in the next section which considers
various ways to define farm typologies.

Above the farm is the disturbance regime, which is a collective term that refers to all
possible disturbances that can impact a social-ecological system (Resilience Alliance 2010).
It contains both biophysical and social disturbances that impact a particular type of farm.
The former includes environmental or climatic disturbances, and the latter refers a wide
range of political, demographic, economic, and cultural disturbances. It is important to note
that disturbances can include anything that elicit change within a system, so even changes
such as economic development are conceptualized as disturbances because they elicit a
response from the existing farms. Further, disturbances are often influenced by cross-scale
interactions, particularly from larger scales (e.g. climate change), but also from smaller
scales (e.g. soil processes). Hence, it is important to understand farm identity in order to
identity the types of disturbances farms can be vulnerable to. Farm disturbances are further
examined in Section 2.4.

At the level below the farm in Figure 2.2, is its response diversity. Similar to the
disturbance regime, the response diversity, in the context of farm resilience, is a collective
term that refers to all possible responses that farmers can make to manage disturbances.
Responses can be placed within three broad categories, namely agricultural change,
socioeconomic change, and environmental change. As with the disturbance regime, it is essential to understand the farm's identity in order to define and evaluate its potential responses.

Consider, for example, a traditional farmer in rural Amazonia who has no access to scientific agricultural innovations and another farmer in a developed country with access to the latest agricultural innovations. Each farmer will manage disturbances in a very different way based largely on their farm's identity and its social, political, cultural, and economic context. These responses, for all farmers, may include adjustments to elements within any of the four farm subsystems (i.e. the cropping system(s), pastoral system(s), ecosystems, and/or the household). Disturbances can be responded to by adopting new agricultural practices or by modifying or abandoning existing practices (i.e. agricultural change).

Farmers can also decide to make socioeconomic changes, such as encouraging rural-to-urban migration of their older children or through livelihood diversification. Farmers can also respond to disturbances by modifying their environment, such as expanding the farm area through deforestation, or by planting wind breaks. However, as explained in Section 2.5, farmers typically change multiple aspects of their farm in order to address disturbances, thus understanding the farm's identity is crucial to understanding its response diversity.

Feedbacks, as shown in Figure 2.2, are also an important part of the adaptive management process. Feedbacks can have either a positive or negative impact on the disturbance regime. Positive feedbacks resulting from specific responses may completely eliminate given disturbances. For example, consider the adoption of organic inputs (an agricultural change) to confront both food security issues (e.g. a social disturbance) and land degradation (e.g. a biophysical disturbance). If successfully implemented in the right circumstances, such an agricultural response could have a positive impact by eliminating or reducing the severity of a biophysical and/or social disturbance. However, feedbacks can also have negative effects on the disturbance regime. Section 2.6 discusses examples of negative biophysical and social disturbances in order to show how farm-level decisions may relate closely to local, regional, and global disturbances.

The four following sections elaborate further on the adaptive management process by examining more closely the concepts of farm identity, the disturbance regime, the response diversity, and feedbacks. In line with the objectives of this thesis, this discussion considers a variety of case studies and examples of farm resilience relate to agricultural expansion.
through tropical deforestation and agricultural intensification.

2.3 THE STRUCTURE, FUNCTION, AND IDENTITY OF FARMS

A common and effective way to evaluate a variety of issues relating to agricultural change, be it expansion and/or intensification, is to establish farm typologies. Farm typologies are multivariate classifications of farms based on a number of key variables that relate to the structure and function of the principal farm subsystems (i.e. cropping system, pastoral system, household organization) (see, for example, Andersen et al. 2007). In the context of farm resilience, farm typologies represent the farm's identity, which is defined by its structures and functions. However, establishing farm typologies raises a number of concerns regarding the subjectivity of the resultant classification. Specifically, there is no consensus regarding which farm characteristics best differentiate different types of farms. To address this issue, the following discussion critically reviews how different farm typologies have been devised to evaluate tropical deforestation and agricultural intensification. Subsequently, it is suggested that better farm typologies can be devised based on agroecological theory, which is a holistic perspective that considers variables from all farm subsystems. Hence, the argument for a holistic approach to farm typologies is strengthened.

2.3.1 Farm typologies

As discussed in Section 2.2.4, farms have four principal subsystems, namely the household, the cropping system(s), the pastoral system(s), and the various ecosystems that make up the farm's property. As noted earlier, farm typologies have been devised based on only a limited set of variables. Although the typologies may serve a practical purpose to examine a particular research question, they may overlook other important variables. In other words, a given farm can fit into any number of different classifications. To illustrate this potential problem, farm typologies are discussed in terms of three important variables, namely household population dynamics, farm size, and technological innovation.

2.3.1.i Typologies based on household population dynamics

A considerable research literature is devoted to understanding the relationships between household population dynamics and environmental change (Entwistle et al. 2005; see, for example, de Sherbinin et al. 2008). Based in part on the writing of Chayanov, a 19th Century economic theorist who observed correlations between the size of peasant households and their land use practices, several recent studies have specifically examined the relationships
between household dynamics and tropical environmental change, notably in the Amazon basin (Marquette 1998; McCracken et al. 1999; Perz & Walker 2002; Perz 2001).

The concept of the household life cycle, as developed by Chayanov, suggests that households pass through various stages of development from the time of their initial formation (Chayanov 1986). This concept was adopted in a notable study by McCracken et al. (1999) to evaluate tropical deforestation in the Amazon basin by early colonizers. They defined five hierarchical stages of household development, namely nuclear households with young adults and small children, nuclear household with adults and older children, nuclear households with adults with teenage children, nuclear household with older adults and teenage/young adult children, and multi-generational households or second generation households. By classifying farms according to their household life cycle locations, McCracken et al. (1999) found that the shifting supply of labour within the household related to different deforestation patterns, thus suggesting a potential link between household demographics and environmental change.

Other studies have also found similar relationships between household demographics and environmental change. For example, Marquette (1998) found that land use patterns in the Amazon were closely associated with household characteristics, including settler agroecological background, household demographic composition, land tenure status, plot size, duration of residence, and access to labour. Other studies have also found a similar relationship between deforestation rates and the age of the household head, the duration of residence, family size, the number of adults, and the number of children (see, for example, Perz & Walker 2002; Perz 2001). These studies provide empirical evidence to support the notion that the human dimension plays an important role in land change processes.

Two important observations emerge from the above socio-demographic studies. First, since the household is the primary source of labour, especially in frontier settings, an increase in the number of people within a household may allow the farmer to expand gradually the agricultural area. Second, a higher number of people in the household also creates a need for increased agricultural outputs, which further necessitates an expansion or intensification of agricultural production. Consequently, according to the studies discussed above, household demographics may may play a significant role in the process of tropical deforestation at the local scale.

However, two problems emerge from this demographic approach to farm typologies.
First, each study uses a different set of household and other variables to classify farms. Without a standardized set of variables, insights from these studies have limited use because the results cannot be compared to each other. Second, the demographic approach largely overlooks equally important farm characteristics that are associated with its other subsystems, such as the cropping or pastoral system(s). Hence, demographic variables are certainly important and must be part of a farm typology, but a more holistic approach must be sought.

2.3.1.ii  **Typologies based on farm size**

Farm size typologies have also been used to examine the rate and pattern of deforestation, particularly in the Amazon basin. Studies have divided farms into either two groups, namely smallholders and largeholders (Aldrich et al. 2006; Pacheco 2009), or three groups by including an intermediate class (Godar et al. 2012). The actual farm area of each class can be arbitrarily selected and/or defined based on local census data. For example, Godar et al. (2012) arbitrarily defined smallholders as properties measuring less than 100 hectares, then used cluster means to determine the area for medium landholders (100-600 hectares), and largeholders (>600 hectares). However, as with household socio-demographics, classifying farms based on property area alone may overlook other important farm variables.

Two contrasting trends are apparent in the Amazon basin when analysing farm classes derived from farm area relative to deforestation rates and patterns. First, several studies have found that smallholders were more responsible for deforestation than largeholders. Aldrich et al. (2006) concluded that smallholders steadily increased their deforestation rate over time, while largeholders were more likely to clear a portion of their property and leave a portion under forest. Similarly, other studies also observed that smallholders tended to clear a higher percentage of their property, such that in areas where smallholders predominate, higher deforestation rates are observed (Michalski et al. 2010; Pacheco 2009).

The second trend is in direct contrast to the first since another study found that higher deforestation rates in particular areas of the Amazon basin were associated not with smallholders, but with largeholders. Godar et al. (2012) examined four municipalities along the Transamazon Highway by comparing deforestation rates to the spatial distribution of smallholders, medium landholders, and largeholders. Their results support the view that higher rates of deforestation are associated with areas dominated by medium landholders
and largeholders (i.e. farms on properties larger than 600 hectares). Thus, different studies support different results, with both smallholders and largeholders sharing responsibility for high rates of deforestation. Hence, farm size alone may not be a suitable variable with which to classify farms.

2.3.1.iii Typologies based on technology

Farms typologies have also been devised based on the level and nature of agricultural intensification (Shriar 2005). Building on the early work of Boserup (1965), one who argued that rising populations prompted societies to intensify agricultural production by adopting new technologies, land change scientists have investigated the relationship between agricultural intensification and tropical deforestation from a farm-level perspective (for example, Perz 2003). This approach provides insight into the social determinants of technological adoption. However, like the farm size examples provided above, the adoption of technology is associated with both increased or decreased deforestation rates.

Two recent studies examined the agricultural strategies of Amazonian farms in relation to deforestation, and produced very different results. De Souza et al. (2013) classified farms by using a multivariate “intensification index” and concluded that low agricultural input levels relate to high levels of deforestation. This trend is explained by the adoption of extensive livestock production that requires low inputs of technology with a high land requirement. In contrast, Perz (2003) conducted a similar farm-level study of the land use patterns in Amazonia by comparing adopters and non-adopters of agricultural intensification practices. The results demonstrated that more technological inputs were associated with higher rates of deforestation and vice versa. Importantly, Perz (2003) noted that although technological inputs can be used to classify farms, local variables, such as population densities and access to markets, contribute greatly to land use practices. This suggests that the level of technological input is unlikely to be a suitable variable to classify farms, but it is one that should nonetheless be considered.

The previous discussion raises two important issues regarding farm typologies. First, since farms demonstrate a high level of variability, it may be problematic to classify them according to a limited number of variables, such as household size or total farm area. Second, it follows that farm typologies should be based on multiple variables derived from the farm’s four subsystems, namely the household (i.e. socio-demographics), the cropping system(s), the pastoral system(s), and the ecosystems that make up the farm's property. One
way to construct such a multivariate farm typology is to understand better the structures and functions of farms. Research in the field of agroecology offers one way to achieve this objective.

2.3.2 Agroecosystem assessment of farms

Since the agricultural structure has significant social and environmental implications, it is desirable to construct practical categories of farms to study how different farm types operate and manage ecological services. In terms of resilience thinking, it was explained earlier that the term “identity” refers to a system's inherent structure and function. Hence, the first objective of a resilience assessment is to define a farm's identity based on its structures and functions. This requires that the potentially innumerable farm variables be reduced into manageable categories. Since agroecology provides one way to conceptualize the structure and function of farms, it can facilitate the process of creating more holistic farm typologies. The task of determining which variables to select for this purpose is at the heart of the agroecological approach.

2.3.2.i Defining agroecology

The term agroecology is derived from the study of agriculture and ecosystem ecology, which examines natural systems and subsystems at various scales (Marten 1988; Chapin et al. 2011). Although the term has been used in the literature to refer to a science, a movement, and a practice (Wezel et al. 2011), Francis et al. (2003, p.100) broadly define agroecology as “the integrative study of the ecology of the entire food system, encompassing ecological, economic and social dimensions”. Fundamentally, agroecology is a systems approach to the study of agriculture (Phillip Tow et al. 2011). This conceptualization helps to explain:

(1) the order of nature, (2) the organization patterns behind that order, (3) the possibility of changing that order through human intervention, and (4) the possibility of evaluating the consequences of human intervention within the ecosystem of study between that ecosystem and its surrounding environment (Caporali 2010, p.5).

Agroecology is built upon a simple premise that to evoke change within a system, it is necessary first to understand how the system is structured and how it functions (i.e. its identity). As a science, agroecology focusses on improving the efficiency and sustainability of particular agricultural practices (e.g. pest management). As a movement, agroecology supports the plight of marginalized, resource-poor farmers by defending social issues relating to equity, such as varying levels of food security and food sovereignty (e.g. Altieri
2.3.2.ii Defining agroecosystems

Agroecosystems are a particular type of social-ecological system that are heavily managed by human action. An agroecosystem is multidimensional according to Francis et al. (2003), who state that its structure and function can be studied at various scales, principally the plot/field, farm, or national/regional/global scales. Agroecosystems have various biophysical subsystems that include crops, pastures, and the environment, and social subsystems that include all aspects of the human dimension, such as household demographics, economic factors, decision making, values, culture, and knowledge (Francis et al. 2003; Wezel & David 2012; Tomich et al. 2011; Keating & McCown 2001). Thus, the key to understanding the identity of a particular agroecosystem is to understand the structure and function of its composite biophysical and social subsystems.

Before considering how agroecologists assess agroecosystems, it is important to identify a number of key characteristics. Thompson and Scoones (2009) note that agroecosystems are complex, interconnected systems that are “embedded in complex ecological, economic and social processes”. As complex, interconnected systems, agroecosystems are also subject to cross-scale interactions, such that actions at one level (e.g. the field) will have numerous implications within other parts of the agroecosystem (e.g. the household). Agroecosystems are local, such that agroecology provides site-specific solutions by understanding local resources, according to Altieri (2002). To understand an agroecosystem often requires multiple epistemologies, which may include a combination of local and scientific knowledge. Following on the last characteristic, practitioners must view the agroecosystem as multifunctional, more than just a productive system, according to Francis et al. (2003). In addition to providing agricultural produce, farms may also have several other functions, such as supporting conservation efforts. In short, an agroecosystem's identity is defined by the structure and function of its biophysical and social subsystems and how they interact locally and within the broader food system. Thus, the adoption of a
holistic approach is crucial to assess agroecosystems.

2.3.2.iii  Agroecosystem assessment

Agroecosystem assessment takes a systems approach to evaluate a number of important properties, namely productivity, stability, sustainability, equitability, and autonomy (Conway 1985; Conway 1987; Bawden 1991; Philip Tow et al. 2011). Agroecosystem productivity is formerly defined as “the yield or net income per unit of resource” (Conway 1985, p.35), and it can be assessed by considering agricultural outputs (e.g. yield, income, or any measure of livestock production) per unit of inputs (e.g. land, labour, capital, energy, and technology). Agroecosystem stability is formerly defined as “the degree to which productivity is constant in the face of small disturbances caused by the normal fluctuations of climate and other environmental variables” (Conway 1985, p.35). It can be assessed using temporal data relating to changes in inputs and outputs. Agroecosystem sustainability, according to Tow et al. (2011), “refers to operating a farm profitably over the long term without loss of or damage to the resource base.” It can be assessed by considering agricultural productivity over time in relation to environmental change, such as deforestation, soil quality, or water quality.

The stability of an agroecosystem is defined as “the evenness of distribution of productivity among the human beneficiaries according to need” (Conway 1987, p.103), and it can be assessed, according to Marten (1988) by comparing access to land, capital, or technical information. Autonomy is the last property of agroecosystems and it is defined as the level of “agroecosystem self-sufficiency” (Marten 1988, p.292). It can be assessed by considering the reliance of farms on external input/output channels, such as chemical inputs or foreign markets. Thus, agroecosystem assessment evaluates the relationship between a farm's structural elements and its associated functional outcomes.

2.3.2.iv  Assessing a farm’s identity and the rule of 5

When examining farms in particular, an agroecosystem assessment consider a wide range of structures and functions. To simplify the assessment, Keating and McCown (2001) differentiated between the biophysical production system including crops, pastures, animals, and the natural resource base from the management system that includes human dimension characteristics (e.g. household demographics). Within each group, there are innumerable variables that could be used to differentiate one type of farm from another. For this reason, resilience thinking recognizes that it is impossible to completely account for all potential
variability within a system. Hence, the Resilience Alliance (2010) proposed that a system's identity can be defined using three to five key variables (Resilience Alliance 2010, p.25).

The key variables to examine should be selected from both ecological and social factors that contribute to the structure and function of the focal system (i.e. its identity). Consequently, in order to accurately categorize farms, their identity should be defined using variables that derive from its cropping systems (e.g. crop type, acreage under crop), pastoral systems (e.g. head count, pasture area), household organization (e.g. demographics), and its natural resource base (e.g. land appropriation). Thus, although farm typologies have been devised using only a limited number of variables, it is essential to consider multiple variables derived from its numerous subsystems in order to evaluate how the whole farm responds to disturbances. Once the farm's identity is defined, it is then possible to examine the disturbance regime's that it may be subjected to and its response diversity.

2.4 THE DISTURBANCE REGIME

Farms rarely demonstrate complete stability over time since farmers must continually manage a variety of social and environmental disturbances. The temporal pattern of disturbances is referred to as the disturbance regime (Resilience Alliance 2010, p.15). Building on this definition, this section elaborates on the characteristics of farm disturbances and considers relevant examples drawn from case studies.

2.4.1 Characteristics of farm disturbances

Farms disturbances have a number of important characteristics. For the purposes of this thesis, a farm disturbance is broadly characterized as having either primarily social or environmental dimensions, although most disturbances have elements of both (e.g. climate change). Some examples of social disturbances include demographic change, social conflict, market stimulus, policy changes, or trade agreements, while environmental disturbances may include such things as land degradation, tropical storms, droughts, climate change, or pest infestations. Farm disturbances are further defined by their duration, frequency, predictability, spatial scale, and severity (Resilience Alliance 2010). Each of these characteristics require further discussion.

2.4.1.i The temporal dimension of farm disturbances

Farms disturbances have three temporal characteristics, namely duration, frequency, and
predictability. The duration of disturbances can range from days to decades (as discussed by Darnhofer et al. 2010). Short, sudden disturbances that may last days or months are termed “pulses” while long disturbances that last years or decades are termed “presses” (Resilience Alliance 2010). It is important to define the duration of a disturbance because pulses and presses may require very different adaptive responses. For example, a pest infestation may last for only one growing season (3 to 4 months), thus it might be considered a short disturbance that can be responded to with a one-time solution. In contrast, climate change is a long-term, “press” disturbance that will likely require consistent management over several decades. One important key to farm resilience is therefore its ability to manage pulses and presses simultaneously. The temporal dimension of farm disturbances is also characterized by their frequency and predictability. A disturbance may be a single, unpredictable occurrence or it may reoccur regularly. Likewise, it may be predictable or it may be a complete surprise. Farmers are able to respond to more frequent and predictable disturbances (e.g. flooding) than they are to less frequent and unpredictable events (e.g. hurricanes). Thus, predictability and frequency of farm disturbances are important characteristics that can either strengthen or weaken farm resilience.

2.4.1.ii The spatial dimension of farm disturbances

Disturbances also have a spatial dimension that range from the field to the global scale. Soil erosion, for example, impacts farmers worldwide (Montgomery 2012), but the problem is most acute for farms located on steep hills (see, for example, Rivera et al. 2011). In contrast, fluctuations in commodity prices may impact farms throughout the world in a similar way. This spatial dimension closely relates to the concept of the panarchy, where farms are linked to higher and lower level systems. When there are major changes in higher level systems, such as the global economic system, the effects may be felt quite widely, whereas local disturbances may only be felt locally. Thus, since farms are integrated within multiple systems that exist at multiple scales (e.g. political, economic, land systems), they may be subject to both local and exogenous disturbances.

2.4.1.iii The severity of farm disturbances

Lastly, farm disturbances can also vary in severity from low impact to high impact. For example, Oerke (2006) found that the total potential loss due to pests varied significantly between different crops. For example, cotton lost up to 80 percent while maize, rice, and potatoes lost 30 to 40 percent. Even single disturbances, such as tropical storms, will not
impact all farmers in the same way. Some will lose their entire crop while others will be completely bypassed. Disturbance severity therefore depends on the farm's identity (i.e. its structure and functions) and its location. In summary, a farm resilience assessment must consider what characterizes each disturbance within the disturbance regime since farmers are likely to respond quite differently to different types of disturbances.

2.4.2 Examples of farm disturbances

2.4.2.i Environmental disturbance

Environmental disturbance is perhaps the most obvious type of disturbance that farmers manage on a regular basis. It includes disruptions to the hydrological cycle, contamination of soil and water, and production losses due to pests and disease. Two principal environmental disturbances include the effects of climate change and loss of soil quality.

For many farmers, climate change represents a significant threat to both crop and livestock production since long term rising temperatures, changing precipitation patterns, and climatic uncertainty may make current agricultural practices untenable (see, for example, Bryan et al. 2013). Jones and Thornton's (2003) study, for example, examined the impact of climate change on maize production in Africa and Latin America. They found that these areas would experience a 10% overall reduction in production by 2055. However, they also found that farmers would experience varying levels of change in yields due to the characteristics of the local setting. Thus, although climate change is associated with new challenges for farmers, specific disturbances will likely vary in space and time.

Another major environmental disturbance is the loss of soil quality through soil degradation, which is a process associated with the decline of the soil biological, physical, and chemical properties. For example, soil erosion causes significant disturbances to farmers by causing the costly loss of nutrients. Rivera et al. (2011) identified this effect in their research on the economic losses associated with erosion in Honduras. Likewise, soil compaction has been associated with significant yield decreases in tropical agricultural production, particularly sugarcane production (see, for example, Martinelli & Filoso 2008). Hence, since soil quality is the basis of agricultural production, it is one of the most direct sources of environmental disturbance.

2.4.2.ii Social disturbance

In addition to environmental disturbances, farmers also manage a variety of social
disturbances at various spatio-temporal scales and levels of severity. These disturbances may relate to economics, the health sector, demographics, political change, or socio-cultural change. From an economic perspective, Bowman and Zilberman (2013) explain that smallholders are particularly susceptible to any disturbances that relates to their management practices, such as input price volatility, dynamics of labour availability, price variability, transportation costs, supply chain transactions costs, and consumer attitudes. They further note that aspects of the farm’s household may also contribute to farm disturbances, such as his/her attitudes towards conservation, level of knowledge, risk preferences, cropping decisions, attitude towards technology, and incomes or resource base. Similarly, in their comprehensive evaluation of the future of small farms, Hazell et al, (2010) cite several sources of disturbances for smallholders, namely changing production methods, increased concentration in the supply chain, low world commodity prices, international competition, changes in agriculture research, environmental degradation, climate change, the impact of HIV/AIDS, and changes in policy environment (Hazell et al. 2010). Such policies and regulations are, according to Bowman and Zilberman (2013), an important source of disturbances since they can potentially hinder trade, influence farmers’ decisions, and directly influence the cost of production through regulations, taxes, subsidies, or standards, or indirectly my imposing water, labour, or immigration policies. Given the apparently complex nature of social disturbances, the questions of how this aspect of the disturbance regime can be evaluated is important.

In this context, Hazell and Wood (2008) summarized global-, country-, and local-scale drivers of agricultural change. These drivers can be understood as sources of disturbances in resilience thinking. According to this study, global disturbances (or drivers) include international trade and globalization of markets, low world prices for agricultural commodities, high energy prices, and OECD agricultural policies. Country-scale drivers relate to increases in per-capita income that favour large farms, increased urbanization as a result of rural-to-urban migration, changing market chains, and shifts in public policy. Local-scale drivers of agricultural change include poverty, population pressure, health issues like the HIV/AIDS epidemic, technological innovations, changes to property rights, infrastructure, market access, and non-farm opportunities (e.g. wage labour). Thus, farmers face a variety of disturbances that operate at multiple spatial and temporal scales.

In summary, while a particular farm disturbance can be characterised as either social or environmental and further defined by its duration, frequency, predictability, spatial scale,
and severity, all farm disturbances are collectively termed the “disturbance regime”. Different types of farms are impacted by a variety of disturbances at any one time, so adaptive management is a continual and critical process that must address multiple disturbances. How farmers respond to their particular disturbance regime is discussed in the next section.

2.5 RESPONSE DIVERSITY

The previous section considered how farmers are exposed to the disturbance regime, but little was said about how exactly farmers respond to particular disturbances. Walker and Salt (Walker & Salt 2006, p.70) define response diversity succinctly as “[t]he range of different response types available within a functional group”. Response diversity, therefore, refers to the various ways in which a farmer or a higher scale institution (e.g. non-governmental organization, agricultural collective, political body) responds to particular disturbances. Hence, response diversity is of utmost concern in a resilience assessment because it is, essentially, at the root of the adaptive management process and therefore a crucial component of resilient systems. This subsection briefly discusses how the ecological concept of response diversity helps to understand farm resilience and highlights important examples that relate to farm resilience.

2.5.1 Defining response diversity

Different species within terrestrial and aquatic ecosystems respond differently to given disturbances. In ecology, this response diversity is defined by Elmqvist et al. (2003, p.488) as “the diversity of responses to environmental change among species that contribute to the same ecosystem function”. Through empirical case studies, ecologists have observed that response diversity is critical in maintaining ecosystem resilience since functional groups (i.e. groups of species within a particular ecosystem) with higher response diversity are often the least affected by disturbances (see, for example Chillo et al. 2011; Mori et al. 2013). In coral reef ecosystems, for example, Nyström (2006) observed that the response diversity of functional groups contributed more to resilience than a high level of biodiversity. This suggests that how functional groups respond to disturbances is more critical to maintaining resilience than the total number of responses (Nyström 2006). Hence, since groups with greater functional diversity typically result in greater response diversity, in order to understand farm resilience, it is necessary to understand the various types of
potential responses.

Thus, when applied to farms, response diversity suggests that different subsystems can collectively or individually respond to a particular disturbance. For example, a farmer may respond to lower yields caused by erratic rainfall patterns by installing drip irrigation and by encouraging family members to seek off-farm employment to help support the household financially. However, if different subsystems are not well developed (i.e. less functional diversity), the farmer is left with fewer potential responses to the disturbance regime. How exactly farmers respond to disturbances requires further clarification.

2.5.1.i Three types of responses

Farmers can respond to disturbances by modifying, adding, or removing any components of their farming subsystems, namely the cropping system(s), pastoral system(s), household organization, or the land resource base. As shown in Figure 2.2, this thesis examines three broad categories of responses, namely agricultural, social, or environmental change. Agricultural change includes any change to the elements that make up the cropping and/or pastoral systems, such as the adoption of agrochemicals as part of a nutrient management system or the reduction of tillage to help prevent erosion. Social change refers to any change within the human dimension, such as modifying the demographic structure of the household through immigration or emigration to either increase available labour or decrease the number of dependants. Environmental change refers to any anthropogenic environmental change that is made to address a disturbance, such as deforestation to expand the agricultural area or planting a windbreak. Hence, in the context of farm resilience, response diversity simply refers to these various types of potential responses to the disturbance regime.

2.5.1.ii The temporal and spatial dimension of responses

Similar to disturbances, responses are also characterized by their duration and frequency (Resilience Alliance 2010). A response can be short, such as a single spraying of pesticides to combat a certain pest, or it can be long, such as the incremental increase in fertilizer use to maintain optimal yields. Likewise, a response may also vary in its frequency ranging from a single response to multiple responses, such as frequent irrigation to combat low precipitation. Thus, responses to disturbances will vary form short single responses to multiple responses over a long period of time.

Responses will also vary spatially from local to global scales. When a farmer chooses to
apply pesticides to a single field to address a pest disturbance, it can be said that this is a local or field-scale response. However, if a centralized authority, like a growers cooperative, decides to spray aerially for the same pests over a larger area, the response is said to be regional. Responses can also be global, such as the growth of the livestock sector in developing countries to address increasing demand for animal products (as discussed by Thornton 2010). Another global response may be to establish fair prices through such organization such as Fairtrade to help elevate rural poverty in developing countries. To illustrate farm response diversity further, the following presents case study examples.

2.5.2 Examples of farm responses

2.5.2.i Agricultural change

One of the most obvious ways that farmers can address farm disturbances is through understanding agricultural change. One study on the agricultural impact of climate change found that Kenyan smallholders responded to disturbances by changing crop varieties and type, planting dates, fertilizer application strategies, and soil and water conservation strategies. Some farmers also planted trees, decreased the number of livestock, diversified production, and provided supplemental feed to livestock (Bryan et al. 2013). Agricultural change can therefore be considered along a spectrum from unsustainable to sustainable practices. Intensive techniques may include the use of agrochemicals, heavy tillage, and/or irrigation (see, for example, Jackson et al. 2011; Tilman et al. 2011). Sustainable practices may include a range of strategies under the umbrella term “conservation agriculture”.

Conservation agriculture includes a reduction of soil tillage, building living barriers, mulching, planting along contour lines, organic manure, terraces/stone walls, drainage ditches, cover crops, and diversification of crop rotations (Wollni et al. 2010; Scopel et al. 2013; McDermott et al. 2010). However, farmers in a particular region may adopt a range of practices, some considered to be conservation agriculture and others intensive, as Rice (1999) observed with coffee farmers in Central America. Thus, a farm resilience assessment must consider a wide spectrum of potential agricultural responses that can include conservation and intensive agricultural practices.

2.5.2.ii Environmental change

Similar to agricultural change, farmers may also decide to modify some aspect of the environment to address a particular disturbance. Expansion of the agricultural area through deforestation, as discussed in a previous section, is a primary response by farmers to a
variety of disturbances. For example, there has been considerable expansion of sugarcane production in Brazil through deforestation in the past decade due largely to increased demand for sugar and biofuels (Martinelli & Filoso 2008). Similarly, the demand for livestock products has contributed to increased deforestation in the Brazilian Amazon basin. In addition to expanding the agricultural area, farmers may also make other environmental changes to address disturbances, such as building live barriers to prevent erosion and financial loss (see, for example, Rivera et al. 2011). Thus, environmental change as a response to disturbances is exemplified by any change to the natural landscape to address a particular disturbance.

2.5.2.iii Social change

Changes made to the social structure of rural household and communities are also important as a response to various disturbances. Rural out-migration is a primary social response to a variety of farm disturbances, such as drought, market instability, and the growth of competing markets (e.g. employment opportunities in cities). Meyerson et al. (2007) observed that although migration patterns and causes are complex, rural out-migration is the dominant cause of urban growth in the Americas. Indeed, they note that the rural population remained relatively stable since 1970 at about 190 million people while the urban population grew by over 80%.

Although many factors account for this trend, Meyerson et al. (2007, p.184 note that “long-term droughts in parts of the Americas are likely to lead to rural migration to more promising agricultural regions and urban areas.” Indeed, population dynamics, either growth, decline, or movement, are often associated with an adaptive response to agricultural disturbances (see, for example, Pfeffer et al. 2005; de Janvry et al. 1989; Satterthwaite 2014; García-Barrios et al. 2009). Thus, social change must also be considered when evaluating the response to farm disturbances, both at the household and community levels.

In summary, response diversity refers to the range of responses that can address the disturbance regime. Each response can be described as either an agricultural, social, or environmental change that is characterized by its duration, frequency, and spatial scale. The response reveals much about a system's resilience because, as Leslie and McCabe (2013) have observed, there is likely a link between a farm's functional diversity and its ability to respond to disturbances. In other words, a farm may only demonstrate resilience if it has the capacity to respond to a variety of disturbances through a diverse set of potential responses.
For farm systems, the response diversity relates to the adaptive management process since it is organized to address environment, political, social, and economic change. Thus, response diversity of farms is an important part of the farm resilience assessment.

2.6 FEEDBACKS FROM FARM RESILIENCE

The discussion in the previous sections of this chapter have conceptualized farm resilience as a process by which farms continually respond to the prevailing disturbance regime in order to maintain their essential structure and function over time (i.e. their identity). Only a small number of studies have examined the relationship between farm response diversity and farm resilience (see, for example, Eakin & Wehbe 2009). This section discusses how response diversity at the farm level can feed back into the disturbance regime and create new or modify existing social and environmental disturbances.

The environmental and human impacts of deforestation and agricultural intensification are used to illustrate this feedback process by which farm-level decisions can contribute to the disturbance regime. It is suggested that in addition to external pulses and presses, the process of farm resilience can itself be a source of disturbance. Hence, this section considers possible environmental and social feedbacks that relate to farm resilience.

2.6.1 The environmental impacts of deforestation and intensification

Combined, deforestation and agricultural intensification can have numerous environmental consequences from the local to the global scales (Adedire 2002; Foley et al. 2005; Horrigan et al. 2002; Matson et al. 1997; Tilman 1999; Werth & Avissar 2002). Three prominent environmental impacts that result from agricultural expansion and intensification include land degradation, water shortages, and global climate change. This section discusses how these three environmental impacts feed back into the disturbance regime to impact farm resilience.

2.6.1.i Land degradation

Deforestation and agricultural intensification impacts on the chemical, biological, and physical/structural properties of soil, especially in tropical areas where soils are most often old, weathered, and nutrient deficient (Ehigiator & Anyata 2011; Juo & Franzluebbers 2003). Land degradation is broadly defined as “a long-term loss of ecosystem function and services, caused by disturbances from which the system cannot recover unaided” (UNEP
Thus, land degradation impacts the agricultural system by reducing the suitability of land for agricultural production and by increasing the cost of production. Responses that promote land degradation may help to create a number of new disturbances by feeding back into the prevailing disturbance regime.

2.6.1.ii Water shortages

Overuse and contamination of water resources are two major environmental impacts that relate to deforestation and agricultural intensification. Agriculture, including crop and livestock production, accounts for 70 percent of global water consumption (FAO 1996). This number is expected to rise due to the ongoing expansion of irrigated areas. Global water shortages and competition for clean water threaten agricultural production in many areas, especially in regions that regularly experience drought conditions or have low water tables (Matson et al. 1997). In this context, Tilman (1999) found that the overuse of
agrochemicals can pollute groundwater, cause the eutrophication of waterways due to phosphorus run-off, and it can create “dead zones” (i.e. hypoxia) in marine ecosystems. To mitigate these impact, forests act as a natural buffer to protect waterways from environmentally damaging run-off, hence, when deforestation and agricultural intensification occur concurrently, their impacts can destabilize agricultural production by polluting local freshwater resources.

In the Latin America and Caribbean (LAC) region, there are nearly 28,000 cubic metres/person/year of freshwater available. However, diminished water quality and availability are now regarded as limiting factors “for the socio-economic development of some Latin America and Caribbean areas” (UNEP 2007, p.242). Further, industrial nations, such as the United States, that rely heavily on agrochemical inputs have polluted the majority of their freshwater resources. Horrigan et al. (2002) reported that in the United States, 70 percent of freshwater resources have been contaminated by agricultural activity (Horrigan et al. 2002). Thus, overuse and contamination of water resources as a result of deforestation and agricultural intensification represent another feedback into the disturbance regime.

2.6.1.iii Climate change

Global climate change and the modification of the hydrological cycle are major impacts of tropical deforestation and agricultural expansion (Fearnside 2006; Fearnside 2011; Fearnside 2012). When forests are cleared through burning, greenhouse gases that are sequestered in their biomass are released into the atmosphere, and this process contributes to global warming (Fearnside 2005; DeFries et al. 2004). Clearing forest by burning for agricultural land is estimated to contribute as much as 20 percent of human-induced greenhouse gas emissions (Don et al. 2011; Horrigan et al. 2002).

Globally, climate change alters precipitation patterns, increases temperatures, contributes to the thermal expansion of oceans, accelerates the melting of glaciers, contributes to ocean acidification, and changes atmospheric chemistry (Adedire 2002; Garcia-Carreras & Parker 2011; Avissar & Werth 2005; Ray et al. 2006; Malhi et al. 2008; Ganzeveld & Lelieveld 2004). Locally, these impacts alter agricultural productivity by causing water shortages, landslides, lowering of the water table, a decline in regional precipitation, hydroelectricity deficiencies, declining soil moisture, changes in solute dynamics in soil water, sedimentation of tropical estuaries, and changes in stream flow
(Adedire 2002; Fearnside 2005; Ataroff & Rada 2000; Clark 1987; Wolanski & Spagnol 2000; Coe et al. 2011; Bruijnzeel 2004; Williams et al. 1997). Thus, deforestation and agricultural production influence changes in global climate patterns and its impacts feedback into the local disturbance regime experienced by farmers.

In summary, land degradation, water shortages or contamination, and global climate change exemplify environmental feedbacks that result and can impact on farm resilience. As farmers decide to clear new land and adopt new technologies, their choices can address an immediate disturbance, such as productivity declines, but they can also create or intensify future disturbances. In addition to these environmental feedbacks, farm resilience can also contribute to social disturbances.

2.6.2 Social feedbacks

Despite the obvious economic and social benefits that come from increasing food and fibre production through deforestation and agricultural intensification, numerous social factors also affect farm resilience. Food security issues, human health issues, and social conflict exemplify these potential human impacts.

2.6.2.1 Food security issues

Food security, especially in developing countries, is an international problem that is intensified by global environmental change (UNEP 2007). The FAO calculates that from 2010 to 2012 12.5 percent of the global population was undernourished (in terms of dietary energy supply), with the vast majority of the affected individuals being in developing countries (FAO 2012). By 2050, it is expected that global food production will double as the per capita demand for food will increase by 100-110% relative to 1960 figures (Tilman et al. 2011).

As discussed previously in this chapter, this demand will likely be met through both expansion and intensification of agricultural production, and these changes will likely contribute to land degradation, water shortages, and global climate change. This cycle will contribute to food insecurity by lowering farm incomes, increasing poverty, and shifting production from staples to intensified monoculture production (e.g. soy farming in the Amazon). The FAO (2012, p.28) observed that “agricultural growth is particularly effective in reducing hunger and malnutrition.” However, the environmental impacts from this growth have the potential to trump the socioeconomic benefits if farm resilience depends too heavily on unsustainable practices such as deforestation and agrochemical intensification.
Thus, a balance is needed between increasing production and environmental impacts.

2.6.2.ii Social conflict

Social conflict is another potential disturbance associated with farm resilience. Farm expansion, particularly through deforestation, can create conflict between different stakeholders with conflicting views on resource management, land tenure, and conservation. Social conflict, manifested as political upheavals, protests, violence, or even genocide or ethnocide is commonly associated with land conflict (Sponsel et al. 1996). Although the complex link between environmental change and violent conflict has been criticized (see, for example, Bernauer et al. 2012), numerous case studies have reviewed the links between violent conflict and the effects of tropical deforestation, land tenure, resource scarcity, and issues relating to forest governance (see, for example, Durán et al. 2011; Messina et al. 2006). In addition, a global review of the relationship between conflict and environmental change also identified hotspots where forest conflict is more acute, with the majority being experienced in tropical regions (Mola-Yudego & Gritten 2010). The central theme observed in these case studies is that, in certain circumstances, agricultural expansion and intensification can both cause and contribute to other forms of social conflict. Hence, social conflict exemplifies another potential consequence of farm resilience.

2.6.2.iii Human health

Deforestation and agricultural intensification impacts the health of individuals within farming communities and the population at large (Colfer 2008). Three types of human health consequences relate directly to agricultural expansion and intensification, namely the associated health consequences of dietary change, illnesses due to the use of agrochemicals, and increases in the incidence of vector-borne diseases.

Changes in agricultural practices and production relate to changes in human diet, a trend that has been observed since the Neolithic revolution some 10,000 years ago (Simmons 2011). Indeed, dietary changes play a pivotal role in determining the health status of human populations (Pinhasi & Stock 2011). Recently, agricultural intensification of crops and livestock has occurred alongside changes in the amount and types of food consumed globally. For example, although the subject of considerable debate, increased consumption of high animal fat products have been associated with chronic degenerative diseases such as heart disease, type II diabetes, and colon, breast, and prostate cancer (Horrigan et al. 2002; McMichael et al. 2007). Furthermore, not only are humans consuming more types of
potentially harmful foods, they are doing so on a more regular basis and in larger quantities.

The increased production and consumption of contributing food is therefore associated with numerous health concerns, including the global obesity epidemic. These concerns have led some researchers to promote a “sustainable diet” that is both healthy for humans and contributes to environmental health by being low in greenhouse gas emissions (see, for example, Macdiarmid 2013). Change in crop production strategies and the types of crops produced affect the diet of the population at large, including farm households. Hence, changes in diet exemplifies a feedback into the disturbance regime.

However, some agrochemicals pose serious human health risks. The debate on the human and environmental impacts of agrochemicals was initiated in the 1960s by Rachel Carson's *Silent Spring*, which examined the environmental impact of the pesticide DDT. This was followed by such works as Wright's *The Death of Ramon Gonzalez: the modern agricultural dilemma*, which discussed the harmful effects of agrochemicals on farmers in rural Mexico. Studies have since shown that pesticide exposure is positively associated with various types of cancers, notably non-Hodgkin lymphoma, leukemia, brain cancer, and prostate cancer (for a review, see Alavanja & Bonner 2005; Dich et al. 1997; Bassil et al. 2007).

Children are most susceptible to the harmful effects of pesticides and fertilizer exposure. Research has found that the former can have negative neurological effects (Rosas & Eskenazi 2008; Keifer & Firestone 2007), while the latter can lead to conditions such as blue baby syndrome (Majumdar 2003). Recent research has also identified a variety of other disorders that are associated with pesticide exposure both on farms and through the food chain (Ritter et al. 2006; Gilden et al. 2010; Popp et al. 2013). Thus, the choice to intensify agricultural production with agrochemicals comes with considerable risk to human health, and although technological inputs may address immediate production concerns by increasing yields, they can also cause new social disturbances.

Deforestation has been linked with to higher incidences of vector-borne diseases, most notably malaria, dengue fever, and Lyme disease (for reviews, see Guerra et al. 2006a; Patz et al. 2008; Vittor et al. 2009). The Amazon basin, for example, is the hotspot for malaria in the Americas. Stefani et al. (2013) found that 89% of malaria cases in the Americas occur in this tropical region. Specifically, a meta-analysis found that 1.5 million square kilometres are at risk in the Amazon basin region, exposing 11.7 million people to higher risks of
contracting malaria (Guerra et al. 2006a).

Globally, Guerra et al. (2006b) used risk mapping to determine that deforestation and changes in associated ecosystems placed 2.5 billion people at possible risk of transmission of malaria \((P. falciparum\) and \(P. vivax\)) in 2005. This number is likely to increase as the human population grows. In addition to the obvious health costs associated with exposure to higher risks of malaria, Asenso-Okyere et al. (2011) also found that malaria negatively impacts agricultural productivity by reducing the agricultural labour force and by slowing the adoption of new technologies. Thus, as agricultural areas expand in tropical locations, farming communities and the surrounding populations are exposed to a greater number of health and economic disturbances.

2.7 SUMMARY

Resilience thinking offers a suitable assessment framework to address the human dimension of agricultural change. Building upon both resilience thinking and research developments in land change science, this chapter has argued in favour of a more holistic, integrated, and multidisciplinary assessment of agricultural change to understand better associated processes of environmental change. With its focus on change within social-ecological systems, resilience thinking offers a different perspective for land change scientists to explore interconnections within complex agricultural landscapes. However, in order to evaluate farm resilience, it is necessary to comprehend the identity of farm systems. Various characteristics have been used to classify farms, but few studies take a whole farm perspective. Building on agroecological research, an argument is presented for a more holistic approach to farm typologies that considers variables relating to cropping, pastoral, household, and land resources. It was argued that resilience thinking provides additional insight because a resilience assessment relies on multiple variables to define the identity of farm systems. Further, a resilience assessment also considers how farmers manage social and environmental disturbances through environmental, social, and agricultural responses. Insight was also gained by considering social and environmental feedbacks and cross-scale interactions. Thus, the objective of a farm resilience assessment is to identify how farms change over time through the adaptive management process.
3 FARM RESILIENCE IN THE LAC REGION AND BELIZE

This chapter applies the concepts discussed in the previous chapter to examine agricultural development and farm resilience in Latin America and the Caribbean (LAC) region in general, and in Belize in particular. The discussion considers the disturbances, responses, and feedbacks that relate specifically to farm resilience and builds upon Chapter 2 by presenting a regional and national case study of farm resilience. Additionally, necessary background information is presented to help understand developments within the thesis study area of Northern Belize.

3.1 HISTORY OF LAND CHANGE IN THE LAC REGION

The LAC region is defined by the United Nations Environment Program (UNEP) as the area that includes the 33 countries of South America, the Caribbean, and Central America (UNEP 2007). Agriculture is a primary economic activity in the region, though considerable variability exists both between and within the subregions in terms of farm organization (i.e. productivity, diversification etc.), farm resilience, exposure to disturbances (i.e. vulnerability), and response diversity. This section summarizes the agriculture sector in the LAC region by providing a brief historical overview before discussing specific indicators of resilience that are examined later in the thesis.

3.1.1 Agricultural development in the LAC region

Agriculture has a very long history in the LAC region. Among the ancient inhabitants of the region, the Mayas are perhaps best known for having cleared an extensive agricultural area and for practising a range of intensive farming techniques, such as building raised fields in swamp areas and terraces along hillsides, managing water, and by applying organic soil inputs (see, for example, Beach & Dunning 1995; Dunning et al. 1998). Since the colonial period in the LAC region (15th to 19th centuries), agriculture has changed significantly through expansion and intensification. With a current population of over 560
million people (UNEP 2007), the LAC region's agricultural area covers some 7.37 million square kilometers, an area that has grown consistently since first being recorded in 1961 by the FAO (FAOSTAT 2014). This growth has resulted from various historical developments within each subregion. Thus, a distinction can be made between historical developments as they relate to agriculture in the Latin America (i.e. Central and South America) and Caribbean subregions. The following subsections discuss general historical developments in each of these major subregions.

### 3.1.2 Agricultural development in Latin America

Latin American economic development from the colonial period (late 15\textsuperscript{th} to 18\textsuperscript{th} Century) to the present day proceeded through three distinct phases. In what Robinson (2003) calls the first phase of capitalist expansion, Latin American economic development was initially controlled by colonial powers, mainly the Spanish in Central and South America. Along with the British, Dutch, Portuguese, and French, the Spanish imposed a mercantile system that promoted the extraction of natural resources to support colonial interests (Robinson 2003). There was very little agricultural development throughout Latin America until the 1700s when henequin and coffee were first produced for export (Solbrig 2006, p.348). Along with the success of these crops, further export-led development (ELD) occurred in Latin America.

Following the colonial period, Robinson (2003) observed that a competitive capitalist system eventually developed that placed increasing emphasis on crop and livestock production over natural resource extraction. For example, Foster (2007) observed that after 1860, population growth alongside international market volatility for logwood and mahogany forced Central American nations to diversify agricultural production. This general trend occurred throughout Latin America at this time. Amid this regime of agricultural expansion and diversification, new export crops were developed throughout Latin America, namely sugarcane, bananas, cacao, and cotton, alongside increases in beef production (Booth et al. 2009; Solbrig 2006). Despite the period of agricultural development from 1850 to 1950, Solbrig (2006, p.503) acknowledged that Latin American nations only depended on one to five commodities and they practised a low level of produce elaboration (e.g. exporting wheat not flour). Thus, growth in ELD after 1850 established agriculture as the backbone of Latin American economies. However, there was considerable room for further development.
Since 1950, Latin America experienced a period of rapid agricultural expansion and intensification as part of a process known internationally as the Green Revolution (Murray 1994). New types of crops were introduced (e.g. soybeans, citrus, rice, wheat) and inputs, such as fertilizer, pesticides, and irrigation, began to be used widely as farms increasingly mechanized to become less dependent on manual labour inputs (Solbrig 2006). Consequently, FAOSTAT (2014) observed that from 1961 to 2010 the total agricultural area expanded by over 31 percent in the LAC region, while the rural population only grew by about 6 percent. Thus, the expansion and intensification of agriculture since the 1950s contributed heavily to economic growth, yet the region currently has the highest income inequality in the world according to the UNEP (2007). These changes had serious socioeconomic impacts throughout the region.

Despite the economic growth and agricultural development since the 1950s, Latin America has lacked political and economic stability. For example, the 1980s is known as the lost decade in Latin America. Civil war, labour disputes, corruption, and genocide led to the death of over 300,000 people (Foster 2007). Volatile international commodity markets and trade liberalization recurrently destabilized portions of the agricultural sector (Solbrig 2006). Such civil and economic strife contributed heavily to shifts in economic strategies.

In Central America, for example, there was a shift away from traditional crops in some nations and an increased emphasis on maquiladora manufacturing, non-traditional agricultural exports (NTAE) such as flowers, tourism development, labour exports, and remittances (Robinson 2003). Further, as largeholders grew, smallholder agriculture was increasingly marginalized (Solbrig 2006). Thus, although globalization since the Green Revolution expanded the agricultural sector, it also was a source of socioeconomic instability, which intensified a variety of disturbances. Chief among these new disturbances was the great divide between the rich and the poor.

3.1.3 Agricultural development in the Caribbean

The Caribbean was colonized mainly by the British, Spanish, French, and Dutch. Agricultural development in this subregion differed since the conquest period from developments in neighbouring Latin America in many ways. Export agricultural development, for example, earlier in the Caribbean than in Latin America and was supported initially by slavery until its abolition in the mid-19th Century. The British established sugarcane production throughout the Caribbean in the mid-18th Century (for a review, see
Heuman 2013), and a century later coffee production spread throughout Latin America (Foster 2007). As Bulmer-Thomas (2012) observed, sugarcane plantations consumed the most productive land because they were the primary source of income for the Caribbean colonies until the 1950s. In addition coffee, cocoa, cotton, bananas, rice, citrus fruits, coconuts (copra) and tobacco were also eventually produced for export (Gumbs 1981). However, while Latin America was on the brink of the Green Revolution in the 1950s, the Caribbean followed a very different development pathway.

The 1950s and 1960s were a period of major political, economic, social, and agricultural change in the Caribbean. Politically, thirteen nations gained independence from their former colonial powers during this time while another twelve gained more autonomy. Economically, the region experienced periods of growth when governments used their newfound independence to increase spending within the public sector (Bulmer-Thomas 2012). However, instead of increasing production since the 1960s, the Caribbean sugarcane industry declined, especially after 1984 when the US soft drink companies switched from sugar to high fructose corn syrup. The eventual demise or reduction of the export agricultural sector in most (though not all) Caribbean countries was replaced by the export service sector, notably tourism and financial services (Bulmer-Thomas 2012; Heuman 2013). Thus, it can be said that the subregion experienced a regime shift in the 1950s and 1960s that placed increasing emphases on non-agricultural sectors of the economy.

The changes since this time period had several important consequences. The decline of export-led agricultural development, alongside other factors including natural disasters, trade liberalization, and globalization, contributed to rural depopulation, the marginalization of smallholders, the growth of largeholders, increased urbanization, widespread poverty, and an increasing dependence on imports to maintain food security (Barker 2012; Boruff & Cutter 2007; Gumbs 1981). Hence, both Latin America and the Caribbean grappled with similar socioeconomic problems associated with agricultural expansion and intensification, or the lack thereof, but agricultural production increased in the former and declined in the latter. These consequences are examined further in the next section by considering several indicators relating to agricultural resilience in the LAC region.

3.2 INDICATORS OF FARM RESILIENCE IN THE LAC REGION

The previous section briefly reviewed the history of agricultural change in Latin
America and the Caribbean since the early colonial period, and identified several sources of social, political, and economic disturbances, especially since the 1960s. Despite civil wars, political strife, natural disasters, and globalization, agricultural development still flourished in some areas. Resilience thinking helps conceptualize how farmers in these areas adapted and transformed over time to manage the disturbances. In the LAC region, indicators suggest that agricultural expansion and intensification are prominent among the numerous potential responses to disturbances. The following sections consider several economic, demographic, and land change indicators of farm resilience that relate, directly and indirectly, to agricultural expansion and intensification.

3.2.1 **Indicators of agricultural expansion**

As discussed in Chapter 2, agricultural expansion through the process of tropical deforestation is driven by multiple proximate and underlying causes, such as economic opportunities, demographic change, and environmental change. By understanding these drivers, it is possible to associate changes in the agricultural sector with the process of agricultural expansion. Three useful indicators of agricultural expansion exist in the LAC region, namely land change, changes in agricultural productivity, and the contribution to gross domestic product (GDP) by the agricultural sector. Each of these drivers of change is discussed in the following sections.

3.2.1.i **Land change indicators**

Deforestation is the most visible indicator of agricultural expansion in Latin America since forests are the primary source of new farmland (Gibbs et al. 2010; Hosonuma et al. 2012). Since 1990, forests in the LAC region have declined by almost 9.3 million hectares, even with a slight net forest gain in the Caribbean during this period (FAO 2011). Since the 1960s, between 70 and 80 percent of cleared forest areas in the LAC region were used for agriculture (i.e. crop or pasture) (FAOSTAT 2014). These changes in land cover and land use are closely associated with historical developments in the region.

Consider, for example, the contrast between agricultural development in Latin America and the Caribbean since the 1950s. In general, the LAC region experienced growth in its agricultural sector since the 1950s, but most of this growth was confined to Latin America since the Caribbean experienced a decline as it shifted economic development towards the service sector. These two contrasting trends are visible in the land change data collected and maintained by the FAO (FAOSTAT 2014). These data suggest that the agricultural area in
the LAC region expanded by 7.5%, while the forested area declined by 9% from 1990 to 2010, reflecting the fact that the agricultural sector was resilient to a number of economic, environmental, social, and political disturbances because it continued to expand.

However, while the Latin American agricultural area expanded by over 8 percent and its forests declined by 9 percent from 1990 to 2010, the Caribbean nations experienced a 17.5 percent increase in forest cover through secondary forest succession. This trend was accompanied by an almost 4 percent decline in its agricultural area. Thus, land change processes like deforestation, reforestation, and expansion or contraction of the agricultural area suggest various types of responses to disturbances in the LAC region. Specifically, forest changes are associated with general economic changes within the study area.

3.2.1.ii  Agricultural productivity indicators

Changes in agricultural productivity may also indicate agricultural expansion and reveal further aspects of farm resilience. Since productivity relates to various inputs in addition to the consumption of land, such as agrochemicals, irrigation, and mechanization, changes in production may likewise indicate both expansion and intensification. However, substantial productivity increases over time relative to periods of deforestation. On a regional scale, sugarcane production increased by over 300 percent since 1961 (FAOSTAT 2014). This increase was driven primarily by the expansion of the sugarcane ethanol industry in Latin America and it led to substantial deforestation and pasture conversion (Martinelli & Filoso 2008).

Despite this increase in Latin American countries, the collapse of the sugarcane industry in the Caribbean resulted in a 77 percent decline in productivity from 1980 to 2010. Hence, Bulmer-Thomas (2012) observed that the collapse liberated land which was either used for domestic crop production or reforested, a fact that is well represented in the Caribbean-wide increase in forest area and the reduction in the agricultural area. Thus, despite the complexity of productivity, major changes in agricultural outputs likely relate, at least indirectly, to the expansion or contraction of the forest and agricultural area.

3.2.1.iii  Economic indicators

In terms of the agricultural economy as a whole, value-added as a proportion of GDP indicates the net output of the agricultural sector. This statistic is used by the FAO to measure the contribution of agriculture to GDP. It can be used to evaluate farm resilience at regional, subregional, and national scales. Despite tremendous growth in the agricultural
sector from a land use and productivity perspective, the agricultural sector's contribution to
the LAC region's GDP declined steadily from 16 percent in 1965 to about only 6 percent in 2010. Although Central America's shift to industrial production resulted in a 26 percent decline in its agricultural sector, by 2010 agriculture only contributed around 4 percent to the Caribbean GDP, as compared to just over 9 percent in Latin America (World Bank 2013). This contrast reflects a variety of social, economic, and political changes through each subregion. Thus, such economic metrics can only be used as indirect indicators of agricultural expansion or reduction. Nevertheless, the current state of the Caribbean and the Latin American agricultural sectors, as reflected in such economic metrics, are comparable to historical developments in each subregion, and they serve to strengthen the view that these indicators can be used to evaluate farm resilience.

In summation, agricultural expansion and contraction are primary responses of the agricultural sector in the LAC region to a variety of disturbances. These relationships are directly reflected in forest change data and the changing size of the agricultural area, and indirectly related to production data and economic metrics. Such direct and indirect indicators clearly reflect the fact that the agriculture sector expanded in Latin America since the 1960s while it contracted in the Caribbean. However, other changes within the agriculture sector, namely agricultural intensification, have also occurred since the start of the Green Revolution. Hence, farm resilience is also maintained through intensification, which also can be examined by evaluating direct and indirect agricultural, environmental, and economic indicators.

### 3.2.2 Indicators of agricultural intensification

The Green Revolution in the 1960s drastically changed the way crops were produced in the LAC region as well as globally. Agriculture was intensified by adopting chemically-intensive techniques, irrigation, and mechanization. Thus, there are direct indicators of agricultural intensification that relate to changes in agricultural production strategies and output, and indirect indicators that relate to sociodemographic and environmental changes.

#### 3.2.2.i Direct indicators

Despite the growth of the LAC region’s agricultural area since the 1950s, the region also experienced increased yields per hectare. For example, from 1961 to 2010 sugarcane yields per hectare increased by 51 percent in Latin America, and maize yields increased by almost 250 percent throughout the region (FAOSTAT 2014). These and other yield increases
were achieved by adopting new technologies, such as fertilizers, pesticides, and mechanization. These changes are well documented by FAOSTAT (2014) and a recent review by the FAO (2010) which demonstrates increasing use of agrochemicals in the region. Thus, intensification is suggested by both increased yields per hectare and by the increased use of inputs. Such indicators are the most direct evidence of agricultural intensification. However, indirect indicators also exist.

3.2.2.ii Urbanization as an indirect indicator

Among the indirect indicators of agricultural intensification in the LAC region is high rates of urban population growth at the expense of rural population growth. This trend suggests that there is less reliance on labour inputs within rural areas despite considerable growth in the total agricultural area. That is, the adoption of new technology decreases the need for a large labour pool. Although rural populations continue to grow through natural increase, they do so at a much slower rate than urban areas because many rural individuals choose to emigrate from urban areas.

Globally, according to O’Neill et al. (2010) urban population growth exceeds rural growth. In the LAC region, the UNEP (2007) has observed that urbanization is comparable in scale to that in the developed world. Urbanization is attributed to both natural population growth and rural-to-urban migration, a trend that has occurred at varying rates throughout the region. Not all rural outmigration is directly related to agricultural intensification, however, Grau and Aide (2008) observed that it is often associated with the abandonment of marginal land in areas that would otherwise require costly inputs to achieve optimal yields.

Thus, the slower rate of rural population growth, a trend associated with rural outmigration, is a useful indirect indicator of agricultural intensification, and in the LAC region it suggests that such demographic change is at least partially associated with the marginalization of smallholders who must seek their livelihoods in urban areas.

3.2.2.iii Environmental change as an indirect indicator

The environmental impacts associated with agricultural intensification also serve as indirect indicators of agricultural intensification. These impacts primarily include land degradation, land desertification, air pollution, and water stress and/or contamination. In areas like the LAC region where there has been significant expansion and intensification, the level of environmental contamination and change is a useful indirect indicator of agricultural intensification.
The UNEP (2007) calculated that roughly 16 percent of the LAC region’s land is degraded and 25 percent of the area suffers from desertification. Compounding this problem, The United Nations' Millennium Development Goals summarize the state of water in the LAC region, and suggest that water demand has increased due to irrigation, livestock production, urbanization, industrial growth, and deforestation (United Nations 2005). Further, water quality is declining due largely to the contamination of surface water and groundwater "owing to the use of fertilizers, herbicides, pesticides, and organic waste..." (United Nations 2005, p.173).

Conversely, these trends were not observed in areas where agricultural development was not as intensive, such as in the Caribbean countries, where Bulmer-Thomas (2012, p.429) recognized that the subregion (excluding Haiti) “does not suffer from the kind of extreme degradation found in many other parts of the world.” Thus, environmental changes can serve as indirect indicators of agricultural intensification in the LAC region.

In summary, as with the expansion of agricultural production, agricultural intensification can be evaluated using numerous direct and indirect indicators. For the LAC region, the indicators discussed above suggest that there was an overall propensity to intensify agricultural production since the 1960s, though less so in the Caribbean where the same indicators tend to affirm the observation that agriculture in this area has been in a state of decline over the past 50 years. Thus, direct and indirect indicators of expansion and intensification are important within the broader resilience framework that is considered in the following section.

### 3.2.3 Farm resilience in the LAC region

Since European colonization, the agricultural sector in the LAC region has demonstrated a high level of resilience to a variety of social, economic, political, and environmental disturbances. Applying a resilience framework to this sector helps to elucidate the agricultural development processes that are underway in the LAC region. This section considers the region’s development as a growth adaptive cycle, the disturbance regime, and possible social and environmental feedbacks.

#### 3.2.3.i A growth adaptive cycle in the LAC region

A useful way to conceptualize agricultural development in the LAC region is to view it as a growth adaptive cycle, as discussed in Chapter 2. From the conquest period to the 1950s, the region experienced a period of agricultural growth through export-led
development, namely coffee in Latin America and sugarcane in the Caribbean. This was followed by a period of reorganization since the 1950s, during which time many Caribbean countries experienced a regime shift as they focused more heavily on the services sector (Solbrig 2006). Central America developed industrial production alongside an expanding agricultural sector that now focussed heavily on sugarcane production, and most South American nations further developed their agricultural sector by diversifying into new crops and livestock production.

With continual growth in the agricultural sector, the region as a whole has apparently not experienced a “release” period. This may not be the case, however, in the Caribbean where such a process may be currently occurring following the demise of the sugarcane industry since the 1980s. Thus, agricultural resilience in the LAC region was achieved over time by continually adapting and transforming the sector. This prompts two important questions, namely will the region experience further reorganization and will there come a release phase during which the agricultural sector drastically changes? There is no way to predict how the agricultural sector will change, but understanding the impacts of current and past changes is imperative in order to guide development along a more sustainable pathway.

3.2.3.ii Disturbances and feedbacks

If agricultural development continues to expand and intensify in the LAC region, disturbances may eventually destabilize the sector. This concern is central in the UN’s Millennium Development Goals for the LAC region, which highlight various socioeconomic, political, social, and environmental disturbances (United Nations 2005). In socioeconomic terms, globalization drives up the costs of production, decreases commodity prices, marginalizes smallholders, and further contributes to income differentials in the region (Eakin & Lemos 2006; Morton 2007). The political instability of the 1980s destabilized the agricultural sector, but since 1990 new types of political disturbances have emerged in the form of subsidies, taxes, and trade liberalization, which some argue has directly impinged upon the livelihood of farmers (Hecht 2010; Solbrig 2006).

From an environment perspective, land degradation, land desertification, water quality and quantity issues, natural disasters, and climate change all disturb agricultural production by reducing yields, reducing the amount of arable land, destroying crops, and increasing the risk of drought (see, for example, Hillstrom & Hillstrom 2004; Jones & Thornton 2003; UNEP 2007). The fundamental problem in this case is that despite being increasingly
globalized, much of the disturbance regime in the LAC region is the result of negative social and environmental feedbacks (UNEP 2007). Thus, mitigating the potential negative effects of agricultural development on the social-ecological system will support long-term agricultural sustainability in the LAC region. The following section discusses efforts to reverse or reduce the environmental impacts of agricultural development.

3.3 CHANGING THE RESPONSE DIVERSITY IN THE LAC REGION

Despite the ongoing high rates of deforestation and increasing environmental degradation, there is evidence that parts of the LAC region are on course towards a more sustainable pathway of agricultural development. Although environmental and socioeconomic problems persist, promising changes have been made in forest recovery, sustainable agricultural intensification, and within the policy domain.

3.3.1 Forest transitions in the LAC region

Mather (1992) coined the term “forest transitions” to describe the process by which there is a shift from net deforestation to net reforestation. This is not an isolated or rare land change process since 38 percent of countries on Earth experienced an increase in forest cover in the 1990s, thus prompting researchers to examine the social, political, economic, and environmental dimensions of such forest transitions (Barbier et al. 2010; Rudel et al. 2010; Rudel et al. 2005). Research has revealed that forest transitions also occurred throughout the LAC region, notably in the Caribbean (Aide et al. 2013; Clark et al. 2012; Rudel et al. 2000), Ecuador (Rudel et al. 2002), Mexico (Bray & Klepeis 2005; Klooster 2003), Puerto Rico (Rudel et al. 2000), parts of Amazonia (Neeff et al. 2006; Perz & Skole 2003), El Salvador (Hecht et al. 2006; Hecht & Saatchi 2007), and Costa Rica (Kull et al. 2007). However, despite considerable theoretical and case study research in the LAC region, there remains a great deal of uncertainty regarding the exact circumstances that lead to forest transitions.

Globalization is generally acknowledged as a key driver of both deforestation and forest transitions (see, for example, Grau & Aide 2008; Hecht 2010; Liverman & Vilas 2006; Meyfroidt et al. 2013; Meyfroidt & Lambin 2011). Like deforestation, forest transitions are caused by various social, political, economic, and environmental factors. Thus, just as the causes of deforestation are variable and complex, so too are the precise drivers of forest transitions. However, a fundamental commonality underlying both forest clearance and
recovery are changes within the agricultural system. The former is driven primarily by the expansion of the agricultural area, while the latter is associated with a reduction in the agricultural area. This prompts the question of what specifically drives forest transitions?

Building upon Mather’s (1992) view that the State actions can trigger forest transitions, Rudel et al. (2005) identified three relevant circumstances, namely the creation of non-farm jobs that pull farmers off their land, agricultural intensification that permits marginal land to revert back to forest over time, and with declining forest resources in some areas and increasing costs for forest products, forests may be replanted through State or corporate initiatives.

According to Hecht (2010), in the LAC region, these drivers were one consequence of a shift from the Cold War period authoritarian regimes to the new democratic constitutions that emerged in the 1990s. With this change, Hecht and Saatchi (2007) observed a shift from State-led development to market-led development through the adoption of neoliberal policies. Hecht (2010) explained that “neoliberal polices sought to facilitate trade through free trade policies, elimination of tariffs and subsidies, and modifications of banking systems” (Hecht 2010, p.163). Forest transitions were fundamentally a by-product of the political and economic change in the LAC region, such that other types of market-led development (e.g. tourism, maquiladora (manufactured good), NTAEs, remittances) had an observable impact on forest cover. Thus, since each subregion, and indeed each country, exhibited its own unique pathway towards market-led development, forest change is likewise variable within the LAC region, within each subregion, and even within individual nations.

Forest transitions can have several environmental benefits, including improvement of hydrology, reducing erosion, increasing above-ground biomass, and regenerating soil carbon. However, these changes are not guaranteed since they are contingent upon the type of forest transition taking place (e.g. natural forest succession versus tree plantations) and various local environmental conditions (e.g. soil type, remaining forest stands) (Hecht & Saatchi 2007; Meyfroidt & Lambin 2011). In certain environmental contexts, however, forest transitions can have positive effects on the environment by mitigating certain disturbances that effect farm resilience, most notably issues relating land degradation and freshwater contamination. Thus, from an environmental perspective, forest transitions exemplify a potentially positive step taken within the LAC region to reverse deforestation and its associated negative human and environmental consequences.
3.3.2 Sustainable agricultural intensification

Efforts have been underway since the 1980s to adopt more sustainable agricultural practices in the LAC region with the general goals of improving the efficiency of the food system, while reducing its negative environmental and human impacts (Altieri & Toledo 2011). Since numerous social and environmental disturbances were earlier shown to originate from intensification, sustainable agricultural practices seek to mitigate impacts while improving and increasing the efficiency of food production over the long-term (Tilman et al. 2011). In recent decades, two dominant approaches developed to achieve sustainable intensification, namely the modification of conventional agricultural practices and the adoption of agroecological practices.

Conventional agricultural practices drive many environmental and social problems since they favour increasing yields at the expense of environmental services. Modification of conventional agricultural practices is therefore one way to minimize or even reverse the negative impacts of intensification. Tilman et al. (2002) suggested that such impacts can be lessened by increasing nutrient- and water-use efficiency with precision agriculture (PA) methods, substituting agrochemicals for organic inputs, employing integrative pest management, introducing agroforestry into conventional crop systems to reduce erosion, and increasing overall soil fertility though crop rotation, reduced tillage, cover crops, fallow periods, and manuring. It is further suggested that these changes could be implemented by offering cash incentives to farmers who adopt sustainable practices, taxing those who continue to practice unsustainable farming techniques, or through consumer incentives that encourage the purchase of sustainably-produced agricultural goods.

In the LAC region, non-government organizations have contributed greatly to reducing the impact of intensification on both the environment and farming communities, but, in resilience terminology, such changes merely modify the existing system state rather than causing a regime shift. Conversely, others have suggested that the modification of conventional agriculture fails to achieve sustainable intensification since it maintains farmers’ dependence upon external sources of knowledge, technology, energy, and markets (Altieri & Toledo 2011). Thus, another option for farmers in the LAC region has been a regime shift in the food system through the adoption of agroecological practices.

Agroecology is a practice and a movement that is the basis of many sustainable agricultural systems in the LAC region, since it offers new responses to farm disturbances
(Gliessman 2013; Horlings & Marsden 2011). Agroecology emphasises smallholder food, technological, and energy sovereignty that is achieved by optimizing productivity through low external inputs, diversification, recycling of farm nutrients, integration of crop and livestock production, and community-oriented approaches and empowerment (Altieri & Toledo 2011). In the present era, agroecology is seen as the basis of a food system transformation that includes changes to both social and natural processes (Gliessman 2013; Tomich et al. 2011). Altieri and Toledo (2011) explain further that “[t]he key idea of agroecology is to go beyond alternative farming practices and to develop agroecosystems with minimal dependence on high agrochemical and energy inputs” (Altieri & Toledo 2011, p.588). Although agroecology is the complete opposite of the conventional agricultural practices that spurred global agricultural development since the 1960s, it has made significant progress in the LAC region.

Latin American smallholders, who number over 65 million, play an integral role in the region’s food security because they control between 30 and 70 percent of the agricultural land (Tscharntke et al. 2012). In addition to being the primary producers of domestic staples such as maize, beans, and rice, smallholders also demonstrate a higher level of resilience than other, larger farmers, especially in the face of natural disturbances like hurricanes and soil erosion (see, for example, Altieri & Toledo 2011). Citing examples of agroecological programs in Cuba, Brazil, Central America, the Andes, and Mexico, Altieri and Toledo (2011) conclude that some rural areas in Latin America are actually experiencing a “re-peasantization” that is based largely on the resistance to conventional agriculture and neoliberal policies. Through such resistance, smallholders in the LAC region have strengthened their resilience through food, technological, and energetic sovereignty, and, consequently, they have achieved higher yields in some areas than industrial agricultural operations (Altieri & Toledo 2011).

Thus, agroecological movements exemplify one way in which the response diversity of farms has been modified to help decrease the number of feedbacks into the disturbance regime. Furthermore, unlike the modification of conventional agriculture, that seeks to change from above through subsidies, taxes, or consumer incentives, agroecology exemplifies a bottom-up strategy that empowers local farming communities directly. Hence, agroecology is, essentially, a regime shift in the food production system that transforms farm systems into a new stability domain.
3.3.3 PES and REDD+ in the LAC region

Tropical forests provide a range of environmental services (ES), especially carbon sequestration and storage, biodiversity protection, watershed protection, and landscape beauty (Wunder 2005). Since the 1990s, payments for environmental services (PES) have gained increasing popularity as an effective way to help conserve tropical forests that would otherwise be converted to agriculture (for a review, see Wunder et al. 2008). The Center for International Forest Research (CIFOR) formally defines PES as:

“(1) a voluntary transaction where (2) a well-defined ES (or a land-use likely to secure that service) (3) is being ‘bought’ by a (minimum one) ES buyer (4) from a (minimum one) ES provider (5) if and only if the ES provider secures ES provision (conditionality)” (Wunder 2005, p.3).

PES programs vary considerably, especially between developed and developing countries (Wunder et al. 2008). Although debate exists regarding the efficacy of PES programs (Pattanayak et al. 2010), they have nonetheless spread throughout the LAC region and have been shown to produce positive impacts on the livelihoods of rural farmers.

The Pago por servicos ambientales (PSA) program in Costa Rica is a globally-recognized and widely-studied example of a PES initiative (Locatelli et al. 2013; Pagiola 2008; Pattanayak et al. 2010). Despite once having one of the world’s highest deforestation rates, Costa Rica has experienced a net increase in forest cover since 2000 (FAOSTAT 2014). Although many factors have contributed to the ongoing forest transition, the PSA program likely had positive effects by paying landowners directly to establish timber plantations and/or conserve forested areas (Pagiola 2008). Indeed, Pagiola (2008) estimates that in 2005 there were upwards of 270,000 participants in the program and as much as 10% of Costa Rica’s forested areas were protected.

However, the success of the PSA program in protecting ES is debatable, notably since it is difficult to measure the status of ES and according to Pattanayak et al. (2010) existing attempts to achieve this lack scientific rigour. Nonetheless, the widespread and enthusiastic participation in the program has demonstrated a willingness amongst rural Latin American farmers to adopt this response to farm disturbances, especially when there are financial incentives for them. Further, from a socioeconomic perspective, Wunder et al. (2008) observed that such programs also benefit developing nations by helping to alleviate the rural poverty that exists throughout the LAC region. The task remains to learn from these local, subnational PES programs in order to develop effective national-level programs.
The Reducing Emissions from Deforestation and Forest Degradation (REDD+) policy initiative is one attempt to develop a national-scale PES program by altering decision-making at the farm level through economic incentives (for a recent review, see Agrawal et al. 2011). The program has become a global initiative since it was first conceived by the Coalition for Rainforest Nations in 2005 as a way to offer economic incentives to developing countries for reducing greenhouse gas (GHG) emissions. REDD+ programs currently focus on five main activities, namely the reduction of emission from deforestation, the reduction of emission from forest degradation, conservation of forest carbon stocks, sustainable management of forests, and the enhancement of forest carbon stocks (Scriven & Malhi 2012). These activities are implemented through a three phase process that begins with a period of capacity building, during which time strategies and policies are developed. This is followed by a second phase when policies are piloted and a third phase during which time the policy-derived benefits are measured and verified (Agrawal et al. 2011). Despite sometimes harsh criticism for this program in recent years (for a review, see Brown 2013), the REDD+ policy initiative has achieved important footholds in the LAC region (see, for example, Kaimowitz 2008; Pacheco et al. 2010; Scriven & Malhi 2012).

Since the REDD+ initiative is still quite new, most developing countries are still within the first phase of development. For example, Kaimowitz (2008) reviewed the potentials for REDD in Central America and suggested that several developments in the subregion are in line with the policy initiative. Specifically, capacity building (phase 1) for REDD+ in Central America would be expedited due to the pre-existence of environmental institutions and laws that prevent forest degradation and deforestation. In addition, various other sustainable developments in the LAC region would support REDD+, such as the existence of vast protected areas (estimated at around 50 percent of the forested area in 2006), experience with community and indigenous forest management, experience developing sustainable forest products, experience and innovation in the area of PES development (e.g. Costa Rica), and macroeconomic and agricultural policies that attempt to limit deforestation. However, Kaimowitz (2008) adds that the implementation of REDD+ policies in the LAC region would require strengthening of natural resource monitoring and law enforcement. Hence, the REDD+ initiatives in the LAC region are still developing, but as it is conceptualized, the existing policy and institutional framework has the capacity to provide farmers with alternative responses to disturbances.

In summary, although the land change history of the LAC region presents contrasting
trends and some internal variability, the general picture is one of agricultural expansion at
the expense of tropical forests and environmental services. Though deforestation rates have
fluctuated within the LAC region due to a variety of environmental and socioeconomic
factors, forest conservation and agricultural development remains a central policy issue for
the region as a whole. Fortunately, forest transitions exist in the region that may relate to
changes in agricultural strategies that rely less on expansion and more on intensification.
However, whether or not such intensification is sustainable remains speculative.

By promoting a reduction in the use of conventional agricultural techniques and
encouraging the adoption of agroecological practices, it is hoped that the LAC region will
move towards a more sustainable pathway. To support these efforts, PES and international
programs such as REDD+ may provide much needed support to help compensate rural
landowners for preserving invaluable environmental services. To examine further the
interrelated themes of agricultural development, intensification, deforestation, and
conservation in the LAC region, the next section examines the specific land change history
of Belize and the role of farm resilience in this Central American country.

3.4 HISTORY OF LAND CHANGE IN BELIZE

As in the rest of the LAC region, the history of land change in Belize is closely tied to
the processes of agricultural expansion and change, especially since the Green Revolution of
the 1960s. The following will discuss the history of agricultural development, and then
consider the relationship between farm resilience and land change.

3.4.1 History of land change since the colonial period

Belize is a former British colony with a land area measuring about 22,966 square
kilometres, located on the western coast of the Yucatan peninsula in Central America
(Figure 3.1). Due to its geographical location and its ethnic diversity, Belize identifies as
Central American, Caribbean, and, more broadly, Latin American (Woods et al. 1997). The
country shares its neotropical environment and climate with its closest neighbours in Central
America, but having 385 km of coastline on the Caribbean sea and possessing the second
longest barrier reef in the world (~700 sqkm), Belize is also very much part of the
Caribbean (Day 2003). Historically, Belize shares a common early history with Central
America that dates from the earliest human occupation of the area some 10,000 years ago
through the ancient Maya period (Sharer & Traxler 2005). Also, as a former British colony,
Belize shares many political and economic ties with Caribbean nations, and has had formal relationships via such economic organizations as the Caribbean Community (CARICOM) since 1974. The country's cultural, economic, political and social ties to both the Caribbean and Central America have played significant roles in its economic and agricultural development.

![Map of Central America showing the location of Belize.](image)

The modern history of land change in Belize dates to the colonial period. In 1638, a crew of Baymen, mainly British pirates and buccaneers evading the Spanish, were shipwrecked along the coast of Belize. The Baymen began a lucrative export business focused on forest products, namely logwood and mahogany. The Spanish, who saw a British presence as a threat to their regional economic interests, launched attacks on the fledgling settlement throughout the 1700s. By 1763, the Treaty of Paris ended the hostilities and in 1786 the Convention of London recognized British rights to forest exports and disallowed agricultural development in the area. Forests exports continued though the 19th Century, but by the 1860s world prices for mahogany and logwood fell, and Central American nations,
including Belize, began to diversify through agricultural development (Foster 2007). It was at this time, in 1871, that British Honduras was declared a British crown colony and efforts were then made to develop an export agricultural sector. By the 1950s, the timber industry was almost completely replaced by export agriculture.

Land change in Belize since the 1950s relates closely to political developments. By 1963, British Honduras had self-government, in 1971 the capital was moved from Belize City to Belmopan, and in 1973 the colony's name was officially changed to Belize. The movement for independence from Britain, which began in the 1950s alongside the other British colonies in the Caribbean, came to fruition in 1981 when Belize achieved nationhood and joined the Commonwealth and the United Nations. The road to independence strengthened agricultural development by creating a new constitution and new institutions that governed economic development and environmental management.

Since the 1960s, Belize developed and expanded its agricultural sector through exports, staple agricultural crop production, and livestock production with the explicit aim to provide adequate food for the nation and to support and expand export-led development (Day 2003; IICA 1995). By the 1970s, agriculture represented about a quarter of the GDP, and this trend continued through 2007 (Martin & Manzano 2010). Although considerable growth has occurred in the services sector in recent years, especially the tourism industry, the agricultural sector continues to play an important economic role as the largest employer in the country. However, despite sustained growth over the past three decades, only about 9.7% of potential arable land was being used for agriculture in 2010, implying that there is considerable room for growth within the sector. The next section further examines changes in the agricultural sector, as evidenced by changes in agricultural production.

3.4.2 Agricultural production since 1960

Since the 1960s, the agriculture sector in Belize grew mainly through the production of livestock, domestic staples, and export crops. The following discussion briefly reviews production changes in each of these sub-sectors.

3.4.2.i Domestic staples

Rice, red kidney beans, and maize are the main crops produced for domestic consumption, alongside a range of seasonal fruits and vegetables. Nationally, FAOSTAT (2014) reported that production of rice, beans, and maize increased by almost 700 percent since the 1960s. As in the rest of the LAC region, production increases were achieved
through intensification, as evidenced by yield per hectare increases, and expansion, as evidenced by changes in the area harvested (both strategies were discussed in Section 3.3). The fivefold increase in bean production, for example, was achieved principally by expanding the area harvested, whereas rice and maize both increased production by around 700 percent by both intensifying and expanding production. By 2010, Belize produced nearly 21 tonnes of beans, 186 tonnes of maize, and 66 tonnes of rice per capita (FAOSTAT 2014), an increase that has helped to ensure domestic food security.

3.4.2.ii Export crops

Export crop production of bananas, citrus fruit, and sugarcane has sustained the growth of the agricultural sector in Belize. Indeed, a recent policy report observed that:

...agricultural exports in Belize have provided an outlet for production above and beyond the needs of the domestic market and thus have sustained growth and enabled the sector to expand more rapidly than agricultural production for the domestic market alone would have (Martin & Manzano 2010, pp.109–110).

By 2008, sugarcane, bananas, and citrus represented almost 44 percent of the total agricultural output (Ramírez et al. 2013). However, as a result of landscape variability between the north and south parts of the country, export agricultural production is highly localized, such that bananas are produced primarily in the south, citrus fruits are produced in the central and southern regions, and sugarcane is produced primarily in the north (Cherrington et al. 2010; Day 2003). Production has increased for each of these primary export crops, though not entirely in the same way.

Sugarcane is a smallholder crop that is produced on over 26,000 hectares by about 5,300 farmers in northern Belize (IICA 1995). Mestizo Belizeans began sugarcane production as early as 1848 in Northern Belize, but industrial production only expanded in the 1950s and 1960s. By 1964, northern sugarcane farmers delivered cane to one of two processing facilities, namely the La Liberdad mill in Corozal or the mill in Tower Hill, Orange Walk Town. Since the 1997 closing of the Corozal factory, the Tower Hill factory has processed all sugarcane from the two northern districts. Annual production increased from the 1960s to the 2000s by an average of 179 percent, though yield per hectare actually declined during this period by an overall average of 9 percent. Thus, the total production increase is attributed to an increase in the harvested area, which doubled to 26,000 hectares and covers about 4 percent of the Orange Walk and Corozal districts.

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1 Based on personal communication with representatives at the Belize Sugar Cane Farmers Association in Orange Walk Town, getting accurate measurements for the sugarcane harvest area is problematic.
The other major export crops, bananas and citrus fruit, increased production during this period, specifically by increasing both yields per hectare and harvest area. Banana production increased by 1628 percent since 1960, while citrus production increased fivefold through expansion and intensification (FAOSTAT 2014). By 2010, the three crops were grown on almost 50,000 hectares of land, representing 30 percent of the total agricultural area of the country (FAOSTAT 2014). However, since 2000, the three export crops declined while crude oil exports have more than doubled since 2006 to 36.5 percent (Ramírez et al. 2013). Hence, agricultural export production has increased significantly since the 1960s, but recent declines may be related to growth in other agricultural sub-sectors. One growing sub-sector in Belize is livestock production.

3.4.2.iii Livestock production

Livestock production, including cattle, pork, and poultry, is the most rapidly growing agricultural sub-sector since 1980 (IICA 1995). By 2008, livestock represented almost 25 percent of total agricultural outputs (Ramírez et al. 2013). Production ranges from smallholders keeping a single cow or pig and a few chickens, to industrial operations with thousands of head of cattle. The three major animal products, namely cattle, chicken, and pigs, increased production considerably in Belize from 1961 to 2010. The national cattle stock grew from about 30,000 head in the 1960s to almost 70,000 head in the 2000s, representing a 127 percent increase. Indigenous cattle meat production likewise increased by 237 percent. Pork production increased by only 52 percent, but chicken meat, a staple in the country, increased by almost 3000 percent.

To support the growing national stock, farmers increased the pasture area to 119,000 acres by the mid-2000s and expanded cropland to grow supplemental feed (Richardson 2009). Despite the growth in the livestock sub-sector, it still only supports the domestic meat market because food safety and trade regulations prevents Belizeans from legally exporting animals or animal products to the neighbouring Mexican and Guatemalan markets. However, with a rapidly growing population in Belize, it is likely that the meat industry will continue to grow even if it only supports the domestic market.

In summary, overall growth in the Belizean agricultural sector since the 1960s was achieved through domestic and export crop production and by expanding the livestock sub-sector. Through such productivity increases, Belizean farmers have demonstrated resilience to many of the same economic, political, social, and environmental disturbances faced by
other farmers in the LAC region.

The following section examines the current state of knowledge regarding Belizean farm resilience. This is accomplished by reviewing what is known about environmental and social disturbances, how farmers respond to these disturbances, and how such responses feed back into the disturbance regime. Due to a lack of research in Belize, much the following relies on governmental and non-governmental reports and publications.

3.5 FARM RESILIENCE IN BELIZE

As noted in the previous sections, farm resilience in Belize likely contributed much to the increased production of both domestic and export crops and livestock since the 1960s. The following subsections discuss Belizean farm resilience based on the framework shown in Figure 2.2 by reviewing the disturbance regime, the response diversity, and how responses can feed back into the disturbance regime.

3.5.1 Farm systems in Belize

Farm systems in Belize vary from low-input milpa (i.e. subsistence farming through slash-and-burn) systems to fully industrialized farms. The largest group of farmers in the country are smallholders, defined as “rural producers, predominantly in developing countries, who farm using mainly family labor and for whom the farm provides the principal source of income” (Morton 2007, p.19680). Indeed, of the estimated 11,000 farmers in Belize, 75 percent farm on less than 10 acres (Richardson 2009). These smallholders are the primary maize, bean, rice, and sugarcane producers, thus they support both domestic food security and also contribute to the export agriculture sub-sector. However, several categories of farmers exist in Belize.

King et al. (1992), who surveyed land and agricultural systems in Belize, observed and defined several types of farming systems. The most prominent include estates, family farms, mechanized family farms, and milpa systems. At the smallest scale are the milpa farmers, the smallholders who produce subsistence crops and sugarcane. Family farms generally produce the same crops as milpa farmers but do so on larger areas (although still <20 hectares). Some family farms have become mechanized over the years, particularly in the Mennonite areas (see Section 3.5.1.i), and currently produce both livestock and crops on larger areas of land. The largest farms, termed estates by King et al. (1992), are larger than 400 hectares and produce export crops and/or livestock on an industrial scale.
King et al.'s (1992) farm classification is based primarily on farm area, the primary type of agricultural production, and the level of mechanization. Hence, this farm classification fails to acknowledge a wider range of household and farm practice variables that have a demonstrable contribution to a farm's identity. Also, the classification places 75 percent of Belizean farmers into two categories, family farms and *milpa* systems. A better classification scheme is therefore required. An important starting point is to understand the history and agricultural traditions of the two main ethnic groups within the agricultural sector, the Mennonites and the Maya-Mestizos, the majority of whom are smallholders, but with quite different farm identities, as defined by their agricultural practices and traditions.

### 3.5.1.i Mennonite smallholders

The Mennonites are an Anabaptist Christian group of European decent who have established agricultural colonies throughout the Americas since the late 19th Century. They colonized parts of Belize in 1957. At this time, British Honduras officials signed an agreement with representatives of the Reinland Mennonite Church of Chihuahua and Durango, Mexico, which granted land and religious freedom for their community (Everitt 1983; Roessingh 2007). In exchange, the Mennonites were obligated to “produce food not only for themselves but for local consumption and for the export market” (Sawatzky 1971, p.335). Shortly after the agreement was ratified, three groups moved and established three separate communities, namely Blue Creek and Shipyard in the Orange Walk District, and Spanish Lookout in the Cayo District (Sawatzky 1971). These Mennonites were the descendants of those who had fled southern Russia in the 1870s first to Canada, fled Canada to Mexico during the second World War, and then ultimately, in the 1950s, left Mexico for Belize, where they currently reside.

Since the initial colonization, the Belizean Mennonites have contributed greatly to agricultural development as the chief producers of maize, beans, sorghum, and livestock (IICA 1995). Despite comprising less than 10 percent of the population, the Mennonite communities have achieved prominence in the agricultural sector through the early adoption of several agricultural innovations, notably tillage implements, irrigation, and the use of agrochemicals. Today, Mennonite farms exemplify a diversity of activities that include both livestock and crop production. Thus, their presence in Belize has contributed greatly to the observed increases in agricultural production since the 1960s, yet their farm systems differ greatly from the neighbouring Maya-Mestizo communities.
3.5.1.ii Maya-Mestizo smallholders

Through natural population growth and immigration from surrounding countries, the Maya-Mestizo population in Belize has grown considerably since the 1960s. Thousands of Maya and Mestizo refugees arrived in Belize from the 1960s through the 1990s escaping civil unrest in neighbouring Guatemala (Everitt 1984). Similarly, refugees fled to Belize from El Salvador during the civil war in that country that lasted from 1980 to 1992. Today, people of Maya and Mestizo decent (the latter group are also referred to as “Hispanic”) combine to represent almost 60 percent of the Belize population, according the 2010 national population census.

Upon their arrival in Belize, many immigrants turned to agriculture as a source of income and household food security. Over time the traditional milpa agricultural system was gradually replaced with more intensive techniques that increasingly relied on external sources of inputs (e.g. fertilizer, pesticides). Today, Maya-Mestizo farmers are prominent producers of domestic staples, namely maize, rice, beans, and vegetables, but they very rarely produce livestock for anything more than household consumption. Hence, there are upwards of 5000 Maya-Mestizo farmers who grow sugarcane in Northern Belize, and this practice is reserved only for this group (i.e. Mennonites are not permitted to farm sugarcane) (IICA 1995). Consequently, by focusing more on both domestic and export agricultural products and less on livestock production, the land use practices of the Maya-Mestizo farmers differ from Mennonite farming systems. How exactly they differ and how these differences relate to farm resilience and the environmental impact of agricultural development has yet to be investigated.

3.5.2 Environmental disturbances

Farmers in Belize face the same environmental disturbances that are endemic to the rest of the neotropics, namely erratic and unpredictable precipitation patterns, a pronounced and temporally variable wet and dry season, high average temperatures, exposure to a large and diverse pest complex, and diseases that attack crops and livestock. To compound these factors, Belize's geographic location and geology intensify some environmental disturbances, such as the disturbances associated with land suitability and those that relate to the effects of climate change. The following discussion reviews these acute environmental disturbances.
3.5.2.i Land suitability and degradation

Land suitability is a primary source of farm disturbance in Belize since it places direct limitations on agricultural production. Belize is divided between two physiographic regions that include the highlands of the Maya Mountains and the northern lowlands. The latter is the area most suitable for agricultural production (Day 2003). The lowlands are a karst environment dominated by Cretaceous and some younger limestone that produce a variety of soil types of varying quality (Day 2003). Despite this soil variability, an ecosystem assessment determined that almost 80 percent of Belize's land area is some form of natural ecosystem, be it forest, wetland, savanna, or water (not including the ocean) (Meerman & Sabido 2001). Consequently, due to the geological, ecological, topographic, and soil variability within Belize, the agricultural area lacks productive uniformity (King et al. 1992; Day 2003). In other words, the production of some crops may be limited to specific regions, while yields within these regions may also vary.

The relationship between agricultural production and land systems was investigated by King et al. (1992) in Belize. Based closely on the FAO land suitability framework (FAO 1981), their approach classified land based on the pattern of landforms, soils, and vegetation. The assessment defined 76 distinct land systems, each of which has up to seven sub-units (i.e. sub-types within the larger land system groups). This results in hundreds of distinct land units each with its unique agricultural suitability defined along a continuum from highly suitable, to marginal, to permanently not suitable. For example, there were 31 land systems in the Orange Walk District alone, each of which ranges in area from 10 to 103,326 hectares.

Land systems in Orange Walk are dominated by flat, undulating plains that were formerly broadleaf forests. These areas were considered marginally suitable for agriculture since they possessed numerous limiting factors including workability issues (e.g. clay soil), nutrient deficiency, limited root room due to shallow soils, and drainage constraints. King et al. (1992) further determined that the agricultural area could expand into areas in Belize deemed unsuitable for agricultural production. This conclusion was repeated in a more recent government report that cited expansion and unsustainable agricultural practices as the chief contributors to land degradation (Meerman & Cherrington 2005). Thus, expanding into unsuitable areas could potentially raise input costs, decrease yields, and/or increase the rate of land degradation, all of which significantly disturb smallholder livelihoods.
3.5.2.ii Climate change and hurricanes

Global climate change is unequivocal. According to a recent IPCC (2013) report which presents empirical evidence of climate change symptoms, scientists have documented the warming of the atmosphere and oceans, less snow and ice, the rise in sea levels, and higher concentrations of greenhouse gases in the atmosphere. Although the precise impacts and severity of these climate change symptoms is complex and remains the focus of considerable debate among scholars and politicians, it is clear that it can have many negative impacts on tropical agricultural production, particularly for smallholders (Altieri & Nicholls 2013). For example, in some areas climate change can cause lower yields, crop damage, soil erosion, an inability to cultivate on saturated land, heat stress to crops, fires, more frequent insect infestation, land degradation, crop failure, and a loss of livestock (Ramírez et al. 2013). These potential impacts are of great concern for developing countries where the economy and food security often depends more on the productivity of the local agricultural sector than in developed countries. One problem, however, is that the impacts of climate change are currently and will certainly be felt quite differently around the world. Thus, it is necessary to understand local-scale case studies to assess the impacts of climate change.

The local impact of climate change in Belize was investigated in two recent reports. The United Nations Development Programme (UNDP) investigated the costs of climate change on various sectors of the economy in Belize, including the agricultural sector (Richardson 2009). This report explained that climate change in Belize is characterized by warmer temperatures (2-3°C increase), less precipitation, water salination, and exposure to more frequent and severe meteorological events (e.g. droughts, floods, forest fires). All of these factors have the potential to alter agricultural productivity and the length and quality of the growing seasons.

Climate change may also pose serious human health consequences, such as increasing malnutrition and increasing the rates of tropical diseases, such as malaria and dengue fever. Although Richardson (2009) acknowledged that the impact on agriculture and smallholder communities will likely be localized and variable, such that some areas will experience declines while others experience increases in productivity, he acknowledged that “small holders and subsistence farmers are expected to be relatively more vulnerable to negative impacts” (Richardson 2009, p.20). Further, citing a previous study by Green (2007) that examined crop-specific vulnerability to different climate change scenarios, Richardson
(2009) stated that staple products and the main exports of sugarcane and bananas are among the crops that may be most severely impacted by climate change. Since there are an estimated 11,000 farmers who depend on these crops for their livelihoods, the report concluded that climate change represents a significant threat to the sustainability of the agricultural sector and the economy that it supports.

A more recent report, published by the Economic Commission for Latin America and the Caribbean (ECLAC), further evaluated the projected economic impact of climate change on Belize's agricultural sector (Ramírez et al. 2013). This report echoed many of Richardson's (2009) conclusions regarding the potential negative impacts of climate change on the local agricultural sector, especially since it is dominated by smallholders who practice rain-fed agriculture. The report predicts that under a business-as-usual scenario there could be a 6 to 20 percent economic decline from the 2007 GDP. This prediction was based on the idea that future climate change will impact a variety of social and environmental factors, notably “production, infrastructure, ways of life, health and safety of the population, and it will also weaken the environment’s capacity to provide vital resources and services” (Ramírez et al. 2013, p.5). Due in part to the organization of Belize’s agricultural sector and its geographic location on the Caribbean coast, where it regularly faces tropical storms, the report noted, using a climate risk index, that Belize faces the highest risk of GDP loss due to climate change among all Central American countries. However, the report also acknowledges that Belizean farmers have the ability to respond to climate change by adjusting planting dates, adjusting crop varieties, relocating crops to more productive and resilient areas, enhancing erosion control, and reducing risk through crop insurance. Consequently, managing climate change symptoms in Belize will require continual adaptation and transformation within the agricultural sector. Thus, farm resilience will play a vital role in the process of climate change mitigation.

One of the most visible impacts of climate change in Belize, according to Ramírez et al. (2013), is the potential for higher frequency and more intense of tropical storms during the hurricane season, which typically lasts from June to December. Tropical storms have struck Belize for at least 7,000 years, according to paleohurricane data (see, for example, McCloskey & Liu 2013), but recent events are particularly devastating to contemporary agriculture and its large monocultural plantations. Since 1930, 16 hurricanes have struck Belize, including eight major hurricanes. Barker (2012) observed that these storms inflict serious damage in the Caribbean and Central America because, in addition to the human
cost and property damage, they can also wipe out entire agricultural sectors in multiple countries. In the forty years from 1967 to 2006, the Atlantic basin averaged 11 named storms, 6 hurricanes, and 2 major storms per year (Brennan et al. 2009), and this figure may rise even further as a result of climate change (Ramírez et al. 2013).

Hurricane Dean was one of the most severe hurricanes in recent history to strike Belize directly. It made landfall along the northern Belize-Mexico border as a Category 5 storm in 2007, the first such storm for 15 years since Hurricane Andrew in 1992. The storm was responsible for 32 deaths and almost two billion dollars in property damage throughout Central America and the Caribbean. It also severely impacted the agricultural sector in the surrounding region (Franklin 2008). News reports cited the destruction of crops in Jamaica, Dominica, St. Lucia, Martinique and Guadeloupe, and Belize (see, for example, Wilkinson 2007).

The hardest hit areas, such as Dominica's banana industry, lost up to 99.9 percent of crops (Wilkinson 2007). The Government of Belize (GoB) estimated that the storm caused $100 million (USD) damage in Belize alone. In addition to making 2000 people homeless by destroying 1500 houses and causing millions in property damage, the storm also destroyed the entire papaya crop in northern Belize worth $20 million (USD), caused $1.2 million in damage to sugarcane crops, and thereby severely affected the livelihood of smallholders (Anonymous 2007). Since countries in the LAC region rely heavily on international aide for recovery, hurricane events often result in increased debt and slower economic growth (Fraser 2013; Wilkinson 2007). Thus, by severely impacting the agricultural sector, tropical storms like Hurricane Dean devastated the agricultural sector in multiple countries, and with increased frequency hurricanes represent a source of significant disturbance to Belizean farmers.

### 3.5.3 Anthropogenic disturbances

Farmers in Belize will also likely face a number of anthropogenic disturbances in the future. According to two recent policy assessments for the country by Ramírez et al. (2013) and Martin and Manzano (2010), the most acute disturbances in the agricultural sector relate to infrastructure deficiencies, economic issues, rural poverty, and social conflict/disputes. Although all farmers are, of course, not vulnerable to each type of disturbance, these issues are the most prominent within rural areas of the country. The following sections discuss each of these disturbances in turn.
3.5.3.i **Infrastructure deficiencies**

According to Martin and Manzano (2010), infrastructure deficiencies represent a significant problem within the agricultural sector. In particular, a lack of crop storage and drying facilities, cold chain facilities, high port costs in Belize City, and an almost total lack of irrigation with only about 2 percent of cropland irrigated all pose significant challenges to the agriculture sector. However, chief among the infrastructure deficiencies that impacts the agricultural sector is the road network.

Although many improvements have been made to Belize's road network in recent years, by 2007 only about 20 percent of the 3281 km of roads were paved, while 59 percent were unpaved rural roads that are not usable all year around. According to Martin and Manzano (2010, p.80), these unreliable roads are predominant in agricultural areas where they constrain economic development and limit competitiveness by raising the overall costs of production. Many of the infrastructural problems that impact on agriculture stem from a lack of fiscal support from the GoB.

3.5.3.ii **Economic disturbances**

Farmers in Belize are potentially vulnerable to numerous economic disturbances. As previously explained, the dependence on a limited number of export products, namely sugarcane, citrus, and bananas, exposes export crop producers to fluctuating foreign markets and makes their livelihood subject to trade agreements (Ramirez et al. 2013). The economic disturbances associated with this lack of export diversification is further exacerbated by a number of domestic economic disturbances, namely high interest rates, a lack of investment in agriculture, fiscal policies that do not favour agricultural development, and price controls.

Martin and Manzano (2010) and Ramirez et al. (2013) agree that access to capital is a major farm disturbance because the total annual cost of loans ranges from 15 to 20 percent, banks are not located near agricultural areas, and there is little incentive to invest in agriculture, as demonstrated by the fact that only 9 percent of loans were allocated to the agriculture sector between 2004 and 2008. It is uncertain whether or how this situation has changed since 2008. Further, the government only dedicates one percent of its fiscal expenditures to the agricultural sector, and further imposes price controls that favour consumers rather than producers for agricultural products such as sugar, rice, flour, bread, and red kidney beans (Martin & Manzano 2010). Consequently, whether farmers produce domestic or export agricultural goods, they may be vulnerable to numerous economic
disturbances that originate at either the international or national scale.

3.5.3.iii Rural poverty and population growth

Belize, like much of the LAC region, suffers from a high level of poverty, and this too has a severe impact on the agricultural sector. In 2009, 33 percent of households and 43 percent of the population were considered poor, most of whom reside in rural, agricultural areas (Martin & Manzano 2010, p.117). Poverty has many negative impacts on the agricultural sector. It can limit access to capital (see, for example, Avila 2010) or it can indirectly compound other social problems, notably a high incidence of communicable diseases such as malaria, dengue fever, and HIV/AIDS, noncommunicable diseases such as diabetes and heart conditions, and conditions such as malnutrition and stunting of normal growth (Martin & Manzano 2010, p.203). Hence, the research of Martin and Manzano (2010) in Belize highlights the widely known link between health, economic development, and poverty.

Demographic change in Belize also contributes to the observed high rate of poverty. Belize is the least populated country in Central America, though the total population grew by 117% from 1980 to 2010 (Table 3.1). By 2010, the total population was about 312,000, with 52 percent living in urban areas and 48 percent in the rural areas. However, unlike the rest of the LAC region which saw its rural populations shrink since the 1960s, the rural population actually doubled in Belize at an annual rate of 3.5 percent from 1980 to 2010. However, an increasingly smaller proportion of the rural population is engaged in agricultural activities. FAOSTAT (2014) report that only half of the rural population was engaged in agricultural activities in 2010, as compared to 77 percent in 1980. Hence, as the rural population has grown, individuals are apparently less likely to participate in agricultural activities and are therefore more likely to be unemployed, since very few other industries exist in rural areas. This trend likely contributes to the high incidence of poverty in agricultural areas since marginalized farmers are forced to seek other livelihoods. This trend is likewise observed for the LAC region as a whole.

3.5.3.iv Social conflict

Social conflict also impacts farmers in Belize, and this is especially true for smallholders. In the 1990s, a land rights conflict between the GoB and Mopan Maya smallholders arose in the Toledo District when the government granted logging concessions near their reserve (for a review, see Anaya 1998; Campbell & Anaya 2008; Steinberg 1998).
These concessions threatened the smallholders' ability to farm, hunt, and gather non-timber products in their traditional homeland. Another example concerns social conflict relating to smallholders who grow for the export market. For example, labour disputes occurred among citrus fruit growers in Stan Creek District (see, for example, Moberg 1990), and sugarcane growers in northern Belize (Escalante 2010). Both situations entailed conflict between the interests of small growers versus large, multinational processing companies. These examples suggest that land rights and labour disputes have had a direct impact on farm systems in Belize. The following section advances this discussion by considering how farmers have responded to the anthropogenic and environmental disturbances discussed in this section.

<table>
<thead>
<tr>
<th>Population (000s)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>73</td>
</tr>
<tr>
<td>Urban</td>
<td>71</td>
</tr>
<tr>
<td>Total</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 3.1: Demographic changes in Belize from 1980 to 2010. Source: FAOSTAT. 2014

### 3.5.4 Response diversity

With the continued growth in the Belize agriculture sector discussed earlier, smallholders have demonstrated resilience to the many environmental and anthropogenic disturbances that have been identified. As discussed in Chapter 2, farm resilience is achieved by adapting and transforming the properties and elements of individual farm systems as a response to disturbances. Two primary responses are the expansion of the agricultural area and/or the modification of agricultural practices. The latter commonly involves intensification through the adoption new technology (e.g. agrochemicals, tillage, irrigation), but may also involve more sustainable intensification strategies (e.g. agoecology). Responses in Belize, as in most other countries, can also come from the top-down via policy interventions and government institutions. Further, other responses may also exist at the farm-level, such as income diversification, rural-to-urban migration, and remittances from family members who work abroad (e.g. USA). The current state of knowledge regarding these various responses in Belize is limited. Hence, the following discussion reviews current knowledge and identifies the opportunities for further investigation.
3.5.4.i Policy and institutional responses

It is important to recognize that farmers in Belize, both smallholders or industrial farms alike, receive support through international and domestic policy interventions to address specific agricultural disturbances. Several programs have been established by the international community to support Belize's agricultural sector and its farmers. For example, international economic support has been received from the European Union (EU), the United Nations Development Programme (UNDP), and the Food and Agricultural Organization of the United Nations (FAO). This international support has enhanced export production as well as rural development through the EU's Belize Rural Development Programme and the Agriculture Enterprise Development Project. Further, several government and non-governmental organizations operate programs in Belize to support agricultural development. These include the Inter-American Institute for Cooperation on Agriculture (IICA), Geo-Environmental and Resources Research Center (CIGAR), the United States Agency for International Development (USAID) and other organizations. Although this international support has played an important role in agricultural development, according to Martin and Manzano (2010), national level policies and institutions play an equally important role.

The main source of government-based, front-line support for farmers is through the Belize Agricultural Health Authority (BAHA) that was established in 2000. BAHA manages quarantine and laboratory analysis, monitors agricultural production and food safety issues, and provides veterinary services for the livestock industry. Martin and Manzano (2010) cite that BAHA suffers from inadequate funding and other problems that limit its capabilities. For specific agricultural products (including both crops and livestock), associations exist to help manage production, logistics, processing, and marketing operations. For example, the Belize Sugarcane Growers Association provides extensive logistical and financial support that includes pest management, research, laboratory analysis, marketing, and discounted or free agrochemicals.

All government-based agricultural organizations work closely with the Ministry of Natural Resources and the Environment (MNRE) and the Ministry of Agriculture (MoA) to pursue a balance between economic development and conservation. Thus, farmers have a substantial support network that includes the government of Belize and local growers' associations, and they can often draw additional support from programs established by international organizations. The effectiveness of these policies and institutions to address
disturbances is difficult to quantify. Hence, data on deforestation and agricultural change must be relied upon as more direct indicators of farm resilience.

3.5.4.ii Deforestation

Deforestation is the primary response by farmers in the tropics to a variety of disturbances, such as declining productivity, a need or desire to increase production, the creation of new farms, or market stimulation may influence farmers to clear more land to increase export production (e.g. sugarcane). As noted earlier in this chapter, Belize is a “highly forested nation” compared to other tropical countries, since over 60% of its land is under subtropical, moist, or semi-deciduous broadleaf forests in 2010 (Cherrington et al. 2010). However, agricultural expansion through deforestation comes at a significant environmental cost.

Belize is ecologically diverse with 85 distinct ecosystems located from the highlands of the Maya mountains, to the lowlands of the northern districts, and out to the cayes that extend into the Caribbean sea (Day 2003; Meerman & Sabido 2001). Within these landscapes, Belize's forests are part of the Maya Tropical Forest, which is an ecologically diverse neotropical forest measuring some 25,000 square kilometers and covering Northern Central America. Hence, the county's forest is part of the largest tropical forest north of the Amazon (for a thorough review of the Maya Tropical Forest, see Matola & Poót 2003; Nations 2006; Primack 1998). Belizean forests have a high level of biodiversity, containing over 4000 species of flowering plans, over 700 native species of trees, five types of wild cats (jaguar, puma, ocelot, jaguarundi, and margay), over 500 types of birds, and thousands of other types of insects, reptiles, amphibians and mammals, many of which are currently endangered (Day 2003; Hartshorn et al. 1984; Matola & Poót 2003; Miller & Miller 1995). In addition, the Belize forests contain about 300 known archaeological sites (Brown & Witschey 2010), and the forest composition in some areas also preserves information about ancient Maya “forest gardens”, patches of forest that were once managed by the Ancient Mayas (Ross & Rangel 2011).

Belize's forests are also a source of many non-timber resources, such as those that have medicinal properties and supplemental food items like berries and nuts. Although Belize currently protects about 40% of its forests, deforestation, driven mainly by agricultural expansion, continues to represent a major environmental issue (Cherrington et al. 2010; Matola & Poót 2003; Young 2008). Thus, for a small country that contains such a high level
of biodiversity, agricultural expansion through deforestation has important environmental
and social impacts. Despite these highly diverse and important characteristics, current
research suggests that the rate of deforestation is increasing in Belize (Cherrington et al.
2010).

Large-scale deforestation began in Belize in the 1960s when agriculture replaced the
extraction of forest products (Young 2008). However, the actual area of forest cover prior to
1980 is uncertain due to a lack of cloud-free satellite data and aerial photographs. In the
1990s, deforestation was first studied using remote sensing data in some areas of the
country, notably in the Toledo district (Chomitz & Gray 1996) and eventually nation-wide
using LANDSAT data (White et al. 1996). However, due to a lack of accuracy assessment in
these and other early land cover assessments, a new assessment was completed in 2010 for
the entire country (Cherrington et al. 2010).

Based on this new analysis, it is estimated that the forests in Belize experienced a
17.4% relative decline from 1980 to 2010 at a mean annual rate of -0.66% (Cherrington et
al. 2010). This rate of deforestation is comparable to neighbouring Central American nations
but higher than South America for the same time period (FAO 2011). While forests were
being cleared in Belize, the agricultural area expanded by about 65 percent (FAOSTAT
2014), suggesting that agricultural development contributed greatly to deforestation. In line
with this interpretation, Cherrington et al. (2010) observed the highest deforestation rates
occurred in the Orange Walk and Corozal districts of northern Belize, particularly in the Rio
Hondo and New River watersheds where sugarcane is grown.

Although these statistics reveal a link between agricultural expansion and deforestation,
they also raise a number of questions regarding the specific causes of deforestation. Except
for a few studies that have examined deforestation at the sub-district scale (see, for example,
Chomitz & Gray 1996; Wyman & Stein 2010), the causes of deforestation in Belize have
not been fully investigated. Specifically, little is known about the types of disturbances and
adaptive responses that lead smallholders to clear more forest. There is also almost a
complete lack of local-scale data on forest change and agricultural production, so the link
between specific agricultural practices and change in forest cover remains unclear. In other
words, except for watershed-scale deforestation data and some district-scale agricultural
data, little is known about how different types of smallholder farms have responded to

2 Cherrington et al. (2010) provide a comparative review and comparative analysis of previous land
cover mapping in Belize. The main problem with previous studies was the lack of accuracy
assessment.
disturbances by expanding their farms.

3.5.4.iii Agricultural change and intensification

Agricultural change and intensification are another primary response to farm disturbances. However, data relating to agricultural change and intensification in Belize are sparse, except, perhaps, for a few documents describing changes in agricultural practices, such as Wright et al.'s (1959) early assessment of land use in Belize and Hall's (1978) description of early Mennonite adaptation to the neotropical environment. Insight can also be gained from agricultural censuses and government documents (see, for example, Furley & Robinson 1985). Although there are limited data that can be used to evaluate agricultural change, the available data confirm that Belizean agriculture did become more intensive through the adoption of Green Revolution technologies as farmers intensified as a response to environmental and social disturbances.

Agricultural intensification in Belize, as in the rest of the LAC region, can be evaluated using several direct and indirect indicators. Yields, which are expressed as hectograms/hectare (Hg/Ha), increased for most export crops and domestic staples since the 1960s (FAOSTAT 2014). Of Belize's export crops, only sugarcane experienced a decline in yield since the 1960s, a trend that is associated with a variety of factors (e.g. pest infestations, hurricanes) (see Chapter 5 for a detailed assessment). In general, yield increases commonly relate to increases in the use of agricultural inputs, such as mechanization equipment, fertilizer, and pesticide. Indeed, although data have not been recorded annually, FAOSTAT (2014) confirms that farmers in Belize did increase use of agricultural technology during this time period. However, the same data indicate that yield increases are not associated with irrigation, which has only increased slightly since the 1960s to occupy 2 percent of total cropland (FAOSTAT 2014).

A GoB report cites that “...fertilizer intensity for all crops has increased in the country from 289 pounds per acre in 1999 to 391 pounds per acre in 2003” (2008, p.25), providing one of the few direct indicators of agricultural intensification. Further, the same report identified that export crop production consumed the highest amount of agrochemicals per acre, most notably in the citrus and banana industries (Government of Belize 2008). Freshwater contamination also indirectly indicates a high level of agricultural intensification in Belize. For example, high concentrations of organochlorine compounds (OC) and other agrochemicals have been identified in Morelet's crocodile (Crocodylus moreletii) eggs, a
freshwater species that lives within the country's river systems (see, for example, DeBusk 2012; Rainwater et al. 2007; Rainwater et al. 2002; Wu et al. 2000).

Thus, although little is presently known about the agricultural practices of smallholders throughout Belize, these indicators suggest that agricultural intensification is a common response to disturbances. Further insight on Belizean farm resilience can be gained by considering how such responses contribute to the disturbance regime via feedbacks.

### 3.5.5 Evidence of feedbacks

Few scientific studies have investigated the environmental or anthropogenic impacts of agricultural expansion and/or intensification in Belize, and, as of 2008, the country still did not regularly monitor primary environmental health indicators, such as water quality (Government of Belize 2008; Martin & Manzano 2010). The following discussion reviews key studies concerning the environmental and anthropogenic impacts of agricultural expansion and intensification in Belize, and considers how these feedbacks can further impact on the agricultural practices of smallholders.

#### 3.5.5.i Environmental feedbacks in Belize

Agricultural intensification has had several negative environmental impacts in Belize. Notable examples of these impacts were identified in Chapter 2. In Belize, water contamination is a major concern, especially the contamination of groundwater due to livestock production (Government of Belize 2008). Likewise, land degradation is directly caused by agricultural activity (Cherrington et al. 2010). Agricultural intensification also contributes to nitrogen loading, a process that is linked specifically to pest infestations, notably frog hoppers in sugarcane areas (BSCFA 2012). Another study has found evidence of insecticide resistance in a common pest, which was likely caused by agricultural practices that depended too heavily on specific types of pesticides (Dusfour et al. 2010).

Further, deforestation to expand pastures has increased livestock-felid conflict in Belize which has resulted in the loss of livestock and the unnecessary death of big cats (e.g. jaguar). This is a problem faced by livestock producers worldwide (Inskip & Zimmermann 2009). Although these examples are limited, they do suggest that current agricultural practices can have a deleterious effect on farm systems by either depleting the natural resource base or by creating new, previously unknown disturbances. These limited examples call for more focused research on the impact of environmental problems on the agricultural practices of smallholders.
In addition to the environmental feedbacks noted above, agricultural expansion and intensification is also a source of numerous anthropogenic feedbacks in Belize. As explained in a recent IFAD (2013) report, deforestation creates additional household expenses for farmers and farming communities because it limits or eliminates access to non-timber forest resources, such as meat, nuts, fruit. These are crucial non-monetary components of household income in rural areas. Thus, when forests are removed, household must depend more upon the purchase of these staple household items.

Deforestation in Belize has also been linked to higher rates of vector-borne diseases, notably malaria (Hakre et al. 2004; Pope et al. 2005). Indeed, research throughout the tropics has determined a direct link between deforestation and increased incidence of malaria and a number of other diseases (see, for example, Guerra et al. 2006b; Patz et al. 2008). Thus, with a high deforestation rate, the population in Belize faces a number of disease-related feedbacks.

There are also a number of known health risks associated with the intensification of agriculture in Belize, namely those associated with the exposure to pesticides and water contamination. Bravo et al. (2011) quantified import data for Central American countries and found that of the 33 million kg of active ingredients were imported each year from 2000 to 2004. This included a high volume of hazardous pesticides. In Belize, pesticide drift is a major concern since harmful chemicals (e.g. organochloride) have been found in soil and water (Kaiser 2011; Somerville & Liebens 2011). Moreover, insecticide residence has resulted from overuse of certain pesticides in Belize, according to a study by Dusfour et al. (2010). In addition to the harmful environmental impact that resistance causes, it also contributes to production losses and further exacerbates economic hardships. Thus, contamination resulting from pesticide applications are a common feedback from agricultural intensification.

Water contamination that results from agricultural intensification causes additional health problems in Belize. Marfia et al. (2004) conducted a chemical analysis of surface and ground water in Belize, and found that groundwater aquifers were rapidly recharged from surface water. This suggests that when surface water is contaminated it can quickly leach into groundwater, which therefore impacts drinking water quality. For example, Nair and Taylor (2010) conducted water analysis and surveyed a villager in southern Belize, and
found a relationship between health problems, such as respiratory illness and skin problems, and water contamination. Further studies like this one are needed, particularly in the northern districts where intensive production of sugarcane occurs, to understand better the impact of agricultural intensification on water quality in Belize.

Thus, even this limited evidence suggests that the expansion and intensification of agriculture in Belize contributes to a variety of anthropogenic disturbances, most notably by disturbing the socioeconomic and health status of smallholders.

3.6 SUMMARY

This chapter has reviewed the history of agricultural development, land change, and farm resilience in the LAC region and in Belize specifically since the conquest period. Although historical developments in the Latin American and Caribbean subregions differ, the region as a whole experienced increased agricultural development, particularly since the 1960s. Despite numerous environmental and social disturbances that impact farmers, agriculture in the LAC region has demonstrated considerable resilience. Based on a variety of evidence relating to land change, economic indicators, and sociodemographic indicators, it is suggested that the two primary ways farmers have responded to disturbances was by expanding and/or intensifying agricultural production. Since these two responses have numerous environmental and social impacts, mitigation is necessary to support farm resilience and environmental quality. Three possible ways to mitigate the potential negative effects of agricultural development were reviewed, namely forest transitions, sustainable agricultural intensification based on agroecological techniques, and PES schemes like REDD+. This section concluded that farms in the LAC region have demonstrated considerable resilience, but mitigation is required to limit the potential negative effects of farm-level responses to disturbances.

Land change history and farm resilience in Belize was also reviewed. As in the rest of the LAC region, land change in Belize was shown to be closely tied to political changes in the country, especially the development of export-led development since the 1950s. Alongside this development was the steady production of domestic staples, which is the basis of local food security and an important source of income for the country's growing rural population. More recently, livestock production has become a lucrative agricultural sub-sector. Although farmers in Belize face numerous environmental and social
disturbances, farm resilience has strengthened through policy interventions, agricultural expansion, and agricultural intensification. The concern today is that a resilient agricultural sector may have devastating impacts on the natural resource base of the country. Thus, mitigating negative feedbacks from farm-level responses is crucial to support long-term agricultural sustainability.

The following chapter examines farm resilience within a 700 square kilometres study area in Northern Belize. Based on a land change assessment that relies on a LANDSAT time-series, this chapter investigates the various responses to disturbances by the area's farmers. Specifically, contrasts are discussed between the area's Maya-Mestizo and Mennonite farmers, and various forms of farm resilience are proposed.
4 LAND CHANGE IN NORTHERN BELIZE

This chapter addresses the first objective of the thesis by presenting a local-scale land cover change assessment of a culturally and agriculturally diverse area located in Northern Belize. The assessment is based on LANDSAT time-series data dating from 1980 to 2010, and is further informed by a variety of third party datasets that focus on environmental and socio-demographic data. The assessment quantifies major land cover change patterns that indicates how farmers in different areas have responded to social and environmental disturbances in different parts of the study area. Insights are gained about farm resilience by identifying the dominant adaptive management strategies in the study area. Thus, this land cover change assessment to helps structure the farm-level analysis that follows in Chapter 5 by providing an overview of the response diversity and disturbances regime.

4.1 STUDY AREA

4.1.1 Boundaries and zones

The 700 km$^2$ study area is located in the Orange Walk District in Northern Belize. It is home to two Mennonite communities, ten primarily Mestizo villages, and Orange Walk Town, the district capital. As shown in Figure 4.1, the study area is defined as the land west of the New River and south of Orange Walk Town towards the Rio Bravo Conservation and Management Area (CMA), a private forest reserve located at the southernmost tip of the New River Lagoon. The northern and eastern boundary of the study area is the main road that runs east from Orange Walk to Yo Creek, then south through San Felipe to the Rio Bravo CMA. The area was chosen due to its ethnic diversity and high agricultural output in both the domestic and export sectors. To evaluate and compare land cover changes within the study area, this study examines only the inhabited area, so the Lamanai Archaeological Reserve and the Rio Bravo CMA areas are not investigated at a local-scale. The inhabited area was then subdivided into four zones. Three Mestizo zones, numbered 2 to 4, cover about 254 km$^2$ and one Mennonite zone, numbered 1, covers about 375 km$^2$ (Figure 4.1).
Figure 4.1: Map showing the four zones within the study area.
4.1.1.i The boundaries of Zone 1

Indian Creek and Shipyard, the two Mennonite communities, make up the Mennonite portion of the study area. Although the boundary of the Mennonite area is not officially established, numerous sources of information were used to define a boundary for this study, including expert knowledge of the area, ground observations, observations made using high resolution satellite imagery, official boundaries for edges adjacent to either the Lamanai Archaeological Reserve or the Rio Bravo CMA, and the project boundaries. The main difference between the Mennonite zone and the Mestizo zones is that Mennonites are not likely to own or occupy land in non-Mennonite areas and non-Mennonites are not likely to own land within the Mennonite zone. Hence, the boundary of Zone 1 represents land held exclusively by Mennonites within the study area.

4.1.1.ii The boundaries of Zones 2 and 3

Zones 2 and 3 contain the most populous Mestizo communities (as discussed below in section 4.1.2), so it was deemed necessary to divide the area into two zones to avoid having a disproportionately large amount of the population in a single zone. The majority of farmers in the northern, Mestizo part of the study area do not live on their farmland, but in the surrounding communities. Although the majority of land within these zones is likely to be farmed by members of the surrounding communities, there are exceptions where land is managed by farmers who live further abroad. Likewise, farmers in the six communities are also likely to farm on land located outside the study boundaries. The boundaries were defined using a Voronoi diagrams, the project boundaries, the Mennonite boundary, expert knowledge of the area, and high resolution imagery on Google Maps. Hence, the boundaries of Zones 2 and 3 represent the land that is likely, though not exclusively, farmed by members of these six northern Mestizo communities.

4.1.1.iii The boundaries of Zone 4

The boundaries of Zone 4 contain the southernmost Mestizo communities, namely August Pine Ridge, San Felipe, Indian Church, and San Carlos. The boundaries for this zone were derived using Voronoi diagrams, high resolution imagery, the Mennonite area boundaries, the project boundaries, and the official boundaries of the Rio Bravo CMA and the Lamanai Archaeological Reserve. Although the Mennonite area divides the zone in two, based on expert knowledge of the area, these communities are closely linked through familial ties, agricultural production strategies, and a close relationship with the
neighbouring Mennonite communities.

In total, the inhabited portion of the study area contained almost 15,000 people, 68 percent of whom were reportedly engaged in agriculture (Table 4.1). This figure is comparably higher than the distinct total which stood at about 47 percent in 2010 and the national total which stood at 35 percent in 2010 (2010 Belize Census). Thus, the study area represents a highly dense agricultural area where more than half of the population are engaged in agriculture. The following section reviews the social and environmental setting within the inhabited portion of the study area, which was also used to help define the Zones in this study.

4.1.2 Population and the built environment

4.1.2.i Zone 1: The Mennonite area

Zone 1 contains two Old Colony Mennonite communities (see Table 4.1). Shipyard, whose population was 3353 in 2010, was one of the original Mennonite colonies established in 1957. Due to increased immigration and natural population growth, land was becoming scarce by the 1980s for the next generation of farmers in Shipyard. Officials within the community opted to purchase 15,000 hectares of land near Indian Church and San Felipe. In the 1990s, the land was redistributed between a few hundred Shipyard residents and a new Mennonite community was developed called Indian Creek. Since then, Indian Creek grew to 904 people by 2010 (Statistical Institute of Belize 2011). Thus, by 2010 there were over 4,200 inhabitants in the Mennonite area.

Within these Mennonite communities, about 92 percent of the population is engaged in agriculture, according to 2010 population census results (see Table 4.1). This is substantially higher than most nearby Mestizo villages, except for Guinea Grass, the largest Mestizo village in the study area, and San Carlos, the smallest Mestizo village. Thus, since the majority of the population in zone 1 is engaged in agriculture, it is likely that the Mennonites have had a substantial environmental impact through agricultural expansion and intensification. However, very studies have investigated environmental or agricultural change in this area.
4.1.2.ii Zones 2 to 4: the Mestizo area

The majority of individuals living within zones 2 to 4 are of Mestizo descent, or broadly classified as Hispanic by the Belize Statistical Institute. The Mestizo population represents over 77 percent of the population in the Orange Walk District, a figure that is substantially higher within many rural villages. However, despite sharing a common ethnic designation, Mestizos are a diverse group of Belizeans, Salvadorians, Mexicans, Hondurans, and Guatemalans who brought diverse agricultural practices and traditions to Belize (as discussed in Chapter 3). Also, in addition to agricultural diversity, there is a high degree of livelihood diversification within the Mestizo areas since the agricultural population ranges from about 26 to 94 percent at the village-level. Thus, even though the Mestizo population represents the largest ethnic group within the study area, their livelihood and ethnic diversity suggests, at least tentatively, that different land change patterns may exist within different areas.

4.1.3 Environmental setting

The study area is located in the lowlands of northern Belize, an area that is characterized by flat to rolling plains, wetlands, savannah, lowland broadleaf forest, and a

Table 4.1: Demographic profile of the study area.

*Data provided by the Statistical Institute of Belize, and derived from the 2010 population census.

<table>
<thead>
<tr>
<th>Zone within study area</th>
<th>Village/Community</th>
<th>Population (2010)*</th>
<th>Households (2010)*</th>
<th>Agricultural Population (2010)*</th>
<th># People/house</th>
<th>#</th>
<th>% of pop.</th>
<th>Main ethnic group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Indian Creek</td>
<td>903</td>
<td>150</td>
<td>6.0</td>
<td>843</td>
<td>93.4</td>
<td>Mennonite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shipyard</td>
<td>3,353</td>
<td>618</td>
<td>5.4</td>
<td>3,072</td>
<td>91.6</td>
<td>Mennonite</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>4,256</td>
<td>768</td>
<td>5.5</td>
<td>3,915</td>
<td>92.0</td>
<td>Mennonite</td>
<td></td>
</tr>
<tr>
<td>Zone 2</td>
<td>Guinea Grass</td>
<td>3,223</td>
<td>608</td>
<td>5.3</td>
<td>1,844</td>
<td>57.2</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trinidad</td>
<td>571</td>
<td>143</td>
<td>4.0</td>
<td>534</td>
<td>93.5</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>3,794</td>
<td>751</td>
<td>5.1</td>
<td>2,378</td>
<td>62.7</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td>Zone 3</td>
<td>Chan Pine Ridge</td>
<td>446</td>
<td>106</td>
<td>4.2</td>
<td>296</td>
<td>66.4</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>San Lazaro</td>
<td>1,062</td>
<td>231</td>
<td>4.6</td>
<td>412</td>
<td>38.8</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tower Hill</td>
<td>314</td>
<td>80</td>
<td>3.9</td>
<td>83</td>
<td>26.4</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yo Creek</td>
<td>1,411</td>
<td>328</td>
<td>4.3</td>
<td>1,066</td>
<td>75.5</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>3,233</td>
<td>745</td>
<td>4.3</td>
<td>1,857</td>
<td>57.4</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td>Zone 4</td>
<td>August Pine Ridge</td>
<td>1,797</td>
<td>399</td>
<td>4.5</td>
<td>1,178</td>
<td>65.6</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indian Church</td>
<td>267</td>
<td>62</td>
<td>4.3</td>
<td>122</td>
<td>45.7</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>San Carlos</td>
<td>138</td>
<td>28</td>
<td>4.9</td>
<td>123</td>
<td>89.1</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>San Felipe</td>
<td>1,499</td>
<td>328</td>
<td>4.6</td>
<td>651</td>
<td>43.4</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>3,701</td>
<td>817</td>
<td>4.5</td>
<td>2,074</td>
<td>56.0</td>
<td>Mestizo</td>
<td></td>
</tr>
<tr>
<td><strong>All zones</strong></td>
<td></td>
<td>14,984</td>
<td>3,081</td>
<td>4.9</td>
<td>10,224</td>
<td>68.2</td>
<td>Mestizo</td>
<td></td>
</tr>
</tbody>
</table>
distinct dry and wet season. The study area is 70% within the hydrological boundaries of the New River watershed and 30% within the Rio Hondo watershed, though both are quite similar karst environments characterized by flat to undulating plains with a variety of clayey soils. These soils present moderate to severe limitations to agriculture, notably nutrient limitations, drought, and excessive moisture (King et al. 1992). Perhaps the most dominant environmental feature in the area is the New River Lagoon, which measures about 23km by 0.75km and is the largest freshwater body in Belize. Given this diverse and challenging environmental setting, serious concerns exist regarding the environmental consequences of agricultural development in this area.

4.2 METHODOLOGY FOR LAND COVER CHANGE ASSESSMENT

Two primary methods were employed to evaluate land cover change in the study area, namely post-classification comparison (PCC) and pixel history (PH) analysis. PCC derives statistics from individual time-series images, and compares them over time to observe net change in specific land cover types. For example, once the total forest cover is calculated for a given number of years, it is then possible to calculate the rate of change between different dates.

PH analysis, in contrast, is used to examine pixel-scale trends over time. For example, instead of just quantifying net forest change, PH analysis reveals the types of land cover to which forests were converted, such as cropland or pasture. Moreover, PH can also reveal more complex land cover change trajectories, such as forest transitions, crop/pasture rotations, and areas farmed consistently over a specific period of time (e.g. permanent or steady state cropland). Combined, PCC and PH provide both broad land cover change statistics that suggest major changes in the landscape and pixel-scale statistics that reveal more about the underlying decisions made by residents of the farming communities. These two perspectives support the farm resilience assessment of the study area by providing new land use statistics that help to determine how farmers respond to social and environmental disturbances within the study area.

4.2.1 Satellite data acquisition and pre-processing

The study area is within WRS-2 path/row 19/48 for LANDSAT TM and ETM+ imagery, and WRS-1 20/47 and 20/48 for MSS. Eight LANDSAT images were acquired to assess land cover change in the study area (Table 4.2). Only images captured between
December and March were selected to avoid variations caused by seasonal fluctuations and crop cycles. At this time, most crops would be planted, including corn, beans, and sugarcane. Two cloud-free MSS images were geometrically corrected to within one pixel of the 2000 base image and merged to cover the study area. Three cloud-free TM images dating from 1989, 1995, and 2000 and three ETM+ images dating to 2004, 2006, and 2010 were acquired. All LANDSAT 5 and 7 scenes were geometrically corrected (L1T processing level) and then the horizontal accuracy was further checked with a series of ground control points to ensure that it was within one pixel. Since the study uses post-classification comparison, radiometric correction of the time-series was not necessary.

<table>
<thead>
<tr>
<th>Acquisition date</th>
<th>Sensor</th>
<th>Path</th>
<th>Row</th>
<th>Processing Level</th>
<th>Pixel Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980-11-14</td>
<td>Landsat 3 (MSS)</td>
<td>20</td>
<td>48</td>
<td>L1G</td>
<td>60m (4,5,6,7)</td>
</tr>
<tr>
<td>1980-11-14</td>
<td>Landsat 3 (MSS)</td>
<td>20</td>
<td>47</td>
<td>L1G</td>
<td>60m (4,5,6,7)</td>
</tr>
<tr>
<td>1989-12-27</td>
<td>Landsat 5 (TM)</td>
<td>19</td>
<td>48</td>
<td>L1T</td>
<td>30m (1,2,3,4,5,7), 120m (6)</td>
</tr>
<tr>
<td>1995-01-10</td>
<td>Landsat 5 (TM)</td>
<td>19</td>
<td>48</td>
<td>L1T</td>
<td>30m (1,2,3,4,5,7), 120m (6)</td>
</tr>
<tr>
<td>2000-01-24</td>
<td>Landsat 5 (TM)</td>
<td>19</td>
<td>48</td>
<td>L1T</td>
<td>30m (1,2,3,4,5,7), 120m (6)</td>
</tr>
<tr>
<td>2004-02-12</td>
<td>Landsat 7 (ETM+, SLC-off)</td>
<td>19</td>
<td>48</td>
<td>L1T</td>
<td>30m (1,2,3,4,5,7), 60m (6), 15m (8)</td>
</tr>
<tr>
<td>2006-01-16</td>
<td>Landsat 7 (ETM+, SLC-off)</td>
<td>19</td>
<td>48</td>
<td>L1T</td>
<td>30m (1,2,3,4,5,7), 60m (6), 15m (8)</td>
</tr>
<tr>
<td>2010-02-28</td>
<td>Landsat 7 (ETM+, SLC-off)</td>
<td>19</td>
<td>48</td>
<td>L1T</td>
<td>30m (1,2,3,4,5,7), 60m (6), 15m (8)</td>
</tr>
</tbody>
</table>

Table 4.2: LANDSAT time-series imagery.

Gaps caused by a malfunction in the sensors' Scan Line Corrector (SLC) and clouds were masked out of the 2004, 2006 and 2010 scenes, and then the three images were classified independently. The 2004 classified image was thereafter filled almost completely with the 2006 classified imagery, and time-stamped as 2004. The 2010 gaps were not filled because no suitable data exist within the LANDSAT archive. The final image catalogue covers 622 sqkm, such that 88.9% of the study area is gap- and cloud-free.

### 4.2.2 Image classification

#### 4.2.2.1 Classification of MSS imagery

The LANDSAT MSS satellite data were classified using the maximum-likelihood classification method. Since MSS data have lower radiometric (4 bands) and spatial resolution (90m) than the later LANDSAT TM and ETM+ imagery used in this study, only two land cover classes were classified in the MSS datasets, namely “forest” and “non-forest”, as shown in Figure 4.2. Training data for this analysis was based on expert knowledge, high resolution imagery on Google Earth, Belize topographical maps, and...
imagery itself. Hence, when a pixel history is considered back to 1980, the starting point is either forest or non-forest.

Figure 4.2: Forest and non-forest cover in the study area in 1980.

4.2.2.ii Classification of LANDSAT TM and ETM(+) imagery

The TM and ETM(+) images dating from 1989 to 2010 were classified using a common maximum-likelihood classification method with eight classes, namely, (1) urban, (2) cropland, (3) natural grassland, (4) pastures, (5) forests, (6) water, (7) wetland, and (8) bare soil (Figure 4.3). Six spectral bands were in the LANDSAT products were used for the classification namely the visible blue/green/red spectrum (Bands 1-3), the near infrared band (Band 4), and short-wave infrared bands (Bands 5 and 7).

To classify the images, training data (i.e. location with known land covers) were needed. Since spatial reference data do not exist for the study area for any time from 1989 to 2010, training data were based on expert knowledge, Belize topographical maps (1:50,000m), the image itself displayed in various band combinations and ratios (e.g.
NDVI), recently acquired high resolution imagery from Google Earth, and ecological zone data for the area, as supplied by the Biodiversity and Environment Resource Data System of Belize (BERDS). Using these various lines of evidence, it was possible to identify examples of each land cover and use these locations as input into the maximum-likelihood classification.

Figure 4.3: Land cover classification of LANDSAT TM and ETM(+) imagery.
The land covers containing little or no vegetation include urban, water, wetland, and bare soil. The urban land cover class includes all potential elements of the built environment, such as buildings, paved roads, dirt roads, and other impervious surfaces. Training data for the image classification was selected along roads, in villages, and in Orange Walk Town. The average digital number (DN) shows a spike in the short-wave infrared (Band 5) relative to the DN of other spectral bands (Figure 4.4). Bare soil, which appears mainly in agricultural fields, has a very similar spectral signature to the urban class except for a dip in near infrared reflectance (Band 4).

The water and wetlands classes comprise the water-covered surfaces of the study area. As shown in Figure 4.4, water is the least reflecting surface in all bands when compared to urban and bare soil. Wetland, which contains a certain amount of vegetation, reflects higher than water in all spectral bands, but still lower than urban and bare soil. Hence, land covered with little or no vegetation demonstrate four unique spectral signatures.

![Figure 4.4: Mean digital number values for urban, bare soil, wetlands, and water, based on 2010 classification.](image)

The spectral signatures of the four vegetation land cover types presented less variation, but enough to differentiate between cropland, natural grassland (i.e. savannah), pasture, and forest. As shown in figure 4.5, the typical pattern for vegetation is exemplified by the forest land cover type where there is a low value in the red band (Band 3), which signifies a high concentration of chlorophyll, and a higher value in the near infrared (Band 4), which signifies a higher concentration of green vegetation. Accordingly, the spectral signature for different types of vegetation can differentiated based on the DN value in Bands 3 and 4. For
example, although natural grasslands and pasture are fairly similar in the visible spectrum (Bands 1 to 3), they are different when looking at the near infrared and short-wave infrared bands. Hence, given this variation, it was possible to classify these four types of vegetated land covers.

![Figure 4.5: Mean digital number values for cropland, natural grassland, pasture, and forest, based on 2010 classification.](image)

4.2.2.iii Accuracy Assessment

The classification accuracies were tested by calculating an error matrix for each classified raster, which included the calculation of total overall accuracy and the Cohen's kappa (k). For each of the classes, 50 point were randomly generated, such that a total of 100 points were used to test the MSS image and 400 points were used to test the TM and ETM(+) images. Without ground control data for the study area, these random points were compared to variety of other datasets, including high resolution imagery (Google Earth), topographic maps, ecological maps, land suitability data, and the imagery itself in different image band combinations (e.g. NDVI). Hence, the accuracy assessment does include a certain degree of uncertainty, but this uncertainty was minimized by using multiple lines of evidence to evaluate each point. Tables 4.3 and 4.4 show the results of this analysis.

The overall accuracy of the 1980 MSS image was 96 percent, with only four points being misclassified. Attaining a well classified starting point for the trajectory analysis was critical in order to support the identification of major land cover change trends going back to 1980, such as deforestation and agricultural expansion. Hence, these results indicate that the baseline classification of forest or non-forest is highly accurate.
<table>
<thead>
<tr>
<th>Year</th>
<th>Reference Data</th>
<th>Classification Data</th>
<th>Producer’s Accuracy</th>
<th>Errors of Omission</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td></td>
<td>Forest Non-Forest ROW TOTAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean Accuracy Overall Accuracy Error of Commission User’s Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>48 2 50</td>
<td>96.00% 96.00% 4.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>2 48 50</td>
<td>96.00% 96.00% 4.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Accuracy</td>
<td>96.00%</td>
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<td></td>
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</tr>
<tr>
<td>Mean Accuracy</td>
<td>96.00%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare Soil</td>
<td>50 50</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>2000</td>
<td>96.00% 96.00% 4.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>40 40 80</td>
<td>92.00% 92.00% 8.00%</td>
<td></td>
<td></td>
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<tr>
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<td>0 0 100</td>
<td>86.00% 86.00% 14.00%</td>
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<td></td>
</tr>
<tr>
<td>Pasture</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetland</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare Soil</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
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<td></td>
</tr>
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</tr>
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<td>1989</td>
<td></td>
<td>Urban Cropland Natural grassland Pasture Forest Water Wetland Bare Soil ROW TOTAL Producer’s Accuracy Errors of Omission</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td>Mean Accuracy Overall Accuracy Error of Commission User’s Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>40 40 80</td>
<td>92.00% 92.00% 8.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cropland</td>
<td>0 46 50</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetland</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare Soil</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column Total</td>
<td>40 40 80</td>
<td>100.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User’s Accuracy</td>
<td>95.24%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error of Commission</td>
<td>4.76%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Accuracy</td>
<td>93.00%</td>
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<td></td>
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<tr>
<td>Mean Accuracy</td>
<td>93.00%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kappa</td>
<td>0.877</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td>Urban Cropland Natural grassland Pasture Forest Water Wetland Bare Soil ROW TOTAL Producer’s Accuracy Errors of Omission</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean Accuracy Overall Accuracy Error of Commission User’s Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>39 39 78</td>
<td>78.00% 78.00% 22.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cropland</td>
<td>0 46 50</td>
<td>92.00% 92.00% 8.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural grassland</td>
<td>0 0 100</td>
<td>76.00% 76.00% 24.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetland</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare Soil</td>
<td>0 0 100</td>
<td>92.00% 92.00% 0.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column Total</td>
<td>40 40 80</td>
<td>100.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User’s Accuracy</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Error of Commission</td>
<td>4.88%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Accuracy</td>
<td>91.25%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Accuracy</td>
<td>91.25%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kappa</td>
<td>0.900</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The images from from 1989 to 2010 were classified into eight classes, so a total of 400 random points were used to evaluate the accuracy of each image. As the previous section explained, the difference between many of the vegetated land cover classes was not great, such as natural vegetation and pasture. Consequently, the error matrices for these images demonstrates that it was more difficult to classify natural vegetation and pasture than it was to classify water and forest, two relatively homogeneous land cover classes. Despite this limiting factor, each image had an overall accuracy above 90 percent and a kappa over 0.877. Thus, as shown in Table 4.5, the mean overall accuracy of all the images was 93.0 percent with an average kappa coefficient of 0.91.
4.2.3 PCC methodology

The post-classification comparison analysis compares the summary statistics of a series of classified images, or subsections of images. Overlay analysis was used on the classified images in Esri's ArcGIS Desktop (Version 10.2) and zonal histogram summaries were generated for the entire study area and for each of the four zones. Since gaps only exist in the 2004 and 2010 images, only the pixels present in all images were included in these statistics (i.e. where a gap exists in one image, that pixel was excluded from the analysis). The results for each land cover type were tabulated to calculate the rate of land cover change for each class at each of the two scales.

4.2.4 Pixel histories

While the PCC approach identifies general land cover change trends (e.g. net forest change), it often conceals the reciprocal relationship between different land cover classes over time (Zhou et al. 2008; Carmona & Nahuelhual 2012). For example, a study may identify forest transitions, but summary land cover statistics based solely on PCC analysis do not reveal what types of land were converted to forest. However, pixel-histories compare the classification value of one pixel at more than two temporal intervals to reveal thousands of potential land cover change trajectories. By doing so, change is detected and quantified at a higher spatial resolution and insight can be gained about the nature of local-scale land use decisions over time.

One problem with this technique is that five images classified into eight land cover types produces a maximum of 32,768 (i.e. $8^5$) possible pixel-histories. To reduce this variability, pixel-histories were categorized based on logical transitions according to a method devised by Zhou et al. (2008). A logical transition is defined as any land cover change that is logically possible, such as forest can change into cropland, but water cannot change into urban under normal circumstances. Given the classification errors motioned

<table>
<thead>
<tr>
<th>Image date</th>
<th>Overall Accuracy</th>
<th>Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>96.0</td>
<td>-</td>
</tr>
<tr>
<td>1989</td>
<td>89.3</td>
<td>0.88</td>
</tr>
<tr>
<td>1995</td>
<td>93.0</td>
<td>0.92</td>
</tr>
<tr>
<td>2000</td>
<td>91.3</td>
<td>0.90</td>
</tr>
<tr>
<td>2004</td>
<td>94.8</td>
<td>0.94</td>
</tr>
<tr>
<td>2006</td>
<td>96.5</td>
<td>0.96</td>
</tr>
<tr>
<td>2010</td>
<td>90.5</td>
<td>0.89</td>
</tr>
</tbody>
</table>

| Mean | 93.0 | 0.91 |

Table 4.5: Summary of error matrices.
above, a portion of the resultant pixel histories are classified as “uncategorized” since the
pixel histories are illogical and likely due to misclassification in one or more images. The
relative frequency of different pixel-histories in different areas provides additional
indicators of different land use strategies. For the present study, temporal changes are
calculated using zonal histograms for the study area and each zone.

PH analysis was conducted on the 1989, 1995, 2000, 2004/06 and 2010 classified
imagery. The classified images were stacked and 12 main groups of pixel-histories
consisting of 31 categories were generated, including both natural and human-induced
transitions. Natural transitions can be steady state (e.g. forest no change) or naturally
random, which may include any trajectory that is limited to natural land cover classes,
namely forest, wetlands, water, or grasslands. These types of natural transitions are partly
due to misclassification, but may also result from natural processes such as hurricanes,
flooding, or forest fires that cause one natural land cover to be replaced with another.

There are ten groups of human-induced categories, namely steady state, cropland
expansion, pasture expansion, pasture/cropland conversion, urban expansion, cropland
abandonment, pasture abandonment, cropland/pastures rotations, shifting cultivation in
forested areas, and random human-induced transitions. Transitions are defined as either
single, retrograde, or stepwise depending on how they change over time. Single transitions
are transitions from one land cover type to another, retrograde are transitions between from
one land cover type to another and then back again (e.g. forest to cropland to forest), and
stepwise transitions are between three or more land cover types (e.g. forest to cropland to
pasture). All categories are quantified as a percentage relative to the scale of analysis. For
the purposes of this analysis, pixel-histories were quantified at the study area scale and at
the zone-level.

4.2.5   Environmental and social context of land change

A variety of geoprocessing techniques (e.g. overlay, buffer, etc.) were employed in
ArcGIS Desktop 10.2 to evaluate the environmental context of land cover change in the
study area. This analysis employed a variety of secondary data published by the Biodiversity
and Environmental Resource Data System of Belize (www.biodiversity.bz). The results of
the land cover change assessment were compared to a variety of datasets, including the
location of settlements, political boundaries, roads, and agricultural suitability data. Thus,
comparison was possible between the location where major land cover changes occurred in
each zone.

4.3 RESULTS

This section presents the results of the remote sensing land cover change assessment in two subsections. The first subsection summarizes major trends in land cover change within study area and the second subsection presents the results at the zone level to identify different land cover change trends within different portions of the study area.

Since the focus of the thesis is on forest, cropland, and pasture change, reference will only be made to urban, wetland, water, and natural grassland change when such changes related to issues central to the thesis. Also note that bare soil is combined with the cropland class because it was observed that the majority of bare earth signals occurred in agricultural areas and were likely to be associated with ploughed fields.

4.3.1 Land cover change in the study area from 1980 to 2010

The study area was almost 34% forested in 2010, down from 59% in 1980. This represents a 154 square kilometres (24.8%) decline at an average rate of 600 hectares (-0.97%) per year. Since these statistics include a portion of the Rio Bravo Conservation Area and the Lamani Archaeological Reserve, two areas that sustained minimal land cover change during this period, it is important to focus more on the inhabited portions of the study area, namely Zones 1 to 4.

When combined, forest cover in zones 1 to 4 declined from 57 percent in 1980 to only 28 percent in 2010, which represents a total loss of about 15,858 hectares over 30 years. This change is equivalent to a decline of almost 1 percent per year, which is higher than the national average of -0.7 percent during this period and supports Cherrington et al.’s (2010) observation that Northern Belize witnessed major deforestation since 1980. By looking at changes in the agricultural area, insights can be gained into the factors that drove this high deforestation rate.

Overall, Figure 4.6 shows that the total area of forests declined slowly from 1980 to 1989, then declined at a much higher rate from 1989 to 2005, and then declined at a slightly slower rate from 2005 to 2010. The major driver of deforestation prior to 2000 was the expansion of cropland, which covered about 33 percent of the zones in 1989 and expanded by about 10 percent (or 1473.5 hectares) over the following decade. During this same
period, pastures, which only covered about 3 percent of zones 1 to 4 in 1989, expanded marginally by a few hundred hectares by 2000. Thus, until 2000, deforestation in the inhabited portions of the study area was likely driven primarily by cropland expansion and secondly by pasture expansion on a much smaller scale.

![Figure 4.6: Land cover change in the inhabited portion of the study area (zones 1 to 4).](image)

From 2000 to 2010, total cropland in zones 1 to 4 declined by almost 10 percent while deforestation continued at a fairly steady rate. However, while over 5,800 hectares of cropland came out of production, the total area in pasture increased from just 245 hectares in 2000 to over 1,100 hectares in 2010, a 17 percent increase. The 5,800 hectares of cropland that came out of production was either converted to pasture or abandoned to revert back to forest. Thus, whereas deforestation was driven by cropland expansion in the 1990s, PCC data indicate that deforestation in the 2000s was driven primarily by pasture expansion.

A local, zone-level analysis is required to gain additional insight into these general land change trends. One important reason for a local-scale analysis is because these statistics are only representative of landscape-scale changes. They are informative, but they likely generalize underlying complex land cover trends. Hence, comparing the same trends within each zone provides a more complete understanding of deforestation and agricultural change in the study area.
4.3.2 Zone-level land cover change

The results of PCC analysis for each zone is presented in this section. The discussion considers land cover changes within each zone before presenting a comparative summary in the last subsection.

4.3.2.i Zone 1: The Mennonite communities

Zone 1 covers about 33,237 hectares, which makes it the largest zone in the study area. It includes two Mennonite communities, namely Shipyard and Indian Creek. Prior to the establishment of the Indian Creek community in the late 1980s, over 66 percent of the area was under forest (Figure 4.7). Throughout the 1990s, the area sustained the highest deforestation rate among the other zones with a loss of about 445 hectares (or 1.3 percent) per year. By 2010, only 26 percent of the area was still under forest.

Driving this high deforestation rate in the 1990s was cropland expansion, which expanded by about 4,669 hectares in the 1990s, only to decline by 2,611 hectares in the subsequent decade. In contrast, pasture expansion was slow until 2000, but then it almost quadrupled to cover 10,822 hectares, or 33 percent of zone 1, by 2010. Thus, similar to the study-area-scale trend, PCC data indicate that deforestation in zone 1 was primarily driven by cropland expansion until about 2000, but thereafter driven primarily by pasture expansion while total cropland declined.

Figure 4.7: Land cover change in zone 1 (1980-2010).
4.3.2.ii  Zone 2: northern Mestizo villages

Zone 2 includes the area surrounding Trinidad and Guinea Grass, two Mestizo villages. In 1980, forest covered only 33 percent of the 6,427 hectare zone. By 2010, the forested area had declined to only 23 percent, or less than 1,500 hectares. However, PCC data indicate that the forested area did not simply decline steadily, but decreased to a low of 16 percent in 1995, then recovered to about 25 percent from 2004 to 2010. As figure 4.8 shows, until 2000 deforestation and forest recovery was likely closely linked to changes in the total cropland area. However, after 2000, the cropland area declined steadily as pastures expanded to occupy roughly 12 percent of the zone from 2004 onwards. Thus, PCC data suggest a degree of cropland instability that must be further investigated using PH data.

![Figure 4.8: Land cover change in zone 2 (1980-2010).](image)

4.3.2.iii  Zone 3: central Mestizo villages

Zone 3, which covers 7,218 hectares, includes the area surrounding San Lazaro, Yo Creek, Chan Pine Ridge, and Tower Hill, which are four Mestizo villages located closest to Orange Walk Town. From 1980 to 2010, PCC analysis indicates that forest cover increased in this zone by about 211 hectares (Figure 4.9). However, like zone 2, the forest area fluctuated over time. First, the total forest area declined sharply by 479 hectares from 1989 to 1995, then it increased by 631 hectares from 1995 to 2004, and then it declined again by 53 hectares from 2004 to 2010. The PCC data further indicate that the total cropland area declined by 1,647 hectares while the pasture area increased by only 367 hectares over the three decades. This trend suggests that cropland was not being converted either to forest or pasture, and therefore it raises the question of what happened to over 1600 hectares of
cropland during the study time period.

Natural grasslands changed very little in most zones. However, zone 3 experienced a significant increase in grasslands from 1989 to 2010, and especially from 2004 to 2010. From 1989 to 2010, the area’s grasslands increased by 1,282 hectares. Of this increase, 923 hectares occurred between 2004 to 2010. By 2010, grasslands covered almost 18 percent of the zone, which is at least double the other zones. Given this trend, it is probable that abandoned cropland reverted to natural grasslands, especially if it was just recently taken out of production. Although these areas are not technically classified as natural grasslands, they likely share a similar spectral signature. Thus, PCC data suggest that cropland declined from 1989 to 2010 and was converted partially to forest, but mostly to natural grassland.

Figure 4.9: Land cover change in zone 3 (1980-2010).

4.3.2.iv Zone 4: the southern Mestizo villages

Zone 4 includes four of the southernmost Mestizo villages in the study area, namely August Pine Ridge, San Felipe, Indian Church, and San Carlos. The zone covers only 8,443 hectares and it is the most densely forested zone within the study area. In 2010, 43 percent of the zone was under forest, but in 1980 the area was 67 percent forested (Figure 4.10). Prior to 2000, this decline was largely due to cropland expansion which covered 31 percent in 1989 and 49 percent in 2000. Cropland declined after 2000, and by 2010 it covered only 32 percent of the zone. Meanwhile, pastures expanded quickly to cover 3 percent of the zone in 2000 to 13 percent in 2010. Thus, PCC data indicate a fairly straightforward trend that saw forests decline first as a result of cropland expansion, and then as a result of pasture
expansion.

![Figure 4.10: Land cover change in zone 4 (1980-2010).](image)

### 4.3.2.v Summary of zone-level land cover change

In summary, Table 4.6 shows the common land cover change trends in the four zones. The table shows that the only area that experienced constant deforestation was zone 1, the Mennonite area, while all other zones experienced at least one period of net forest increase (i.e. a forest transition). From 1989 to 2010, cropland declined in all zones, except from 1989 to 2000 in zones 1 and 4. Unlike cropland, pasture increased in all zones and during all time periods, suggesting that either forest was cleared for new pasture or cropland was increasingly converted to pasture. Examining pixel histories helps to reveal more about the underlying land cover change processes taking place in each zone.

<table>
<thead>
<tr>
<th>Land change process</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant deforestation (1980-2010)</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Net forest transition at any time</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Increase in cropland area (1989-2000)</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Increase in cropland area (2000-2010)</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Decrease in cropland area (1989-2010)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Increase in pasture area (1989-2000)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Increase in pasture area (2000-2010)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Decrease in pasture area (1989-2010)</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>

Table 4.6: Land change processes in zones 1 to 4.
4.3.3  **Pixel histories**

The PH analysis results are presented in this section for the three main land covers relevant to this thesis, namely forest, cropland (which includes bare earth), and pasture. Other land cover types, namely urban, wetland, water, and natural grasslands, are only considered when they are directly related to changes in any of these land cover classes. The discussion reviews forest, cropland, and pasture change at the study area and zone-levels of analysis before presenting a summary of prominent pixel histories. These data help explain dominant land cover change trajectories observed in PCC data.

### 4.3.3.i  Forest change

Pixel histories in the study area help to distinguish between the amount of older forest that is at least 30 years old and younger forest that is less than 30 years old. To simplify, these can be referred to as primary and secondary forest, respectively. Zones 1-4 contained a total of about 17 percent primary forest from 1980 to 2010, and the majority was located in the Mennonite area (zone 1) and the southernmost Mestizo communities (zone 4). However, around 8 percent of zones 2 and 3 were covered with primary forest. The remaining forest stands identified in the 1980 MSS images were disturbed in subsequent decades by either cropland expansion (13 percent of the area), pasture expansion (10 percent of the area), and some urban expansion (1 percent of the study area). As observed in the PCC data, the highest rate of these expansions took place in the Mennonite area (zone 1), forest-to-cropland and forest-to-pasture pixel histories covered a total of 31 percent of the zone.

<table>
<thead>
<tr>
<th>Pixel history</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
<th>Zones 1-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest to forest (steady state)</td>
<td>ha</td>
<td>5,839.7</td>
<td>537.8</td>
<td>818.4</td>
<td>2,094.3</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>17.6</td>
<td>8.4</td>
<td>11.3</td>
<td>24.8</td>
</tr>
<tr>
<td>Forest to cropland (linear)</td>
<td>ha</td>
<td>4,585.1</td>
<td>480.4</td>
<td>188.3</td>
<td>977.9</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>13.8</td>
<td>7.5</td>
<td>2.6</td>
<td>11.6</td>
</tr>
<tr>
<td>Forest to cropland (stepwise)</td>
<td>ha</td>
<td>614.4</td>
<td>6.9</td>
<td>8.6</td>
<td>47.0</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>1.8</td>
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<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Forest to pasture (linear)</td>
<td>ha</td>
<td>1,973.7</td>
<td>5.8</td>
<td>2.4</td>
<td>44.8</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>5.9</td>
<td>0.1</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Forest to pasture (stepwise)</td>
<td>ha</td>
<td>3,042.0</td>
<td>17.3</td>
<td>12.3</td>
<td>265.1</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>9.2</td>
<td>0.3</td>
<td>0.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Forest to Urban (linear)</td>
<td>ha</td>
<td>265.1</td>
<td>18.4</td>
<td>6.2</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>0.8</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Forest/Cropland rotations</td>
<td>ha</td>
<td>49.1</td>
<td>5.3</td>
<td>19.6</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*Table 4.7: Forest pixel histories.*

Thus, these results highlight two important underlying trends in the study area. First,
even though the majority of zones experienced a decline in cropland area, PH data indicate that expansion occurred throughout the study area and even in areas where PCC data indicate a net reduction of cropland area, such as in zones 2 and 3. Second, although PCC data indicate that all areas experienced ongoing pasture growth from 1989 to 2010, PH data conversely indicate that the majority of these pasture areas were not the result of direct forest clearance. Instead, PH data indicate that pasture expansion was likely more the result of cropland conversion than deforestation. To evaluate further the relationship between forest change and agricultural change, it is necessary to consider cropland and pasture pixel histories.

### 4.3.3.ii Cropland change

Pixel histories provide insight into the distribution of permanent cropland, abandoned cropland, converted cropland, and areas where crop/pasture rotations are predominate. Although only 9 percent of the total inhabited area (as defined in Section 4.1.1) was under permanent cropland from 1989 to 2010, over 26 percent of zone 2, 17 percent of zone 3, and 10 percent of zone 4 remained cropland throughout this period. Conversely, only about 3 percent of the Mennonite area (zone 1) was permanent cropland. However, in addition to permanent cropland, PH data also indicate that at least 3 percent of the inhabited area experienced a cropland-to-cropland retrograde transition, such that the area changed into pasture for one temporal interval before reverting back to cropland. Thus, combining these two type of pixel histories indicates that over 11 percent of the study area was permanent or near-permanent cropland, and the highest percentages of this land cover were found in northernmost Mestizo areas (i.e. zones 2-4).

Pixel histories also indicate that cropland was converted either to forest or other land covers, such as natural grassland, wetlands, or water. These only occurred on about 7 percent of zones 1-4. However, Table 4.8 indicates that, the percentage of area abandoned to forest or other land cover was at least twice as large in the Meztizo area (zones 2-4) than it was in the Mennonite area (zone 1). Thus, these results suggest that even though the Mestizo area had the largest portion of permanent cropland, there was also a portion of cropland that was abandoned in that area.

In summary, the PH results for cropland change echo the PCC analysis results. The net decline in cropland area occurred as pastures expanded, which suggests that at least a portion of the area under crops was being converted to pasture.
4.3.3.iii Pasture change

As shown in Table 4.9, pixel histories indicate that pastures were rarely ever converted to other land cover classes. The only exception is where pastures were converted to grasslands, water, and wetlands (grouped as “other” in Table 4.9). Thus, the PH analysis results suggest that permanent pasture was quite uncommon in the study area and therefore adds support to the previous observation that rotations between crops and pasture were common, such that fallowed cropland would be used for grazing.

4.3.3.iv Summary of pixel histories

Pixel histories help to identify contrasts between zones. In the Mennonite area, PH data confirm that cropland and pasture expansion were the two primary drivers of deforestation. However, evidence in this area further suggests that, over time, Mennonite farmers increasingly adopted livestock production as large areas of cropland were converted to pasture.

In the Mestizo area, there is considerable variation between the three zones, but a large permanent cropland area is the most distinct trend. However, there is also evidence to suggest that the same tendency to convert cropland to pasture existed in some Mestizo areas. Thus, the contrasts between the Mennonite and Mestizo areas ultimately suggest that a fairly uniform agriculture system predominates in the Mennonite area whereas a more diverse agricultural system likely existed in the Mestizo areas. This aspect is examined further in Chapter 5 using farm-level survey data.

<table>
<thead>
<tr>
<th>Pixel history</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
<th>Zones 1-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland to cropland (steady state)</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,107.6</td>
<td>3.3</td>
<td>26.3</td>
<td>16.9</td>
<td>9.8 8.8</td>
</tr>
<tr>
<td>Cropland to Cropland (retrograde)</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>486.6</td>
<td>1.5</td>
<td>4.7</td>
<td>5.9</td>
<td>2.9 2.6</td>
</tr>
<tr>
<td>Cropland to forest (linear)</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>902.8</td>
<td>2.7</td>
<td>6.6</td>
<td>6.9</td>
<td>5.4 4.1</td>
</tr>
<tr>
<td>Cropland to other (linear)</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>123.9</td>
<td>0.4</td>
<td>2.9</td>
<td>5.1</td>
<td>1.1 1.4</td>
</tr>
<tr>
<td>Cropland to pasture (linear)</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,576.2</td>
<td>7.8</td>
<td>9.1</td>
<td>7.9</td>
<td>6.3 7.7</td>
</tr>
<tr>
<td>Cropland to urban (linear)</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>317.5</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>1.6 1.2</td>
</tr>
<tr>
<td>Cropland/Pasture rotation</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,654.0</td>
<td>5.0</td>
<td>2.2</td>
<td>3.3</td>
<td>2.3 4.0</td>
</tr>
</tbody>
</table>

Table 4.8: Cropland pixel histories.
4.4 DISCUSSION

The land cover change analysis provides insight into the decisions made by farmers within the study area from 1980 to 2010. Further, by integrating land change statistics with other socio-demographic and environmental data, insight is gained about the types of farms possibly operating in the study area. Specifically, integrating these data provides a holistic perspective on the response diversity of farmers to various environmental and social disturbances. Also, this perspective helps to identify the possible existence of several negative feedbacks that may have potentially impacted on local farming communities. In addition, by revealing a degree of diversity within the study area in terms of responses, a justification is made for a closer examination of the human dimension of land change at the farm- and zone-level. Thus, this section discusses the evidence that can be drawn from the land cover change assessment to help reconstruct the response diversity, disturbances, and negative feedbacks within the study area from 1980 to 2010.

4.4.1 Response diversity in the study area

The land cover change assessment reveals several examples of responses within the study area that allow important indicators of farm resilience to be identified. The land cover change patterns help to identify how farmers managed disturbances through environmental, agricultural, and/or social change. These three types of responses are discussed next before considering the disturbance regime and feedbacks thereafter.

4.4.1.i Environmental change

Among the dominant adaptive management strategies of farmers in the LAC region is
the decision to expand agricultural production through deforestation. Although researchers now recognize that there are multiple proximate and underlying causes of deforestation (Geist & Lambin 2006), agricultural expansion remains a dominant trend in the LAC region (Aide et al. 2013). In line with this regional trend, the deforestation rate in Belize is high and is also due largely to agricultural expansion. Also, as in the rest of the LAC region, various social problems relate closely to deforestation in Belize, namely rural population growth, drug trafficking, poverty, unemployment, and the increasingly globalized rural economy for export crops like citrus and sugarcane (Martin & Manzano 2010). As expected, the national-level trend towards deforestation and agricultural expansion is observed in the study area since overall forest cover declined rapidly from 1980 to 2010 as cropland and/or pasture expanded. Thus, evidence of deforestation in the study area signifies that farmers responded to disturbances by expanding specific types of agricultural production, and these decisions may be associated with a number of additional social and environmental disturbances.

However, the purpose of the land cover change assessment was not simply to compare the study area to national or regional patterns. Instead, the objective was to identify different land cover change patterns within the study area that likely relate to different adaptive management strategies. Looking exclusively at the forest change results, it is apparent that three different trends exist within the study area (Figure 4.11). The first, in zone 1, relates to the establishment of a new Mennonite community in Indian Creek. Expansion in this area was not so much a response by existing farmers in Indian Creek to disturbances, because the community itself did not exist prior to the early 1990s. Instead, the establishment of Indian Creek and subsequent deforestation in that area was a response by farmers in Shipyard to overpopulation in that community (King et al. 1992). The deforestation pattern in zone 1 was akin to the patterns observed in other frontier settings within the LAC region, such as in many areas within the Amazon basin (see, for example, Aldrich et al. 2006; McCracken et al. 2002). In these frontier settings, extensive deforestation over a short period of time is typically followed by a decline in deforestation rates once forested land becomes scarce. Thus, although deforestation seems like a persistent trend in the Mennonite zone, there will come a time when deforestation will slow and the remaining forest cover will stabilize. When this will occur and what the lower forest cover threshold will be remains unclear, and is a matter of significant concern among conservationists.
The second important pattern observed in the LAC region is in zone 4. In this area, there was rapid deforestation since 1980 at a rate similar to zone 1. However, deforestation ceased when there was still about 40 percent forest cover in the zone, which is the highest forest coverage in the study area. Once this lower threshold was met, it seems that further expansion was no longer a viable response to social and environmental disturbances. Instead, farmers in this area likely turned to other adaptive management practices, such as intensification. This decision ultimately led to increased forest stability, and even some forest transitions.

The third deforestation trend occurred in zones 2 and 3 where the forest cover in 1980s was the lowest in the study area. The land cover change results show that agricultural expansion occurred from 1980 to 1995, but once forest cover reached a lower threshold of around 16-17 percent, expansion ceased and forest transitions began. These forest transitions continued over the next 15 years as farmers likely stopped expanding agricultural production in favour of other responses (e.g. intensification). Not surprisingly, this area is used primarily for sugarcane production, so farmers must have relied more upon intensification rather than on agricultural expansion to respond to disturbances relating to production, which is a possibility that is further investigated in Chapter 5.

In summary, although the overall trend shows that agricultural expansion through deforestation in the study area is consistent with the overall national trend in Belize, it is
apparent that agricultural expansion was not a viable response at the same times and in all zones. This is consistent with Lambin et al.'s (2006) observation that land cover change eventually gives way to land modifications, which may not be observable in remote sensing data. In other words, the land cover change assessment helps to identify deforestation as a potential response, but it may fail to identify other potential responses to disturbances, such as intensifying production. Hence, environmental change is certainly a common response to social and environmental disturbances, but it is not common throughout the entire study area.

4.4.1.ii Agricultural change

Two main examples of agricultural change are visible in the land cover change assessment, namely the adoption of livestock production and intensification. These changes demonstrate a degree of “transformability” within the different farming communities, and perhaps a changing identity of many farms. However, as with environmental change, not all zones demonstrate the same types of transformations. Above all, these trends are quite consistent with national level trends in Belize as well as trends within the LAC region, where there is both widespread meat production and intensified crop production. However, as with environmental change, variation exists within the study area.

The transition to livestock production has been observed throughout the LAC region and has been increasing in Belize since 1980 with a doubling of the national herd (IICA 1995). The vast majority of pastures are located in the Mennonite area (zone 1) where over 32 percent (or ~10,000 hectares) of the land area was under pasture by 2010. One important reason for this trend is the fact that Mennonites are not permitted by law to produce sugarcane, so during times of market insecurity (e.g. the 1980s), the Mennonites could not turn to sugarcane, which is a perennial, globalized, and increasingly subsidized crop. Instead, they had to rely more on livestock production, which remains a product in high demand. Thus, the decision to convert cropland to pasture represents a response that existed throughout the study area to a limited degree, but mostly within the Mennonite area. A closer consideration of this process at the farm level in Chapter 5 is therefore required to gain additional insight into this adaptive management strategy.

The second example of agricultural change is the evidence of permanent cropland in the study area. The previous discussion in Chapter 3 explained that intensification through the consumption of agrochemicals, irrigation, and mechanization was widespread throughout
the LAC region since the 1960s. Within the study area, the land cover change assessment provides evidence that a vast majority of permanent cropland was located in the northern Mestizo zones, namely zones 2 and 3. This area is primarily used for sugarcane production, which is rarely rotated with other crops. To sustain and increase sugarcane production, farmers must rely heavily on chemical inputs, a fact that has raised a number of environmental concerns in other sugar-producing areas (Martinelli and Filoso 2008). Thus, the establishment and maintenance of permanent cropland represents a distinct adaptive management strategy that depends on high amount of inputs, less expansion, and less crop rotation – all of which were observed in the northern Mestizo zones.

In summary, the adoption of livestock production and the establishment of permanent cropland represents two distinct adaptive management strategies operating within the study area. However, as with deforestation, agricultural change as an adaptive strategy was not evenly distributed throughout the study area. Hence, further investigation at the farm-level is necessary to understand how these practices helped to strengthen farm resilience and how other farmers responded to disturbances without changing their agricultural practices.

4.4.1.iii Social change

It was observed that over 2,000 hectares of cropland were converted to forest from 1980 to 2010, a process that is commonly referred to as forest transition. As discussed previously in Chapter 3, forest transitions result from complex circumstances that typically involve social, political, economic, and environmental factors. More specifically, Rudel et al. (2005) identified three main circumstances that may lead to forest transitions, namely the creation of non-farm jobs, agricultural intensification, or reforestation. Thus, it is likely that the abandonment of agricultural land represents a social response to disturbances that involves a fundamental change in livelihood.

Although it is impossible to consider fully the complexities of forest transitions without relying on socio-economic data, several facts can be derived from the land cover change assessment and the analysis of demographic indicators. Specifically, forest transitions occurred most in the Mestizo zones, particularly in areas where there was a substantial amount of permanent cropland, which is most likely to be sugarcane plantations. The 2010 Belize population census indicated that between 35 and 76 percent of residents in the Mestizo area rent their land, as opposed to only 0.2 percent in the Mennonite area. Furthermore, it was also observed earlier in this chapter that the number of people involved
in agricultural production is substantially lower in the Mestizo area as compared to the Mennonite area. Hence, it is possible that as Mestizo farmers intensified their sugarcane production, other farmers decided to abandon leased cropland. This possibility would explain why less farmers were in operation within the Mestizo zones. The exact circumstances that led to cropland abandonment may remain unclear until further study is conducted in the area. However, from the extensive literature on forest transitions elsewhere in the tropics, it is fairly certain that this type of land cover change involves complex social processes at the individual farm level.

4.4.1.iv Summary of responses

In summary, the land cover change assessment reveals that there are four prominent responses by farmers to disturbance, namely expansion, intensification, modification, and abandonment of the agricultural area. By locating and quantifying the prevalence of these responses within the study area, it is shown that contrast exists between different zones. In particular, the obvious contrast exists between the Mennonites who rely more on livestock production and the Mestizo farmers, who rely more on sugarcane production. Thus, it can be expected that a farm-level assessment will reveal additional contrasts between these two areas. The following section builds on this discussion by considering the possible disturbances and feedbacks associated with the land cover change patterns observed in this assessment.

4.4.2 Farm disturbances and feedbacks in the study area

As discussed previously in Chapter 3, farmers in Belize manage a wide variety of environmental and social disturbances that range in severity across various spatial and temporal scales. The land cover change assessment helps to identify which disturbances are most prevalent within the study area. Thus, the following sections consider four environmental disturbances, namely land suitability, land degradation, water contamination, and hurricanes. After this, three social disturbances are considered, namely issues relating to socio-demographic change, socio-economic change, and infrastructure. This is not an exhaustive discussion, but gaining an understanding of these disturbances and feedbacks provides additional insight into the nature of farm resilience in the study area.

4.4.2.i Land suitability

The question of whether land cover change is influenced by land suitability is an important and complex one. Although it may not be possible to address this issue with the
present data adequately, it is worth comparing land cover change results to the land suitability index devised for Northern Belize by King et al. (1992), which are referred to as land systems. Since farmers in Belize often lack information concerning land suitability prior to establishing or expanding their agricultural production, large-scale expansion in unsuitable areas may result in higher rates of forest transitions or land conversions because agricultural production can become untenable over time due to nutrient deficiencies, loss of moisture, excessive moisture, etc. A classic example of this trend in the study area occurred when the Mennonites first colonized the Shipyard area they saw the dark black soil and immediately recalled similar looking soils in Canada that were of very high quality (Sawatzky 1971). However, soon after establishing their community, these farmers realized that much of the dark soils in Northern Belize are slightly acidic and nutrient deficient.

To explore the possibility that land systems, as defined by King et al. (1992), influenced the rate and pattern of land cover change, consider the location of cropland, pasture, and forest change from 1989 to 2010. First, when evaluating net cropland and pasture change based on PCC results, it is evident in that land suitability was not the primary disturbance impacting on farmers. The total cropland area both declined and increased on land deemed both suitable or unsuitable for crop production. Likewise, even though pasture expanded within almost all land systems, it also declined in suitable areas (i.e. the Xaibe Plain) and increased in unsuitable areas (e.g. the Sibal swamps). Thus, land suitability was likely not a major driver of cropland and pasture change.

Second, evidence of forest transitions derived from PH data also indicates that both suitable and unsuitable land was abandoned throughout the study area. This suggests that the decision to abandon agricultural land was not solely dictated by environmental variables. However, there is no doubt that land suitability was, and continues to be, a major source of disturbance for farmers in Belize since tropical soils are notoriously difficult to farm without considerable nutrient and labour input. Indeed, directing future agricultural development is among the chief objective of the nation's recent land use policy strategies (Meerman et al. 2011).

Land suitability was certainly not the only source of disturbance to farmers in this area of Belize. Instead, a key point to observe here is that the remote sensing data combined with King et al.'s (1992) land suitability indicators suggest a degree of agricultural resilience in areas that suffer from nutrient deficiency, drainage issues, risk of erosion, and excessive moisture. Thus, land suitability exemplifies a manageable disturbance in the study area, and
an important step forward will be to understand exactly how land was managed differently throughout the study area.

4.4.2.ii Land degradation

Comparing the results of the Preliminary Survey of Land Degradation in Belize (Meerman & Cherrington 2005) to the land cover change results for the study area also reveals very little new information about farm disturbances. Meerman and Cherrington's (2005) report examined soil types, topography, and the results of King et al.'s (1992) land suitability study to create an index that ranges from zero (no land degradation potential) to seven (high risk of land degradation). As shown in Figure 4.12, the land degradation potential in the study area is low, with a range from zero to six. Additionally, only 6.2 percent of the study area (or 3,906 hectares) is classified as 4 or above. This implies that the vast majority of the study area faces a marginal or low risk of land degradation with prolonged agricultural activity. However, it is noteworthy that almost all of the 3,906 hectares of higher risk land is located within the boundaries of zones 1 and 4, the southernmost zones. Thus, this prompts the question whether the presence of these higher risk areas disturbed agricultural production in that area. (Table for total area, then table for different land cover types, namely cropland and pasture).

This question can be addressed using the results of the land change assessment which shows two contrasting trends for cropland and pasture expansion. First, cropland located on areas deemed at higher risk (4 and above) changed very little from 1989 to 2010 despite overall growth in the cropland area. Indeed, 5.4 and 5.7 percent of cropland in zones 1 and 4 were located in these higher risk areas in 1989 and these numbers changed slightly to 6.3 and 5.0 respectively by 2010. This suggests that crop production in these marginal areas was not terribly affected by erosion, drought, or other symptoms of land degradation which could force farmers to abandon land in other circumstances. The challenges may have been met by changing some crop varieties or some other agricultural practice. Hence, continual production in these areas indicates that land degradation is likely not a serious disturbance for crop producers in the study area.
In contrast to cropland, the total pasture area in each zone declined in the same higher risk areas from 1989 to 2010. Roughly 15 and 16 percent of area under pasture in zones 1 and 4, respectively, were located on these higher risk areas in 1989. Those figures dropped to 10 and 4 percent, respectively, by 2010. This tends to suggest that areas subject to drought or high moisture would have been unsuitable for pasture production, and farmers therefore chose to expand into other areas, notably onto cropland that had already proven its productive suitability. The decline in pastures in higher risk areas suggests that the effects of land degradation may have disturbed livestock production in these areas. Thus, this indicates that land degradation may be one source of disturbance to the area's livestock producers, but overall it was not a major source of farm disturbance.

4.4.2.iii Potential water contamination

As discussed in Chapter 3, water availability and contamination are serious concerns throughout the LAC region (UNEP 2007). Numerous studies, both within the LAC and abroad, have found a direct correlation between higher concentrations microbial pathogens
and nutrients in groundwater and intensive agricultural activity (see, for example, Almasri & Kaluarachchi 2004; Babiker et al. 2004; Guo et al. 2006; Rawlins et al. 1998; UNEP 2007). This is especially true in tropical areas, where nutrient deficiencies in soil and more frequent pest infestations necessitate a higher consumption of fertilizer and other agrochemicals, and therefore a higher rate of agrochemical run-off and leaching into groundwater and surface water (FAO 1996).

There are three reasons to be concerned about water contamination in the study area as a potential disturbance to local communities. First, the land cover change assessment clearly demonstrates that zones 2 and 3 are at the highest risk because they contain the highest amount of permanent cropland, less evidence of crop/pasture rotations, and the lowest amount of forest and natural vegetation that would otherwise absorb some excess inputs before they reach natural water sources. Further, the primary crop in this area is sugarcane, which has a very high nutrient requirement. Thus, due to the land cover change patterns and the dominant crop type, the inhabitants of the northern Mestizo area may be exposed to higher amounts of agricultural contaminants.

A second concern relates to the main water source within the study area. As shown in Table 4.10, a large portion of the population relies on non-public water sources which are more likely to be contaminated by agrochemical run-off and leaching. Both private piped systems and dug wells are most likely to expose human inhabitants to agricultural contaminants (see, for example, Knobeloch et al. 2000). From the available data published in the 2010 population census of Belize, almost half of the population in the study area relies on non-public sources of water. This raises a number of health concerns for the local inhabitants since contaminated domestic water has been linked to a number of tropical diseases and other health risks, as discussed in Chapter 3.
Third, there is reason to be concerned that the increasing livestock production since 2000, particularly in the Mennonite area, has had adverse impacts on the local water supply. Studies in the LAC region, notably in Uruguay (Ran et al. 2013), found that the intensification of beef production through feed-crop cultivation resulted in higher water use and higher rates of land degradation (i.e. loss of water holding capacity). Since the land cover change results for the study area indicate that there is a shortage of available forested areas to expand, it is possible that present crop-livestock rotations will soon be replaced with permanent pasture areas. Thus, the shift to livestock and its associated feed requirement may contribute to a decline in water availability in the area.

Although extensive water quality analysis and epidemiological data are needed to identify with certainty that water contamination is a disturbance to farmers in the study area, the current land cover change assessment identifies it as a potential disturbance that deserves further investigation in future research.

4.4.2.iv Hurricanes and tropical storms

As discussed previously in Chapter 2, resilience to natural disaster and resilience to the effects of climate change are prominent areas of study. However, it was explained that climatic disturbances are not experienced evenly throughout a region, such that some areas face more frequent and/or more powerful climatic events than others. In Chapter 3, the recent hurricane history in Belize and the Caribbean was reviewed, and it was explained that such events can have devastating effects on agricultural production. Within the context of the current land cover change assessment, it is now possible to consider whether the farmers in the study area were severely effected by recent tropical storm events.

<table>
<thead>
<tr>
<th>Water source</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUBLIC PIPED INTO DWELLING</td>
<td>0.00%</td>
<td>14.36%</td>
<td>50.62%</td>
<td>45.72%</td>
<td>25.85%</td>
</tr>
<tr>
<td>PUBLIC PIPED INTO YARD ONLY</td>
<td>0.61%</td>
<td>51.34%</td>
<td>18.04%</td>
<td>35.45%</td>
<td>25.82%</td>
</tr>
<tr>
<td>PRIVATE PIPED INTO DWELLING OR YARD</td>
<td>83.75%</td>
<td>4.90%</td>
<td>29.02%</td>
<td>0.97%</td>
<td>31.54%</td>
</tr>
<tr>
<td>DUG WELL</td>
<td>3.15%</td>
<td>24.35%</td>
<td>0.80%</td>
<td>14.64%</td>
<td>10.85%</td>
</tr>
<tr>
<td>PRIVATE CATCHMENTS, NOT PIPED</td>
<td>4.77%</td>
<td>0.71%</td>
<td>0.12%</td>
<td>1.30%</td>
<td>1.88%</td>
</tr>
<tr>
<td>RIVER/ STREAM/ CREEK/ POND/ SPRING</td>
<td>2.75%</td>
<td>0.11%</td>
<td>0.43%</td>
<td>0.38%</td>
<td>0.99%</td>
</tr>
<tr>
<td>OTHER</td>
<td>4.98%</td>
<td>3.93%</td>
<td>0.96%</td>
<td>1.51%</td>
<td>2.99%</td>
</tr>
<tr>
<td>NOT REPORTED</td>
<td>0.00%</td>
<td>0.29%</td>
<td>0.00%</td>
<td>0.03%</td>
<td>0.08%</td>
</tr>
</tbody>
</table>

Table 4.10: Percentage of population by zone and their source of water (Belize Population Census 2010).
Figure 4.13 combines the land cover change data derived from the PCC analysis with the timing of major tropical storms and hurricanes (labelled a to g). It is apparent that Belize faced very few severe storms from 1980 to 1998, a time when crop production expanded and forest areas declined. The only notable storm during this period was tropical storm Hermine in 1980 (a). However, from 1998 onwards, Belize experienced at least 11 named storms, namely Hurricane Mitch in 1998 (b), Hurricane Keith in 2000 (c), tropical storm Chantal and Hurricane Iris in 2001 (d), Hurricanes Dean and Feliz in 2007 (e), tropical storm Arthur in 2008 (f), and hurricanes Alex, Karl and Richard and tropical storm Matthew in 2010 (g). Since hurricane Dean alone caused extensive property and crop damage throughout the Caribbean, the frequency and intensity of these storm events in Belize, even if they did not pass directly over Northern Belize, likely had a negative effect on crop production in the study area. Thus, hurricanes may be one factor that contributed to the decline of cropland since 2000 and the overall shift towards livestock production, which is more resistant to the impacts of weather-related disturbances.

Figure 4.13: Land cover change showing the timing of tropical storms and hurricanes in Belize.

4.4.2.v Sociodemographic change

Deforestation, as discussed in Chapter 3, poses a serious concern for the rural communities that depend heavily on forests as a source of timber and non-timber forest resources. Sunderlin et al. (2005) observed that the livelihood of rural inhabitants is negatively impacted when forest products and services are no longer available, and a recent study by the FAO found that smallholders generated a substantial monetary and non-
monetary income from forests. The land cover change assessment, combined with demographic data, provides evidence to suggest that the communities in the study area may be faced by a number of these potential social disturbances.

First, it was explained previously in Section 4.1 that the population grew consistently in each village/community from 1991 to 2010, and in some areas the population actually doubled. With the land cover change assessment data in hand, it is possible to calculate the amount of forest available per capita within the four zones over time. Table 4.11 shows that in 1989/91 (i.e. land cover change data/population census data) there were about 4 hectares of forest per individual within the study area. However, by 2010 that number had declined to 1.0 for the study area. The highest forest cover per individual was in the Mennonite area at all times, which is fortuitous since this area and zone 4 are largely without a stable source of electricity (for both cultural and logistical reasons), so they would depend more heavily on wood for cooking. Also, since zone 4 is located furthest from Orange Walk Town, where most individuals buy their food, forests are a useful source of food (e.g. hunting, fruit, nuts). Although the inhabitants of zone 2 and 3 may not depend so heavily on forests for fuel since they have a relatively stable source of electricity, less forest in these areas likewise limits access to additional food resources supplied by forests. These forest resources are likely quite important to the rural communities in zones 2 and 4 since their main crop is sugarcane, though future research is required in this area. Thus, the increasingly limited access to forests throughout the study area presents numerous potential social disturbances, but further study is necessary to understand how forests are used within these communities.

<table>
<thead>
<tr>
<th>Zone</th>
<th>1989/91*</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>8.7</td>
<td>4.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Zone 2</td>
<td>1.0</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Zone 3</td>
<td>1.0</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Zone 4</td>
<td>3.4</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>4.1</td>
<td>1.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 4.11: Hectares of forest per individual within the study area.

Second, it was also observed previously in Section 4.1 that according to 2010 population census results, the number of people involved in agricultural production differed considerably between each village and community. When these data are combined with the land cover change assessment results for cropland and pasture (Table 4.12), it can be observed that the amount of cropland and pasture per individual is about 1.7 and 1.3 hectares, respectively. However, the Mennonite area (zone 1) has substantially more
cropland and pasture per individual than the Mestizo area (zone 2-4), even though it was observed in 2010 that over 90 percent of Mennonites were engaged in agriculture. Conversely, there was considerably less land per individual in the Mestizo area, where the agricultural population ranges from only 57 to 68 percent. These data suggest that agricultural land is considerably more scarce in the Mestizo area than in the Mennonite area, thus suggesting that land shortages and competition for land rights is likely one source of disturbance in these communities.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Agricultural population (2010)</th>
<th>Cropland (ha) per person</th>
<th>Pasture (ha) per person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>3915</td>
<td>2.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Zone 2</td>
<td>2378</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Zone 3</td>
<td>1857</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Zone 4</td>
<td>2074</td>
<td>1.3</td>
<td>0.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>10224</td>
<td>1.7</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 4.12: Hectares of cropland and pasture per agricultural population by zone.

In short, the evidence derived from the land cover change assessment supports the idea that deforestation and land appropriation for cropland and pasture is one source of social disturbance for farmers in the study area. These disturbances likely include higher fuel costs, increased food insecurity, loss of autonomy as dependence shifts to external sources of food, conflict relating to land shortages, and unemployment and poverty as less individuals have access to land and forest resources. These sources remains speculative, however, the land change assessment does suggest trends that are consistent with these potential social disturbances.

4.4.2.vi Socioeconomic disturbances

Economic growth the non-agricultural sectors, according to the recent policy report published by Martin and Manzano (2010), is one of the most pressing policy issues facing farmers in Belize, and there are several important connections that can be drawn between changes in GDP and the land cover change assessment. For example, the World Bank (2013) reported recently that GDP per capita grew in a stepwise manner in Belize from 1980 until 2010, such that three distinct periods of stagnated growth are separated by brief periods of rapid economic gains (Figure 4.14).
The first period of stagnated growth occurred in the 1980s, a decade which was dominated by civil war and economic downturn in Central America (see Chapter 3). From 1986 to 1992, Belize experienced a period of economic growth, but this period was followed by 6 years of slight economic decline. From 1998 to about 2002, Belize experienced another period of economic growth, which was followed by another decade of economic stagnation. When examining growth at a sectoral level in Figure 4.15, it is apparent that the services sector experienced the most overall growth since 1980, while the agricultural sector declined to about 12 percent of the nation's GDP. Thus, although Belize experienced periods of growth and stagnation, an overarching trend is a decline in the agricultural sector, which certainly caused much hardship for the nation's farmers.

When these economic data are compared to the land cover change results, it is apparent that economic change was an important source of disturbance to farmers in Belize. For example, during the three periods of stagnation in GDP growth, the land cover change assessment reveals lower rates of deforestation (especially in the 1980s) and higher incidences of crop-to-pasture conversion and forest transitions. This was especially visible since 2000, the longest period of economic stagnation. It was also observed during these periods of stagnation that there was an increase in pasture area. This suggests that some farmers modified their production system to include livestock, which a more stable production strategy during times of economic uncertainty.
It is therefore important to appreciate that economic change exposed farmers to a variety of disturbances, from fluctuating commodity markets to higher costs for agricultural inputs. These and other disturbances had two main outcomes that are observable in the land cover change assessment, namely cropland decline and livestock expansion (particularly since 2000). Thus, to understand better how economic disturbances impacted farmers in other ways, it is necessary to examine more closely decisions made at the farm level over time, which are discussed in Chapter 5.

![Figure 4.15: Percentage changes in economic sectors in Belize. Source: World Bank 2014.](image)

**4.4.2.vii Infrastructure**

As discussed in Chapter 3, road conditions were cited as a major limiting factor for agricultural production in Belize in a recent policy assessment (Martin & Manzano 2010), as discussed in Chapter 3. As shown in Figure 4.16, the entire study area, except for the northernmost zone 3, has no direct access to paved roads. Although officially classified as “major roads” according to Biodiversity and Environmental Resource Data System of Belize (www.biodiversity.bz), these roads are primarily unpaved dirt roads, except for a few portions which are paved where they run through adjoining villages (e.g. Trinidad, August Pine Ridge, Guinea Grass). There are no paved roads whatsoever south of August Pine Ridge on the western side of the study area and Guinea Grass on the eastern side. Hence, farmers in the southernmost area face major difficulties to ship produce to Orange Walk Town, particularly during the rainy season. Yet, due to agricultural expansion in this area
from 1980 to 2010, the farmers in this area face higher fuel and vehicle maintenance costs to get their produce to market. Thus, as farmers continue to clear land further from Orange Walk Town, and with no investments in road infrastructure by the national government, farmers in the study area are likely to experience increased farm disturbances.

Figure 4.16: Road classes in the study area. Source: BERDS 2014.

Thus, by combining relevant environmental, socio-economic, and transport data with the results of the land change assessment, it is evident that farmers in the study area face a number of local and regional disturbances and feedbacks from agricultural production that relate to land suitability, water contamination, economic disturbances, and a lack of essential infrastructure. To further examine these results, it is necessary to consult with farm-level data. Hence, Chapter 5 examines farm resilience in the study area at the farm-level to gain additional insight into the farm practices used to manage these various disturbances.
4.4.3 Limitations

Although the results of the land cover change assessment are informative about a number of key issues central to this thesis, remote sensing analysis is also subject to a number of limitations. Beyond obvious potential land classification errors, interpreting remote sensing results is problematic without extensive ground-based analysis. Further, the remote sensing data provide landscape-scale results, so inferences cannot be made about farm- or field-level processes.

The boundaries established for the study area and the zones present a number of limitations. Although the methodology used to define the zones, especially the use of Voronoi diagrams (Alani et al. 2001), are acceptable given the lack of official boundaries, there is still a degree of uncertainty regarding the accuracy of the them. However, approaching this concern systematically by addressing the effects of scale and aggregation, which is typically known as the Modifiable Areal Unit Problem (Longley et al. 2011), is not possible without external sources to validate the boundaries. Further, although portions of the boundaries were derived from Voronoi diagrams, the vast majority were derived based on expert knowledge of the area and aerial photographs. Thus, it is acknowledged that the hypothesized boundaries used in this study likely contain a degree of heterogeneity and errors relating to scale and aggregation.

Despite these potential sources of error and uncertainty, the results clearly show that different land cover change patterns occurred in different parts of the study area. It remains to evaluate the underlying land use processes that created these land cover change patterns with a farm-level assessment, which is presented in the next chapter.

4.5 SUMMARY

This chapter presented and discussed the results of a land cover change assessment of the 700 square kilometres study area located in northern Belize. Based on a LANDSAT time-series dating from 1980 to 2010, post-classification comparison and pixel-history analysis were used to evaluate land cover change processes in the study area and in each of the four zones (one Mennonite area and three Mestizo areas). The results showed that deforestation rates in the study area were slightly above the national average for this time period and that they were driven mainly by agricultural expansion. However, upon closer inspection, it became evident that prior to 2000 deforestation was mainly the result of
cropland expansion, while after 2000 pasture expansion (or conversion) was the main driver.

When examining these changes within each zone, it is clear that several different patterns existed and these landscape-scale processes are not necessarily found in all zones. Several important contrasts were observed, namely that some zones experienced forest transitions while others consistently showed evidence of deforestation. The Mennonite area was the dominant livestock production area, and the largest area of permanent cropland was located in the northernmost Mestizo zones where sugarcane is the primary crop.

These results helped to identify several important environmental, agricultural, and social responses to the local disturbance regime. They also helped to evaluate further the potential disturbances and negative feedbacks in the study area, such as those relating to land suitability, water contamination, tropical storms, sociodemographic issues, socioeconomic issues, and infrastructure deficiencies. In short, the main outcome of this assessment has to demonstrated that different land use practices have likely led to different land cover change outcomes within the study area. Hence, it is likely that farmers within each zone have adopted different adaptive management practices. To gain additional insight into these processes and to examine farm resilience further, the next chapter presents and discusses the results of a farm survey that was conducted throughout the study area in May and June of 2012.
5 FARM RESILIENCE IN NORTHERN BELIZE

Several important studies have been conducted on Belizean agriculture, including agricultural censuses and environmental assessments of the country's agricultural potential (Furley & Robinson 1985; Wright et al. 1959; King et al. 1992). However, except for a limited attempt to define farm types in Belize by King et al. (1992), farm diversity has yet to be evaluated fully, especially as it relates to various processes of environmental change and farm resilience. In order to assess farm resilience in northern Belize, this chapter classifies farms into six types based on variables that relate to a farm's main structures and functions. Next, this farm typology is used to assess the nature of each type of farm by considering its household organization, natural resource management, crop production strategies, and pasture management. The results reveal that different types of farmers in Belize adopt different adaptive management strategies, and are therefore affected by specific disturbance regimes that each require very different responses. Knowing how these different responses impact the environment is crucial to devise effective mitigation strategies to minimise the negative environmental consequences associated with unsustainable agricultural change, expansion, and intensification. Thus, this chapter seeks to evaluate rural farm diversity and resilience in northern Belize.

5.1 FARM ANALYSIS METHODOLOGY

The farm analysis comprises two main phases. The first phase was a farm practice survey in the study area that asked farmers about their household and agricultural organization. The second phase used these results to conduct a multivariate statistical analysis of farm diversity. The following subsections presents the methodology employed for each of these research activities.

5.1.1 Farm survey

The farm survey was designed to replicate similar surveys conducted in developed
countries and was also based on similar studies in tropical areas (McCracken et al. 2002; Brondizio et al. 2002; Moran 2005). The survey instrument was divided into four sections that focussed on general farm information, land conversion and expansion, crop production, and pasture management. The first section asked farmers to report on farm location, demographics, farm area, land appropriation, and water source on the agricultural land. The second sought information on the past land use activities of the farmers and their future plans regarding crop and livestock production. The third section asked farmers about all aspects of crop production, including crop type, planting cycle, sustainable agricultural practices, and intensive practices, such as fertilizer pesticide application, irrigation, and mechanization. Lastly, the fourth section was completed only by those farmers who managed pasture. This section asked farmers about the stocking rate on paddocks, herd rotation, and pasture inputs such as seeding, fertilizer, and pesticides.

The survey was administered during the Spring of 2012 to the primary operators of 145 households. The primary operator is the household member who makes decisions regarding farm activities. These households were located in the same ten Mestizo villages and two Mennonite communities that were reported in the previous chapter. Primary operators were randomly selected to be interviewed based on whether or not they are farmers. Farmers were defined as anyone who owns at least one cow or grows any crops for either household, domestic, or international consumption. The sample represents 5.1% of the 2,850 households in the study area and the respondents manage about 40 square kilometres of land within the study area (or about 5 percent of the total area). Thus, given the population of farmers within the study area, the margin of error for this sample is 7.93 percent at a the 95 percent confidence interval.

5.1.2 Multivariate farm analysis

Numerous studies use multivariate cluster analysis to evaluate farm typologies (see, for example, Novo et al. 2012; Tittonell 2013; Landais 1998; Köbrich et al. 2003). Although there are slight variations between these studies in terms of statistical methodology, it was explained in Chapter 3 that the variables chosen for such studies can vary greatly. Some studies use only agricultural variables, some use farm size, and still others use household demographics to identify statistically significant farm clusters. However, farm identity (i.e. its structure and function) should be defined based on a holistic approach that includes variables relating to both agricultural activities and to the human dimension. For this reason, farms were classified in this study based on household size, an important variable that
relates to labour availability, household lifecycle, household demand for resources, and the percentage of land appropriated for crop production, pasture, forest reserve, and fallow. In total, these five variables were used to classify farms.

K-mean cluster analysis can be used through trial and error when the exact number of clusters is unknown in a sample. This statistical technique is used widely to classify farms, but selecting the number of clusters is always problematic (see, for example, Ryschawy et al. 2012). For the present study, selecting the k-value is difficult because little is known about how farms differ within Belize since precise typologies have yet to be determined, except, perhaps, for King et al.'s (1992) description of farms as either milpa producers, mechanized family farms, family farms, or estates (see Chapter 4). Further, a one-way ANOVA is generated as part of the output for the k-means cluster analysis to verify the statistical significance of the resulting clusters. Before settling on a k-value of 6, the analysis was conducted with 3 to 10 cluster. The only results that has enough members in each class was achieved by using k=6. Thus, it is hypothesised that there are at least six distinct types of farms (two more than King et al.'s typology) that operate within the study area. However, with a larger sample it might be possible to differentiate several more distinct groups of farms.

To further evaluate the differences between the six groups, ANOVAs, frequencies, and descriptive statistics are used. Tukey's honest significant difference (HSD) test was also used as a post hoc statistic on one-way ANOVAs. The following section presents the results for this multivariate analysis of farm variability in the study area.

5.2 RESULTS

The results of the farm classification and the analysis of household organization, land use, domestic crop production, export crop production, and pastoral systems are presented in the following six subsections. Comparison is made between different types of farms while the distribution of farm types within each zone is discussed in Chapter 6 as part of the final discussion in this thesis.

5.2.1 Farm classification results

The final cluster solution divided the 143 farms into 6 clusters using the k-means classifier. As shown in Table 5.1, cluster size ranges from 14 farms in the sixth class to 35 farms in the fourth class. The largest clusters are the fourth and fifth, which represent 58
percent of the total farm sample. Although the size of each sample differs, there were still significant quantitative differences between each cluster. Each cluster is distinct from the others according to at least one variable. For example, the first cluster has a similar mean household size to cluster two, but differs from all other classes by its land appropriation strategy, notably the average 76 percent of land that is left fallow or idle. Hence, despite varying cluster sizes, there are statistically significant differences between each cluster. Further differences between these groups are investigated in the following subsections.

<table>
<thead>
<tr>
<th>Cluster size</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household size (mean)</td>
<td>6.1</td>
<td>5.9</td>
<td>7.4</td>
<td>5.4</td>
<td>4.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Percent cropland (mean)</td>
<td>19.4</td>
<td>10.8</td>
<td>50.3</td>
<td>55.4</td>
<td>94.6</td>
<td>11.3</td>
</tr>
<tr>
<td>Percent pasture (mean)</td>
<td>2.1</td>
<td>81.0</td>
<td>25.4</td>
<td>2.6</td>
<td>0.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Percent forest (mean)</td>
<td>2.3</td>
<td>3.4</td>
<td>3.4</td>
<td>40.5</td>
<td>1.1</td>
<td>86.7</td>
</tr>
<tr>
<td>Percent fallow/idle land (mean)</td>
<td>76.2</td>
<td>4.7</td>
<td>20.8</td>
<td>1.4</td>
<td>4.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 5.1: K-means cluster analysis on 143 farms demonstrate that at least six distinct types of farms exist within the study area.

5.2.2 Household organization

Household organization includes information about the primary operator, including his/her age, sex, marital status, country of birth, ethnic identity, language proficiency, and duration of residence. Household organization also includes information about household demographics and livelihood diversification. These data relate to the household life cycle, non-agricultural income diversification, and cultural differences that may signify different agricultural traditions.

5.2.2.i Head of household: age, origin and duration of residence

The primary operators of the 143 farms did not demonstrate significant differences in age, sex, or marital status. A one-way ANOVA was conducted to evaluate the potential differences between each group due to age, but no significant differences were found. For the whole sample, farmers' age ranged from 24 to 82 and the mean for each cluster ranged from just 50.6 to 55.1. Furthermore, all respondents were male, except for two primary operators, one within each of clusters five and six. Over 90 percent were either married or in a common-law relationship. Thus, in terms of basic demographic variables, the respondents do not demonstrate any significant differences between clusters.
When ethnic identity and country of birth are considered, some differences between the primary operators in each cluster become apparent. Respondents identified as being either Mestizo, Mennonite (Old Colony), or of Maya decent (e.g. Mopan Maya). The ethnic composition of the six clusters is shown in Figure 5.1. Clusters 1 and 4 contain members of all three ethnic groups, Clusters 2 and 3 contain only Mestrizos and Mennonites, and Cluster 6 only contains Mestizo farmers. Mestizos are the largest group of farmers within each cluster except for in Cluster 3 which is 55 percent Mennonite. Although the Mestizos appear to be the largest ethnic group, further investigation into their birth country reveals that considerable heterogeneity exists within the Mestizo community.

As discussed previously in Chapter 3, the Mestizos who immigrated to Belize originate in...
from a number of Central American countries, namely Guatemala, Mexico, El Salvador, and Honduras. The Mennonites who were born abroad typically came from Mexico, and most Mennonite migrants originated since 1957. As shown in Figure 5.2, the clusters with a large portion of Mennonites, namely clusters 1, 2 and 3, had the largest quantity of farmers who were born in Mexico. However, these groups still have a large quantity of farmers who were born in Belize, suggesting that the majority of Mennonite farmers are second or third generation Belizeans. Likewise, the cluster with the largest percentage of Mestizo farmers, namely clusters 4, 5, and 6, also contained considerable variation. It is these clusters that contain the highest quantity of Mestizo farmers born outside Belize in places like Honduras, El Salvador, and Mexico. In fact, at least 21.4 percent of Mestizo farmers in group 6 – a group which only contains Mestizos – were born abroad. Thus, these results indicate that within both the Mestizo and Mennonite communities there are a number of first generation Belizeans.

![Figure 5.2: The country of birth of farmers within each cluster.](image)

Further variation is found when considering language proficiency within each cluster. Although Belize is officially an English language country, Spanish is the *de facto* official language, especially in northern Belize. As shown in Figure 5.3, Spanish is spoken by the majority, if not all, the farmers in each cluster, while English is the second most common language. German, the primary language of the Mennonites that is termed “Low German” by linguists, is spoken among farmers in every cluster that contains Mennonites (i.e. clusters 1 to 4). However, it is also evident that the number of German speakers in clusters 1 and 4 is slightly higher than the number of Mennonites within those clusters, which suggests that
some Mestizos also know German. From conversations with Mestizo farmers during the field research, it was explained that doing business with Mennonites is much easier with a knowledge of German. Indeed, some Mestizo farmers speak three or even four languages. Thus, data on language proficiency suggest that farmers in the study area interact closely with different communities. This fact prompts questions regarding the possible sharing of agricultural strategies, resources, and technology. These questions are discussed more in Chapter 6.

![Figure 5.3: Language proficiency of farmers within each cluster.](image)

Lastly, the duration of residence and the originator of the farm are two related aspects of the primary operator that also vary between clusters. Farms were divided into three groups based on their duration of residence, namely those farms established in the 1960s or earlier, those established in the 1970s or 1980s, and those established in the 1990s or 2000s. As shown in Figure 5.4, there is considerable variation between clusters, yet several important trends can be observed. The largest proportion of old farms dating to at least the 1960s were found in clusters 5 and 6, the two clusters that contain the highest proportion of Mestizo farmers. Conversely, the largest proportion of young farms dating from at the 1990s onwards were found in clusters 2 and 3, two clusters that contain the highest proportion of Mennonites, who expanded into Indian Creek during this period and established hundreds of new farms. However, despite different proportions of new and older farmers within each cluster, Figure 5.5 shows that between 68 and 72 percent of farms in clusters 1 to 5 were established by the primary operator (i.e. first generation farms), while that number was only 50 percent in cluster 6. The wide range of ages of respondents likely contributes to these
observed trends since older farmers likely established their own farms while younger farmers could have established their farms or taken them over from a family member. Thus, variation exists both within and between clusters with regards to duration of residence and the originator of farms. Having considered a number of variables relating to the primary operator, it is important to also consider the demographic profile of the households.

5.2.2.ii Household demographics

One-way ANOVAs were conducted to compare the differences between groups in the number of male and female children below 12 years old and the number of males and females over 12 years old. The results, as shown in Table 5.3, show no significant difference
between households for male, female, or total children. However, the results did show a slightly significant difference for the total number of people over 12 years of age at a p<0.05 level for the six clusters [F(5, 137) = 2.235, p = 0.054]. However, post hoc comparisons using Tukey's HSD (honest significant difference) test showed that the only significant differences in mean values exist between clusters 3 (M=5.1, SD=2.2) and 4 (M = 3.6, SD = 1.8). These results suggest that the largest households (i.e. those within cluster 3) are the ones with the largest number of people over the age of 12 and the ones with the oldest heads of household (M = 55.1). Thus, from a household life cycle perspective, younger households are likely to be smaller than older households.

### Table 5.3: Mean household demographics for each farm cluster.

<table>
<thead>
<tr>
<th>Household demographics</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males 12 and under</td>
<td>1.1</td>
<td>0.8</td>
<td>1.2</td>
<td>0.8</td>
<td>0.5</td>
<td>0.6</td>
<td>0.371</td>
</tr>
<tr>
<td>Female 12 and under</td>
<td>0.7</td>
<td>0.9</td>
<td>1.1</td>
<td>0.9</td>
<td>0.3</td>
<td>0.7</td>
<td>0.089</td>
</tr>
<tr>
<td>Total Children 12 and under</td>
<td>1.8</td>
<td>1.7</td>
<td>2.3</td>
<td>1.7</td>
<td>0.9</td>
<td>1.4</td>
<td>0.106</td>
</tr>
<tr>
<td>Males over 12</td>
<td>2.2</td>
<td>2.3</td>
<td>2.5</td>
<td>1.9</td>
<td>2.1</td>
<td>2.0</td>
<td>0.436</td>
</tr>
<tr>
<td>Females over 12</td>
<td>2.1</td>
<td>1.9</td>
<td>2.5</td>
<td>1.7</td>
<td>1.6</td>
<td>1.7</td>
<td>0.021</td>
</tr>
<tr>
<td>Total people over 12</td>
<td>4.3</td>
<td>4.2</td>
<td>5.1</td>
<td>3.6</td>
<td>3.7</td>
<td>3.7</td>
<td>0.054</td>
</tr>
<tr>
<td>Total people in household</td>
<td>6.1</td>
<td>5.9</td>
<td>7.4</td>
<td>5.4</td>
<td>4.6</td>
<td>5.1</td>
<td>0.010</td>
</tr>
</tbody>
</table>

5.2.2.iii Livelihood diversification

Livelihood diversification is an important part of household organization throughout the LAC region. It includes a number of activities that do not necessarily relate directly to agricultural production, namely wage labour (e.g. industrial labour), on-farm trades like mechanics, and income generated through either domestic or international remittances from family members. Three one-way ANOVAs were conducted to assess whether there were statistically different numbers of wage earners, tradesmen/women, and family members living outside the family home.

The results showed a significant difference in the number of people within the household practising a trade at the p<0.05 level for the six clusters [F(5, 131) = 3.207, p = 0.009]. However, post hoc comparisons using the Tukey HSD showed that only two of the six clusters showed statistically significant differences in mean values, namely the clusters with the highest (cluster 3, M=0.7, SD=1.2) and lowest (cluster 5, M=0.1, SD=0.3) mean values. This suggests that trades are most common among farmers in cluster 3, while all other clusters may have at least some members who rely on such activities as an alternate source of income.
The one-way ANOVAs conducted to evaluate the number of wage earners within the household and the number of offspring living outside the family home found no significant differences between clusters. Although the results are not statistically significant, the highest number of wage earners are found in clusters 1 (M=0.8, SD=0.9) and 5 (M=0.6, SD=0.9) while a higher number of offspring living outside the family home are within clusters 2 (M=3.3, SD=4.3) and 3 (M=4.1, SD=4.2). In fact, when taking the whole sample into consideration, 57.6 percent of respondents reported having no offspring living outside the family home and 70.1 percent reported that no one in their household were employed. Thus, it is likely that wage labour and remittances are not important sources of income for rural households, forcing rural farmers to depend almost exclusively upon agricultural production for their primary source of income.

5.2.3 Land use and resources

Farmers were asked about their land holdings, water resources, past land abandonment, and future plans with regard to land use.

5.2.3.i Land appropriation

The initial classification was based on the percentage of land under different land covers, however, the six clusters also differ in the total area that they allocate to cropland, pasture, forest, and fallow. ANOVAs were conducted to evaluate these differences between clusters. The results show that there were significant differences between clusters at the p<.05 level for cropland \([F(5, 137) = 7.423, p = 0.000]\), pasture \([F(5, 137) = 15.454, p = 0.000]\), forest \([F(5, 137) = 23.427, p = 0.000]\), fallow land \([F(5, 137) = 20.576, p = 0.000]\), and total farm area \([F(5, 137) = 3.033, p = 0.013]\). Looking closer at these results reveals that different agricultural strategies are practised in each cluster.

The clusters can be divided into two groups based on total farm area, namely clusters containing large farms measuring on average 30 hectares or more and clusters containing small farms that measure on average less than 30 hectares. The large farms within clusters 2, 3, and 6 range from about 34 to 43 hectares, as shown in Figure 5.6. Although the farms in each of these clusters have similar total areas, the amount of cropland, pasture, and forest varies significantly. Figure 5.7 shows that the farmers in cluster 2 dedicate an average of 35 hectares to pasture and less than 5 hectares to cropland, the farmers in cluster 3 divide about 31 hectares of land almost evenly between cropland and pasture, and the farmers in cluster 6 only have about 3 hectares of cropland and pasture combined, but on average 29 hectares of
forest. Hence, clusters containing larger farms demonstrate three statistically significant land use strategies, namely livestock specialization, mixed crop-livestock production with some limited fallow areas, and small-scale crop production with a large reserve forest area for future expansion or cropland rotation. Thus, there is no single model that fits for all large farms since there is considerable diversity between these clusters.

In contrast, clusters 1, 4, and 5 contain the smallest farms. The average area of these farms ranges from about 16 to 27 hectares. As with the larger farms, the smaller farms reveal a range of land use strategies according to how land is appropriated to cropland, pasture, forest, and fallow. The farmers in cluster 1 are largely small-scale crop producers with less than 5 hectares of cropland. However, they also maintain, on average, a fallowed area that measures an average of 17 hectares, which is three times their total average cropland. In contrast, despite being among the smallest farms in total area, cluster 2 and 5 are among the largest holders of cropland in the entire sample, such that each has an average of 15 hectares of cropland. However, cluster 2 holds an average of 11 hectares of forest while the farmers in cluster 5 have less than a hectare of either pasture, forest, and fallow land since they dedicate almost all of their land to crops. Thus, smaller farms demonstrate a preference towards crop production over livestock, while some show the tendency to either hold reserve land under forest or fallow land. These practices are discussed in greater depth when crop production strategies are considered.

![Figure 5.6: Mean farm area in each cluster.](image-url)
5.2.3.ii Farm-level deforestation

Tropical deforestation in agricultural areas results mainly from the creation of new farms and from the expansion of existing farms. Without access to current farm census data\(^3\), it is not possible to establish changes in the number of farmers in the study area. However, the results from the current farm survey provide statistics relating to the average growth of farms within each cluster.

A one-way ANOVA was conducted to compare the original farm area within each farm cluster. The result showed a significant difference between clusters at a p<.05 level for each of the six clusters \([F(5, 137) = 3.033, p = 0.022]\). However, post hoc comparisons using the Tukey HSD test indicate that only cluster 2 (M=70.8, SD=89.3) differed significantly from cluster 5 (M=23.8, SD=15.3). Even though the results are not statistically significant for every cluster mean, when compared to the current mean farm area for each cluster, which was discussed previously in this chapter, it is apparent that the mean farm area increased for all clusters since the farms were established. Figure 5.8 shows the difference between each cluster and highlights the fact that not only do clusters 2, 4, and 6 contain the largest farms, they also expanded the most over time by 34.3, 53.2, and 30.9 percent, respectively. In contrast, clusters 1, 4, and 5 only expanded by an average of 12.1, 24.3, and 12.0 percent, respectively. Thus, it is likely that the clusters containing larger farms that expanded more over time also cleared more forest, especially considering their forest holdings were so low.

\(^3\) In 2010 an agricultural census was conducted in Belize. However, those data are currently unavailable. The previous agricultural census was conducted by Furley and Robinson (1985).
and the fact that upwards of 88 percent of new land acquired by farms in this area was reported to be forest. These data are clearly important when integrated with the remote sensing results discussed in the previous chapter.

5.2.3.iii Land abandonment

To gain some insight into the relative stability of farms, the respondents were asked if they had ever abandoned land in the past. The majority of farmers (88 percent) reported that they have never abandoned land in the past. Of those who did abandon land, the reasons cited include changes in agricultural production (e.g. stopped planting sugarcane), land degradation, illness, pest infestations, floods, financial problems, and distance. Moreover, abandoning land was not restricted to farmers in any particular cluster, but found within each. Thus, although not statistically significant, these results suggest that all types of farmers are capable of land abandonment.

5.2.3.iv Water resources

Water is an important and integral part of both crop and livestock production, but a supplemental water source is not readily available to all farmers in the study area. The respondents rely on several sources of surface and ground water. Surface water sources include rivers, streams, dugouts, ponds, lagoons, and rainwater collection, and ground water is accessed via in-field wells.

Upon compiling the responses of the 143 respondents and aggregating them to their respective clusters, it is apparent in Figure 5.9 that different types of farms have different
types of access to supplemental water sources. Surface water is available to farmers in all clusters, but a higher number of small farms from clusters 1 and 4 rely on it as their main source of in-field water. In contrast, clusters 2, 3, and 6, which are the clusters that contain the largest farms, rely mostly on ground water. However, not all farms have access to in-field water. The most numerous groups of farmers without access to water are the smaller farms within clusters 1, 4, and 5. Only 50 percent of farms within these clusters have access to a supplemental water source, which makes irrigation impossible and limits livestock production. Thus, access to in-field water varies between and within clusters, but access is most prevalent among the cluster containing the larger farms.

![Figure 5.9: In-field or near-field water source for farmers in the study area.](image)

**5.2.3.v Distance to land**

The distance from the farmer's home and his/her land is important because it relates to operational costs (e.g. fuel, vehicle maintenance). As shown in Figure 5.10, the distance between house and field was divided into 3 categories, namely on or within 3km of the house, between 3 and 15km of the house, and greater than 15km from the house. When aggregated to the clusters, there are differences between the clusters containing large farms over 30 hectares (clusters 2, 3, and 6) and those containing smaller farms with total area less than 30 hectares (clusters 1, 4, 5). Specifically, larger farms are located closer to their land, especially for clusters 2 and 3 that contain the largest farms in the sample. In contrast, the clusters that contain the smaller farms, namely 2, 4 and 5, have the highest frequency of farms with land located between 3 and 15 km from the house. Lastly, only four of the six clusters contain farms that manage land located over 15 km from the house property. Thus, although not statistically significant, it appears that larger farms are located closer to the
family home than smaller farms.

Figure 5.10: Distance to agricultural land.

5.2.3.vi Future plans

To gain additional insight into the stability of current farms, respondents were asked about their future plans to expand their total farm area, cropland, and pastures. In addition, farmers were also asked if they intend either to sell or lease their land in the near future. The results, presented in Figure 5.11, show that over 50 percent of farmers in all clusters plan to expand their farms in the future. Overall, most farmers plan to expand cropland over pastures, except within cluster that already have a large portion of pasture (i.e. clusters 2 and 3). Thus, when it is considered that below 25 percent of all farms plan either to sell or lease their land, future deforestation will likely be driven by both pasture expansion by current livestock producers and through cropland expansion by smallholders.

Figure 5.11: Future plans of farmers in study area.
5.2.4 Crop production

Of the 143 respondents, 129 (about 90 percent) are crop producers who, when combined, manage a total of 207 fields of varying sizes. These farmers produce either domestic crops, sugarcane for export, or a combination of both. As shown in Figure 5.12, almost half of crop producers are engaged solely in sugarcane production as a cash crop that is grown and sold internationally through a local sugarcane association and mill. The second largest group is domestic crop producers at 40.3 percent. These farmers produce for local consumption, and either consume all their goods within their household, or sell their produce at local markets. The smallest group, who produce a mixture of domestic and export crops, contains only 16 farmers (i.e. 12.2 percent of crop producers). Thus, while the majority of crop producers are either subsistence farmers or specialized sugarcane producers, there are still a few who practice a diversified crop production strategy.

![Figure 5.12: The proportion of domestic, export, and mixed crop producers in the study area.](chart)

When aggregated to the six farm clusters, it is apparent that all clusters, except for cluster 2, contain domestic, sugarcane, and mixed crop producers (Figure 5.13). Furthermore, there is a clear division between the clusters based on the amount of domestic crop producers. At least 50 percent of crop producers in clusters 1 to 3 and 6 exclusively grow domestic crops. In contrast, only about 17 to 22 percent of crop producers in clusters 4 and 5 exclusively produce domestic crops, such that the majority in each cluster produce sugarcane. Thus, it is apparent that different proportions of domestic, sugarcane, and mixed crop producers exists in each cluster, and the distribution of these different types of producers can have various environmental impacts.

To evaluate domestic crop production further, this section presents the results for
fertilizer consumption, pesticide applications, tillage, irrigation, and sustainable agricultural practices. Results are presented for the entire sample of domestic crop producers and at the cluster level. Statistical significance is reported where appropriate.

5.2.4.1 Crop diversity

The crop producers in the study area produce a wide range of crops. As shown in Figure 5.14, the most frequently produced crops are corn, beans, sorghum, and sugarcane. Although sugarcane is the only export crop produced, the respondents reportedly produced at least 16 different types of domestic crops. Mixed crop producers grew mainly beans, corn, and sugarcane, giving them a mix of both staples crops and a cash crop. Conversely, domestic crop producers dedicated a similar percentage of fields to beans and corn as the mixed crop producers, but instead of producing sugarcane, over 33 percent of their fields were used to grow 11 other crop types, such as gourds, rice, and various garden vegetables. Thus, domestic crop producers have the most diversified production systems, followed by mixed domestic/export producers and, of course, export crop producers.

5.2.4.ii Nutrient Management

Crop producers in the study area engage in the variety of nutrient management strategies that may include the use of chemical fertilizer (granular, liquid, or foliar), the application of manure, crop rotation, tillage, and grazing of livestock on fallow fields. Several distinct differences exist between the nutrient management strategies of domestic, sugarcane, and mixed crop producers.

Two types of fertilizer are used by crop producers in the study area, namely traditional
granular or liquid fertilizer that is spread over the growing surface, and foliar fertilizer that is sprayed directly onto plants during the growth period. According to the respondents, foliar fertilizer is a comparatively new technique in the study area, but it was still applied to about 34 percent of fields. Domestic crop producers are among the most common users of foliar fertilizer.

Figure 5.14: Percentage of fields dedicated to different crops, aggregated by cropping system.

Fertilizer in granular or liquid format is widely used in the study area. Respondents reported that it is used on 82 percent of their crop fields, though there is a considerable difference between the frequency of application by the different types of crop producers. Export crop producers used fertilizer on 97 percent of their fields, whereas domestic crop producers fertilized 79 percent of their fields, and mixed crop producers fertilized only 61 percent of their fields. Thus, as expected, as a greater amount of land is used for export crop production, more fertilizer will be applied per hectare of cropland.

In terms of the quantity of fertilizer applied, there is a statistically significant difference between the amount used by domestic, export, and mixed crop producers. Three one-way ANOVAs were conducted to evaluate whether the amount of elemental nitrogen, phosphorus, and potassium fertilizer differed between the three types of crop producers. As shown in Figure 5.15, the results reveal a significant difference at a p<.05 level between the three groups for nitrogen [F(2, 197) = 4.832, p = 0.009], phosphorus [F(2, 197) = 4.568, p = 0.011], and potassium [F(2, 197) = 12.220, p < 0.001]. This indicates that not only do export crop producers use fertilizer on more of their fields, but they also used higher concentrations.
than the other farmers. By applying an average of over 87 kg/ha to their sugarcane fields annually, they surpassed domestic and mixed crop producers who only applied about 66 and 52 kg/ha, respectively. However, although export crop producers apply the most overall fertilizer per hectare, domestic crop producers were found to apply the highest concentration of phosphorus and mixed crop producers applied the second highest concentration of potassium. Thus, although export crop producers use the most fertilizer, domestic and mixed crop producers also depend heavily on fertilizer.

In addition to using chemical fertilizer for nutrient management, crop farmers also use a variety of sustainable agricultural practices to increase, enhance, or stabilize soil nutrients. Specifically, farmers apply manure directly or through grazing, rotate and fallow fields, and apply agricultural lime. Manure is both a source of nutrients and also helps build up the soil's organic matter content (Connor et al. 2011; Haynes & Naidu 1998). Crop rotation with legumes encourages biological nitrogen fixation, thus lessening the farmer's dependency on chemical fertilizer, and agricultural lime serves to primarily to increase the pH of acidic soil (Peoples et al. 1995). Similarly, fallowing fields with cover crops helps to preserve soil nutrients by resting fields at regular intervals and increasing SOM content (Snapp et al. 2005).

As shown in Figure 5.16, domestic crop producers applied these techniques to more
fields than export and mixed crop producers, such that 26 percent of their fields in the study area received manure directly, 36 percent of their fields were grazed, 73 percent of their fields were under a crop rotation (namely a bean/corn rotation), 63 percent of their fields were fallowed, and about 12 percent received applications of agricultural lime. Although more than 30 percent of fields managed by export and mixed crop farmers were fallowed, and the latter also had over 50 percent of their crops under rotation, domestic crop producers used more non-chemical techniques than any other farmers in the study area. Conversely, except for the 36 percent of sugarcane fields that were fallowed and the 11 percent that received manure, export crop producers seem to have abandoned these traditional agricultural techniques in favour of chemical fertilizer. Thus, while domestic crop producers are characterized by their combined use of sustainable techniques (e.g. rotation, fallowing) and agrochemicals, export crop producers depend almost completely on intensive agricultural techniques, such as fertilizer, pesticides, and mechanization.

![Figure 5.16: The use of sustainably agricultural practices by domestic, export, and mixed crop producers.](image)

5.2.4.iii Pest management

The crop producers interviewed use a number of different types of insecticides, herbicides, and fungicides. As shown in Figure 5.17, at least 78 percent of fields managed
by all three types of producers received applications of insecticides and herbicides. The only major difference between the three types of crop producers is that 100 percent of export fields received herbicide applications. Fungicide applications were comparatively less frequent for all types of producers with, at most, 30 percent of domestic crop fields receiving this treatment. Although there is very little variation in the frequency of pesticide use, variation does exist in the number of different products used by each type of producer.

Three one-way ANOVAs were conducted to evaluate differences in the number of types of pesticides used by domestic, export, and mixed crop producers. The results shown in Figure 5.18 indicate that there are statistically significant differences between each group at the p<.05 level for the number of insecticides [F(2, 146) = 7.14, p = 0.001], herbicides [F(2, 174) = 16.49, p < 0.001], and fungicides [F(2, 37) = 9.24, p = 0.001] used on their fields. The results show that domestic crop producers and export crop producers used, on average, the highest number of different products on their fields. Domestic crop producers used the most insecticides and fungicides while export crop producers used the most herbicides. Hence, although all crop types producers depend on pesticides, export and domestic crop producers use more types and on more fields than mixed crop producers.

Farmers also use tillage to manage a variety of pests and to prepare the planting surface. Tillage practices are divided into two broad categories, namely low-till that only uses primary or secondary implements and conventional tillage that uses both primary and secondary implements (Connor et al. 2011). Tillage is also quantified by the total number of
passes that a farmer will make on a field per year and the frequency of tillage (e.g. annually, bi-annually, etc.).

The results show that the majority crop producers relied heavily on conventional tillage, but there are differences between each type of producer. Up to 93 percent of export crop producers rely on conventional tillage, with only a few farmers practising low or no till. The majority of both mixed and domestic crop producers also practice conventional tillage, but it is important to note that within these two groups, almost 20 percent of crops are grown using either no or low till. Thus, although most farmers have adopted a fairly intensive tillage practice, there is still a small number of farmers who practice less intensive alternatives.

Figure 5.18: The mean number of pesticides used by domestic, export, and mixed crop producers.
To investigate further the intensity of tillage practices as a means to minimize or eliminate pest infestation, a one-way ANOVA was conducted to examine potential differences between domestic, export, and mixed crop producers in the total number of passes made by all tillage implements prior to planting (i.e. primary and secondary implements combined). The results found a slightly significant difference between each group at a p<.05 level for the total number of passes [F(2, 204) = 3.159 p = 0.045]. With an average of 2.59 passes (SD=0.985), export crop producers ranked highest, followed by domestic crop producers at 2.29 passes (SD=1.570) and mixed crop producers at 1.95 (SD=1.264). However, since sugarcane is a perennial crop, only about 6 percent of farmers choose to till their land every year, while 59.4 percent of domestic crop producers and 29.3 percent of mixed crop producers till their land annually. Thus, although export crop producers till more intensively, they only do so periodically as compared to the majority of other crop producers.

In summary, pest management is achieved using a combination of chemical applications and tillage. Export crop producers rely heavily on pesticides, which is partially due to the fact that they are unable to till their fields annually to combat pests. In contrast, domestic and mixed crop producers practice the most intensive pest management strategy, incorporating both pesticides and frequent conventional tillage.
5.2.4. iv Water Management

Water management is limited in the study area, so the majority of fields are rain-fed. In total, only about 10.6 percent of the fields surveyed are irrigated. The majority of irrigation occurs on domestic crops using micro-irrigation, hoses, and surface irrigation. Only 2 of the 70 sugarcane fields were irrigated, though local respondents mentioned that this is a practice that they hope will increase to improve yields. Instead, farmers are more apt to rely on fallowing to preserve soil moisture rather than purchasing costly irrigation systems. Thus, although irrigation is considered an important component of agricultural intensification, the limited use of this practice in the watershed leaves very little to investigate.

In summary, within the six clusters there are various proportions of domestic, export, and mixed crop producers. These three types of producers grow a variety of crops using various nutrient, pest, and water management system. When compared, it is clear that export crop producers are the most intensive land users, followed by domestic and mixed crop producers.

5.2.5 Pastoral systems

Livestock production systems in the study area are highly variable even though only 39 (27 percent) of the interviewed farmers report managing pastures. As shown in Figure 5.20, the majority of livestock producers are in clusters 2 and 3, a few are found in clusters 1, 4, and 6, and none are in cluster 5. Two main aspects of livestock production have been assessed in the farm survey, namely pasture management practices and grazing management. The following reports the results for each aspect of livestock production, focusing mainly on cattle production since it has the greatest impact on the landscape.
5.2.5.1 Pasture management

There are two main pasture management systems evident in the study area, namely unimproved and improved pasture (Connor et al. 2011). As shown in Figure 5.21, improved pasture is intensively managed through fertilizer application, by growing various types of grasses and legumes to increase biomass, through crop rotation, and the application of herbicides and pesticides. In contrast, only about 42 percent of unimproved pastures receive any such treatments. The only treatment reported on unimproved pastures is crop rotation and the use of herbicides. Thus, there is a clear division between intensively managed improved pastures and unimproved pastures that receive very little external input.

As shown in Figure 5.22, the majority of improved and unimproved pastures are in clusters 2 and 3, but it is important to note that in clusters 1, 4, and 5, which contain comparatively less livestock producers than the other clusters, unimproved pastures are only found in the first cluster. These results indicate that less intense unimproved pasture management is not practised amongst those livestock producers in each cluster. However, with such a small sample and one that is highly concentrated in two clusters, it is difficult to assess accurately the distribution of each strategy. Thus, it is evident that each strategy employed a different set of management practices, but they were unevenly distributed between the clusters. Next, it is important to consider how each management strategy may differ in terms of grazing management.
5.2.5.ii Grazing management

Livestock producers in the study area employ both continuous and rotational grazing management. Continuous grazing is conducted on a single field without moving livestock to
another location throughout the year. In contrast, rotational grazing operates with numerous paddocks so that livestock can be rotated to fresh pasture throughout the year. Among the two clusters that contain the greatest number of livestock producers, cluster 2 contains the largest percentage of farmers practising rotational grazing, while cluster 3 contains the largest percentage of farmers practising continuous grazing (Figure 5.23). Thus, at least for at least these two clusters, it is possible to differentiate between two different grazing management strategies.

There is also a relationship between grazing and pasture management strategies. As shown in Figure 5.23, about 82 percent of farmers who operate improved pastures also employ a rotational grazing management strategy. In contrast, only about 67 percent of farmers who operate unimproved pastures employ the same rotational grazing strategy. Thus, where pasture have been improved, there is a higher rate of rotational grazing, and, conversely, there are higher rates of continuous grazing on unimproved pasture.

![Figure 5.23: Percentage of farmers practising continuous or rotational grazing, aggregated to the six clusters.](image)

Although this simple relationship seems logical, one would expect that rotational and continuous grazing would also differ in other respects, such as in pasture area, herd size, the stocking rate per hectare, and access to water – a major limiting factor for all livestock producers, especially in the tropics. However, no significant differences were found between continuous and rotational grazing strategies for pasture area, total herd size and stocking
rate per hectare. Furthermore, livestock producers employing either strategy rely on the same types of water sources. Thus, it is suggested that the grazing strategy does not significantly increase a farmer's capacity to raise a larger herd, nor is this practice associated with larger pastures with more access to water. Thus, from a statistical perspective, rotational and continuous grazing management have very similar productive outputs.

Figure 5.24: Percentage of livestock producers operating continuous and rotational grazing on improved and unimproved pasture.
In summary, there is clearly a range of management strategies employed by the livestock producers in the study area. Livestock production ranges from zero inputs with a continuous grazing strategy to high agrochemical inputs alongside a fairly complex rotational grazing strategy. In between these two extremes is a diverse group of livestock producers who employ a range of strategies that include the application of fertilizer and pesticides, the planting of grasses and seed, crop-livestock rotations, supplemental feed, and various ways to get water to their livestock. Although the present study lacks evidence relating to the make-up of individual herds and actual outputs, the evidence does suggest that the intensification of livestock production by establishing improved pastures and adopting a carefully timed rotational grazing strategy is not associated with larger herds. Thus, these results prompt a number of questions regarding the resilience of livestock producers, who employ two different management practices. This is discussed further in the next section.

5.3 DISCUSSION

The farm survey results reveal much about the adaptive management processes operating in the study area by the farming community. Before these results are integrated with the land cover change analysis from the previous chapter, it is important to consider
what these data reveal about farm organization, the disturbance regimes, and the response diversity. The following discussion summarizes and discusses the adaptive managements strategies that are characteristic of each type of farm.

5.3.1 Farm organization in the study area

A central concern in this thesis is to determine the relationship between different types of farms and environmental change. Hence, it was essential to create a farm typology based on a number of key variables. Since the objective was to take a “whole farm” approach that appreciates how farms differ both in terms of their agricultural activities as well as their household organization (i.e. the human dimension), a multivariate approach was imperative. Building upon resilience thinking, five variables were chosen that reflect the household organization and the land appropriation strategy. Next, the resulting clusters (i.e. the different farm types) were further evaluated using a number of other variables. This helped to differentiate further the different types of farms in terms of their specific agricultural practices and socioeconomic circumstances. Since the preceding section reported on each farm subsystem separately, the following discussion presents a generalized profile of each farm type.

5.3.1.i Group 1: Small-scale crop specialists

The first farm type is small-scale crop production operations that are slowly expanding over time. The majority of these farms were established before 1990 and many are family farms inherited by their present-day operators. Their households, which contain an average of 6 people, are headed by a primary operator who, on average, is less than 55 years old, identifies as Mestizo, and is likely Belizean by birth.

The primary agricultural activity of these farms is domestic crop production. Though they possess around 20 hectares of land (most of which is 3-15km from their home), only about 5 hectares is currently in production, while the rest is fallow. They possess more fallow land rather than forest because most of these farms were established prior to 1990 and were likely cleared many years ago. This assumption is supported by the fact that is supported by their comparatively low level of reported on-farm deforestation. Over time, land would have been either rotated, fallowed, or slowly taken out of production due to loss of soil quality or changing socioeconomic circumstances. The result is a group of small-scale domestic crop producers who have more land out of production than they have in production.
The crop system for these farms, which focuses mainly on domestic staples like corn, beans, and a variety of vegetables, is intensive. The farmers rely on a high consumption of fertilizer, insecticides, and fungicides alongside conventional tillage to prepare their fields. However, in lieu of a high consumption of herbicides, farmers also employ a number of sustainable agricultural practices, such as crop rotation, manure application, fallowing, and liming. In terms of water management, irrigation is rare, so their crops are mainly rain-fed. Since they farm such a relatively small area, those who do irrigate, use drop/micro irrigation or watering cans.

Since these farmers only operate on a relatively small area, they diversify their income through non-agricultural activities more than other types of farms. Compared to the other types of farms, households in this group contains more wage labourers than any other farm type. Respondents report that non-farm work includes working on neighbouring farms, as mechanics, as teachers, and in the civil service. Although international remittances from abroad are almost non-existent, a third of households have children living elsewhere in Belize who may also be able to supply some level of financial support. Thus, group 1 are mainly subsistence farms that likely to produce only for their immediate family and generate supplemental income through a variety of other sources.

5.3.1.ii Group 2: Livestock production specialists

The second type of farms are specialized livestock operations that also grow a small amount of crops. This type of farm typically supports a household containing about 6 people and is headed by a primary operator who is less than 55 years old, Belizean by birth, and identifies as either Mestizo or Mennonite. Although about 50 percent of these farms were established before 1990, as many as 30 percent are relatively new, having been established since 2000.

The primary activity of this group is livestock production including cattle, but also some sheep. Livestock production is intensive through the adoption of an improved pasture strategy that includes such practices as seeding, spreading of fertilizer, and use of certain pesticides. These farmers employ a rotational grazing strategy that relies on numerous access points to water and supplemental feed on occasion.

The second main agricultural activity of farmers in this group is domestic crop production. As with the farms in the first group, crop production is intensive through the use of agrochemicals and conventional tillage, but they also use a wide variety of sustainable
practices like crop rotation and fallowing. However, instead of producing crops for human consumption, this group is more likely to produce sorghum, the area's primary fodder crop. Thus, domestic crop production is closely related to livestock production, and therefore less reliant on local markets and less susceptible to price fluctuation for agricultural products.

These farms expanded greatly since they were established. From the time each farm was established, the average total farm area grew from about 20 hectares to just over 40 hectares, making them the largest farms in the study area. Although the majority of farms plan to expand their pastures further in the future, it is important to note that most of the farms only have access to about 5 hectares of either forest or fallow land for such an expansion. Thus, their future expansion would likely be a result of purchasing existing farmland or by clearing forest.

One aspect that differentiates these farms from the other groups is that the households live on or within 3km of their land. Thus, by decreasing or eliminating the travel requirement to and from their land, these farms are less susceptible to a range of disturbances, such as vehicle maintenance and increases in fuel prices.

In terms of livelihood diversification, farmers in this group are less likely to work away from the farm for a wage but more likely than other groups to practice on-farm trades (e.g. mechanic). Thus, for this group, it appears that the primary source of household income is through livestock production, making wage labour unnecessary for most.

5.3.1.iii Group 3: Mennonite crop-livestock systems

These Mennonite farms specialize in crop and livestock production. The farms in this group support the largest households, which contain on average over 7 people. The primary operators are among the oldest and about 30 percent were born outside Belize, notably in Mexico where the majority of Mennonites came from since 1957. Given the age of primary operators, it is not surprising that more than half of the farms in this group were established before 1990 and have since doubled their average total area to over 35 hectares each.

As with the second type of farms, crop and livestock production is intensive by using agrochemical inputs, conventional tillage, improved pastures, and rotational grazing. Although these farms allocate more land to crop production than to pasture, the majority plan to expand crop production further in the future. This expansion could occur on the 7 hectares of forest and fallow land that they current possess, or through additional expansion of the total farm area.
Similar to farms in the second group, these crop-livestock operations were also located on or near the home of the primary operator. Also similar to the second group, supplemental income was more likely to be generated from on-farm trades than from off-farm wage labour. Thus, the mix of livestock and crop production generates sufficient income to support large families while decreasing the need to seek off-farm income.

5.3.1.iv Groups 4 and 5: the Caneros

Farms in group 4 and 5 both specialize mainly in sugarcane production and are colloquially referred to as *caneros*. These farms have among the smallest households, containing only about 4.6 to 5.4 people. They are headed mainly by Belizean-born primary operators who are of Mestizo descent. The farms are among the oldest in the study area, such that over 60 percent were established prior to 1990. Although *caneros* are typically regarded as a fairly homogenous group of farmers, the farm survey results indicate otherwise.

In terms of agricultural production, sugarcane is the primary crop and it is the most intensively grown crop in the study area. It relies on the greatest amount of fertilizer and herbicides, a wide range of insecticides, and uses very few sustainable agricultural practices like fallowing or crop rotation. Their fields are also located 3-15km from primary operators' home, which increases their production costs. However, although both groups operate similarly, one important contrast relates to land allocation. While both groups operate on fields measuring about 15 hectares on average, group 4 has access to almost 10 hectares of forest on which operations could expand. In contrast, group 5 has no such land reserves. It is perhaps for this reason that farmers in group 5 are more likely than farmers in group 4 to have members of their household work for a wage. For farmers in group 5, this additional source of income provides a safeguard against market insecurity and crop failure, while farmers in group 4 can always choose to expand production or sell unused land for immediate financial gains. Hence, both groups produce a similar quantity of sugarcane, but they manage risk quite differently.

Another important contrast between groups of *caneros* relates to their overall ability and willingness to expand their total farm area. Both groups equally expressed a desire to expand crop production in the future, but future expansion is more likely among the farmers in group 4 because they demonstrate a tendency to expand. Although farms in group 4 held a considerable land reserve, they also expanded agricultural production more than farms in
group 5, such that their total farm areas grew from about 15 hectares when first established to over 25 hectares when interviewed. In contrast, farmers in group 5 only expanded by about 5 hectares since being established. Thus, the farms in group 4 are responsible for a greater amount of deforestation in the study area than farmers in group 5, which ultimately suggests that the reserved 10 hectares will also likely be cleared and occupied shortly.

In short, there are definite contrasts that exist between groups of caneros. While some have the ability and means to expand their current operation, others do not. This contrast is further discussed in the next chapter when these results are integrated with the land change assessment results.

5.3.1.v Group 6: New farms and milperos

Farms in group 6 include a number of new Mestizo farms and milperos. The term milperos is used in Belize for farmers who practice milpa, a traditional form of small scale slash-and-burn agriculture, as discussed previously in Chapter 3. Although not all farmers in group 6 are technically milperos, the group shares a number of important characteristics with this form of agriculture.

Their households average compared to the entire sample, headed by a Belizean-born farmer, and they specialize in small-scale crop production. This group is differentiated most from the other groups, however, by the fact that they operate the third largest farms in the study area (~30 hectares), yet they only produce crops on less than 5 hectares of land. The rest of their property is forest – as much as 30 hectares per farmer. Although this group to be subsistence farmers, the opposite seems to be be the case. About 50 percent of this group are, indeed, domestic crop producers, and therefore employ an intensive crop production strategy on a small patch of land. This is typical of pepper, tomato, and other specialized cash crop producers. However, the other 50 percent of farmers are either caneros or mixed crop producers – i.e. 50 percent of farmers in this group produce sugarcane either exclusively or in combination with domestic crops. Thus, this group contains a diverse group of crop producers, some of whom employ intensive strategies while others (the milperos) still practice traditional forms of agriculture.

Another aspect that differentiates this group from the others relates to their livelihood diversification. Many of these farms were established since 2000, so they are headed by younger farmers who are new to the agricultural sector. As a result, less of these farmers work for a wage and even less practice on-farm trades. Thus, it is probable that agricultural
production is a major source of income for these farmers.

In summary, the farms in group 6 are the most diverse in terms of crop diversity and associated agricultural strategies, but unified through their common holding of a disproportionately large amount of forested land. What they do with this forest will have important consequences for the study area, as discussed in the next chapter.

5.3.2 Responses

Having defined six general types of farms in the study area and reviewed the characteristics that help define their identity, additional insight is gained about the response diversity of farmers from the farm survey results. The discussion in Chapter 3 reviewed responses to social and environmental disturbances in the LAC region in general, and Belize in particular. That discussion highlighted four important types of responses, namely agricultural intensification, agricultural expansion, institutional responses, and non-agricultural diversification. In light of the results presented in this chapter, the following sections review these four types of responses.

5.3.2.i Agricultural change: intensification versus sustainable intensification

As explained in Chapter 2, agricultural change is a primary response to a number of social and environmental disturbances (Darnhofer 2010). In the study area for this thesis, farmers choose among many different agricultural strategies to maintain or increase production. Agricultural intensification and sustainable intensification are two strategies that were discussed in Chapter 3, such that the former refers to the use of agrochemicals, mechanization, and irrigation while the latter refers to practices including crop rotation, crop diversification, and fallowing (Tilman et al. 2011). In addition, a distinction can also be made between livestock production that is intensive versus operations that are sustainably intensive.

It was explained in Chapter 3 that since the Green Revolution of the 1960s, farmers throughout the LAC region increasingly intensified crop production. However, as discussed in Chapter 3, there are very few direct indicators of agricultural intensification in Belize, except for overall increases in yield per hectare and some statistics that indicate higher consumption of agrochemicals. Rather, intensification in Belize is more often inferred using indirect evidence, such environment changes like water contamination.

The survey results help to provide direct indicators about the quantity and type of
agricultural innovations implemented by the area's farmers. Specifically, it was observed that the majority of all crop producers, including both domestic and sugarcane producers, adopted a similar form of intensive agriculture to the rest of the LAC farmers that relies heavily on fertilizer, pesticides, and mechanization (United Nations 2005). Indeed, 95.2% of the 208 fields assessed were treated with either fertilizer, pesticides, or tillage. Furthermore, agrochemical consumption increases on the majority of fields, such that fertilizer and pesticide use increased on the majority of these fields since they were established. However, in contrast to the general trend in the LAC region, increased use of irrigation was not found in the study area since crops were more often rain-fed and therefore more susceptible to drought in the study area (UNEP 2007).

Among the intensive crop producers, it is evident that the most intensive farmers are the sugarcane producers. This group represent the majority of farmers in the study area. Based on field conversations with local caneros, the main impetus to intensify sugarcane production came recently through Fairtrade investments that gave farmers discounted or free access to a wide range of fertilizers and pesticides. Thus, the shift from domestic to export crop production is likely associated with the adoption of more intense agrochemical consumption, and therefore more dependence is evident on it to address common farm disturbances, such as pest infestations and decreasing soil quality.

A similar trend towards intensification is also evident with livestock producers. It was noted in Chapter 3 that livestock represents about 25% of total agricultural outputs in Belize. Although data for the last decade are lacking, the nation's cattle stock has grown consistently since 1960. Hence, it is clear that livestock production is an emerging sector based on national statistics, but it is still unclear exactly how farmers at the local-scale are increasing cattle stock besides expanding pasture or establishing new farms (which is discussed below). In this regard, the survey results are informative because they show that the intensification of livestock production through the use of improved pastures and rotational grazing were not significantly related to higher stocking rates. In contrast to crop intensification, the livestock intensification does not relate to higher production. Rather, most farmers in the study area viewed livestock production as a “safe” investment alongside crop production, that can protect them from financial strain caused by crop failure or economic downturns. Thus, from a resilience perspective, since the intensification of livestock production may not increase stocking rates or overall production as it does in the rest of the LAC region, based on the results in this research it does not necessarily help to
strengthen farm resilience in Belize.

In contrast to the adoption of intensive agricultural practices, many farmers still rely on sustainable intensification techniques that help build natural, social, human, and financial capital, as was explained in Chapter 3 and by Pretty (2008) and Tilman et al. (2002). Furthermore, studies have shown that sustainable intensification can increase the resilience of farm systems to a variety of social and environmental disturbances (see, for example, Carter et al. 2009).

Sustainable intensification techniques are more likely to incorporate renewable inputs (e.g. manure), rotate nutrients within the farm through crop-livestock systems, and thereby take better care of the natural resource base. Although the increased production of domestic and export crops in Belize would indicate that farmers are relying more heavily on agrochemical inputs over sustainable intensification, there is evidence that farmers still employ practices such as crop rotations, fallowing, the application of manure, and crop-livestock systems. Of the 208 fields assessed in this research, almost half were fallowed and/or part of a regular crop rotation (usually beans and maize), and almost 15 percent were either grazed by livestock after harvest or were treated with manure applications. Hence, a large portion of crop producers still use sustainable practices to address the social and environmental disturbances discussed in Chapter 3.

It is less clear, however, why sustainable practices are adopted and whether the farmers who use them are making environmentally-conscious decisions. Based on open-ended questions, only a small portion of farmers actually reported choosing to use these techniques. The vast majority either use them because they are part of their agricultural tradition or because they lack the financial means to use other, more intensive agricultural innovations. In general, these techniques are widely regarded as second-best to agrochemicals, and although there is still a portion of farmers who resist agricultural intensification, sustainable agricultural techniques are on the decline.

In summary, crop and livestock production has gradually become more intensive over time. Consequently, farmers are less likely to rely on sustainable intensification techniques as they become more dependant on agrochemicals and mechanization to address common agricultural disturbances, such as the decline of soil quality, climate change, hurricanes, and erratic precipitation.
5.3.2.ii Agricultural expansion through deforestation

Chapter 3 explained that the primary source of new agricultural land throughout the LAC region is tropical forests. Consequently, the deforestation rate in Latin America is closely associated with the rate of agricultural expansion. The same pattern is observed in Belize where there is a decline in forests alongside an increase in agricultural land. Therefore, from a resilience perspective, it is evident that expanding agricultural land (i.e. an environmental change) is an important response of farmers to the social and environmental disturbances outlined in Chapter 3. From a LCS perspective, it is clear that agricultural expansion is the proximate cause of deforestation, according to Lambin et al.’s (2001) terminology. However, it is difficult to decipher the underlying causes of deforestation without local-scale data. Hence, the farm survey results provide important insights into this local-scale process.

Specifically, four important trends were observed that relate to forest change as a farm-level response to local disturbance regime. First, 84 percent of farms in this study were established since the 1980s, a statistic that supports the notion that deforestation is most attributable to the establishment of new farms. This occurs when non-farmers create new farms or existing farmers decide to move away from the family farm to establish their own operation. These two trends are commonly, though not exclusively, observed in the Mennonite communities, especially in the Indian Creek area that was established throughout the 1990s (as discussed in Chapter 4). Thus, the decision to establish a new farm is a common response by the area's farmers.

A second forest change trend relates to farm-level expansion. A number of studies in the Amazon basin, for example, attribute a high amount of deforestation to the expansion of existing farms (see, for example, Brondizio et al. 2002). It was observed that 39 percent of the farms surveyed in this study expanded their total area since being established. This statistic suggests that a sizeable portion of the total forest decline is likely attributable to farmers making the decision either to expand current production, diversify into export or livestock production, or expand in order to maintain current levels of production on poor soils. Thus, it is important to appreciate that not all deforestation is attributable to the creation of new farms.

Third, in contrast to the two previous trends, it is also evident that farmers also cause reforestation by abandoning farmland, a trend that is also observed throughout the LAC
region (see, for example, Rudel et al. 2005). As many as 5 percent of farms surveyed experienced a decline in total farm area. While not all abandoned farmland reverted back to forest (i.e. some was sold to other farmers), some reported during field conversations that some of their land was taken out of production years ago and it reverted back to secondary succession. Thus, amid extensive deforestation, the responses of some farmers actually contributed to reforestation in the study area.

Finally, there are also many farmers who decided against deforestation, but hold a reserve of forested land. Indeed, almost half of the farmers surveyed reported that their total farm area did not change over time while over 46 percent of farmers held a portion of forest in reserve land – some as much as 210 hectares. From a resilience perspective, and in light of the previously discussed results, many farmers may have responded to farm disturbances in ways that did not require expansion, such as by intensifying crop production or through non-agricultural diversification. Thus, forest change, or lack thereof, provides insights into various types of farm-level responses to disturbances.

5.3.2.iii Responses from outside the household

Farm households are part of a complex network with nodes that extend beyond their communities to local districts, countries, regions, and to the world. Chapter 2 discussed the importance of these cross-scale interactions in resilience thinking, and, building upon the work of Meyfroidt and Lambin (2011) and Hecht (2010), Chapter 3 observed that a “new rurality” has developed in Latin America in which farmers are increasingly influenced by exogenous socio-economic forces. Specifically, in some areas of Latin America processes relating to globalization are having demonstrable effects on the processes of forest area change. Three primary examples of such forces include remittances from family members living abroad which help to support rural households, access to off-farm wage labour, and institutional interventions. Thus, especially for sugarcane producers, the farm survey results provide insights into the relationship between external forces (e.g. Fairtrade) and farm-level decisions (e.g. intensification).

The survey results indicate that the majority of farmers in the study area receives very little external support thorough remittances, wage labour, and institutional support. For example, the results demonstrated that only 29 percent of households contain a wage labourer while only 6 of the 143 farms surveyed have offspring living outside Belize, namely in the United States or Canada. Furthermore, according to the respondents, the
institutional support that exists within Belize for farmers through such organizations as Belize Agricultural Health Authority and the Ministry of Agriculture have little impact on the livelihood of rural farmers. Without external support, the livelihood of many farmers depends almost exclusively on agricultural production. Thus, when faced with new types of disturbances, such as pest infestations or hurricanes, these farmers are at a higher risk of being unable to respond adequately.

Sugarcane farmers, who represent 54 percent of the farms in this study, also face high rates of unemployment and lack access to international remittances. However, they are the only group who receive considerable institutional support through an international organization, and are therefore better able to address farm disturbances. Although the Belize Sugar Cane Farmers Association (BSCFA) has been in operation for decades, during which time it has provided substantial support to local growers, in 2008 the organization became Fairtrade certified. This, along with a substantial financial investment, gave cane farmers access to agricultural extension officers, assistance with nutrient and pesticide management, replanting programs to boost production, infrastructure repair and upgrades (e.g. road system), and a range of social programs. Although these programs do not reach all sugarcane farmers, they are having a positive impact on the majority of farmers and their families because they are now better able to address disturbances such as the recent frog hopper infestation, problems relating to nutrient management, and infrastructure deficiencies (BSCFA 2012).

In summary, farmers are continually trying to maintain or increase production while managing the disturbance regime. For farmers in the study area, the disturbance regime will always include soil nutrient deficiencies, erratic precipitation, the effects of climate change, and a variety of socioeconomic disturbances, such as poverty and unemployment. The farm survey results demonstrate that a variety of responses exist within the study area that help to reinforce farm resilience. Among these responses, farmers choose to diversification production (e.g. livestock), expand agricultural production, intensify production, and many choose a number of different strategies to address the disturbance regime. While almost all face considerable hardships with a lack of employment opportunities, sugarcane farmers receive considerable support from Fairtrade, who provides them with tool to address a number of farm disturbances. Although cane farmers face similar hardships to other crop producers, this external support helps to reinforce farm resilience in a very different way. Thus, the response diversity in the study area is highly variable and influenced most by
farm-level decisions and international socioeconomic factors.

5.3.3 Disturbance regime(s)

Many of the disturbances that affect farmers in the study area were discussed previously in Chapter 3 and 4. In general, it is widely recognized by researchers that Belizean farmers are affected by land suitability, land degradation, the negative effects of intensification, water contamination, tropical storms, climate change, socio-demographic change, socioeconomic disturbances, logistic inadequacies, rural poverty, and social conflict. It was also explained that many of these disturbances exist throughout the LAC region and they are endemic to many other tropical regions throughout the world (UNEP 2007). Although the farm survey results did not reveal previously unknown types of disturbances, insights were gained about the specific disturbance regime within the study area. Thus, building upon the farm survey results and personal communication with local farmers, the following discusses how socioeconomic and environmental disturbances affect different types of farmers in the study area.

5.3.3.i Environmental disturbances and feedbacks

Farmers are affected by a number of environmental disturbances. Regardless of what type of operation they manage, all types of farmers report concern about soil quality, precipitation (too much or too little), flooding, climate change and increasingly unpredictable seasons, and pest infestations (weed, fungus, and insects). Livestock producers, who depend heavily on rain for pasture health, fodder crop growth, and livestock hydration, stress that the dry season can be particularly hard when there is a lack of fodder in reserve. For many, a fodder crop failure followed by an unusually dry wet season has devastating effects on the health of herds. Likewise, domestic and export crop producers manage a range of environmental disturbances that threaten overall crop production, leading to frequent crop failures. Thus, although very little additional insight was gained about specific environmental disturbances in the study area, the farm survey results did help confirm that farmers in Northern Belize face very similar hardships experienced by other farmers in the LAC region.

Environmental feedbacks associated with land use and land cover change are a major concern to farmers and environmental managers alike. The farm survey results provide additional insights into the potential negative feedbacks associated with land clearance and agricultural activity in the study area. For example, the agricultural practices of the
sugarcane producers, who have the highest nitrogen inputs and use the greatest number of pesticides, create the potential for a number of serious environmental feedbacks that include the contamination of the water supply through nutrient enrichment (see, for example, Babiker et al. 2004; Guo et al. 2006), higher incidences of insect infestations (e.g. frog hoppers) and, as Grieco et al. (2006) observed, the land use patterns associated with sugarcane cultivation are associated with higher incidences of malaria in Belize. Similar concerns exists for domestic crop producers, who also rely heavily on nutrient and pesticide inputs. Above all, Figure 5.26 shows that cropland is still the largest land cover type and accounts for over 37 percent of the land reported by the respondents in this study. Consequently, crop production in general is also associated with a high amount of GHG emissions, erosion, and all the other negative consequences of tropical deforestation (IPCC 2013; UNEP 2007). Thus, as the number of crop producers increases in the study area, and the as a greater number of farmers intensify their production strategies, the rural population faces greater risks from environmental feedbacks.

Likewise, the growth of the livestock sector in the study area represents a new environmental concern in Belize that will require additional monitoring. Like crop production, nitrogen leaching is a major problem for the local water supply, but the establishment of pastures through deforestation contributes significantly to global emissions of CO₂, methane, and nitrous oxide (Steinfeld & Wassenaar 2007; Nations & Komer 1983).
Within the study area, the survey results report that livestock production occurs on over 32 percent of the surveyed farmland. It is therefore a concern that farmers report that they intend to expand pastures in the future, creating doubt that the remaining 19 percent of forested land on these farms will remain intact. Thus, the major trends associated with agricultural expansion and intensification reinforce the need for more targeted policy interventions to help minimize the numerous potential environmental feedbacks.

5.3.3.ii Socioeconomic disturbances and feedbacks

As with environmental disturbances, farmers in the study area were affected by a number of socioeconomic disturbances. Sugarcane farmers, domestic crop producers, livestock farmers, and mixed crop producers all potentially face many of the same socioeconomic disturbances. As discussed in Chapter 4, within Belize, these impacts include social conflict, market insecurity, demographic change, and rural poverty. However, one challenge when assessing the farm-level impact of socioeconomic disturbances is that they are not easily quantifiable since households manage disturbances very differently through a variety of adaptive management strategies. To gain some additional insight into farm-level socioeconomic disturbances, open-ended discussions with respondents were conducted to supplement the quantitative data derived from the farm survey.

One important dichotomy relates to the subject of farm autonomy, which is a vital component of agroecosystems (see Chapter 2). From an agroecological perspective, farms and farming communities have various levels of integration into the outside world (Wilson 2013). For example, Tomich et al. (2011, p.11) observed that:

> [f]rom an agroecological perspective, biodiversity loss and dependency on petroleum and natural gas, coupled with rising uncertainty about energy prices and climate change, lead to increased vulnerability and decreased resilience of the whole system.

In other words, intensification and the production of export crops integrates farmers into various markets, and therefore erodes their autonomy. In the study area, the farm survey revealed that farm autonomy ranges from completely autonomous to highly integrated farms. Thus, socioeconomic disturbances will affect independent farms and integrated farms very differently. The following discussion illustrates this dichotomy using two examples, namely one that illustrates a typical autonomous farmer and another that exemplifies an integrated farmer.

Farm 9 exemplifies a typical smallholder farm which relies very little on externally
sourced inputs. The primary operator reported that he farms on only 2 hectares of land, while holding 23 hectares in reserve, which is typical of farms like his in group 6. He grows corn and potatoes for domestic consumption, yet only relies on fertilizer and pesticides for the former. He does not irrigate, but practices conventional tillage. In terms of sustainable agricultural practices, he does not fallow his fields nor apply manure, but he does practice crop rotation. As potential sources of socioeconomic farm disturbances, he is mainly dependant on the petroleum market for his tractor, high interest credit, and the agrochemical market for crop inputs. However, since he relies more on his farmland for nutrient and pest management, he relies more on the natural resource base, something that Wilson (2013) acknowledges to be an equally problematic circumstance, especially when that resource base faces a number of environmental challenges (e.g. climate change). Thus, farmers who are less dependant on external inputs may be more dependant on their natural resource base, hence more vulnerable to environmental disturbances than other groups.

In contrast, farm 73 is a very typical sugarcane operation within group 5. The primary operator reported that his total land holding of 20 hectares is under crop. The cropland is neither rotated nor fallowed and no organic inputs are used. Instead, the farmer depends exclusively on fertilizer, pesticides, and conventional tillage. Through intensification, the primary operator becomes less dependant on the natural resource base, and over-dependant on externally-sourced inputs, foreign markets, the labour force for harvesting, access to high interest credit, transportation and logistics, and organizations like BSCFA and Fairtrade to help manage soil quality and crop processing (Martin & Manzano 2010). Thus, through such dependency, sugarcane farmers are exposed to a large number of socioeconomic disturbances, each of which can potentially disrupt farm operations.

The relationship between farm autonomy and exposure to socioeconomic farm disturbances is one that is further examined in the following chapter. It is important to note here that through different agricultural practices, farmers are consistently making decisions, whether conscious or not, either to withhold or release a portion of their autonomy. In general, as farmers lose autonomy, they gradually become more dependant on intensification and less dependant on sustainable intensification strategies. This shift is further discussed in the following chapter by integrating the land change data from Chapter 4 with the farm survey results.
5.3.4 Limitations

One of the main limitations of the farm survey was the inability to conduct farm- and field-level spatial analysis. Many farmers resided in villages while their land was located away from his/her home. Mapping all variables based on the location of the farmer's home would have been irrelevant since most points would cluster within villages. Mapping the location of land was problematic for a number of reasons, but mainly because farmers had difficulty locating their land on aerial photographs. The situation was further complicated when farmers owned multiple tracts of land. Hence, it was essential to aggregate all farmers based on their zone of residence. Consequently, the results were only suitable to be presented in tabular and graph form.

5.4 SUMMARY

In summary, a farm survey of 145 farmers was conducted in Belize. The farm survey results were used to classify farms into six groups using a multivariate statistical approach. The variables used in the classification relate to the household organization, cropping system, pastoral system, and natural resource management. A closer examination of these different types of farms indicates that each is influenced by specific disturbance regimes that are managed with specific types of responses, such as agrochemical applications to manage pests. It was observed that farm resilience is achieved and strengthened in a unique manner by different types of farmers, but farm-level management of environmental and social disturbances can produce numerous potential feedbacks relating to deforestation, agricultural intensification, and livestock production. These results prompt a number of important questions relating to the relationship between farm organization and land cover change processes in the study area. Thus, the following chapter integrates the farm survey results with the land change analysis to address important agricultural, environmental, and socioeconomic policies in Belize.
6 STRENGTHENING FARM RESILIENCE IN BELIZE

The previous two chapters evaluated indicators of farm resilience using two different approaches. A land cover change assessment first evaluated indicators of environmental and agricultural changes at the study area level and at the zone level, which relate directly to farm-level decisions and adaptive management strategies. This land cover change evaluation raised a number of important questions that were further addressed through a farm survey that evaluated agricultural, environmental, and social characteristics. The results of the farm survey were six groups of farms classified based on multiple demographic, agricultural, and environmental indicators. Having similar characteristics, it was observed that they responded to disturbances in similar ways. With a holistic understanding of farm resilience, environmental change, and agricultural developments in the study area, it is now possible to address the third objective of this thesis, which is to assess the potential negative environmental impacts associated with different types of farms in order to support future policy interventions.

To achieve this objective, this chapter integrates both approaches to present a profile of the four zones that specifies potential concerns relating to environmental impacts. The second section examines critically the types of policy interventions that are required to strengthen the various types of farms while protecting the natural resource base in Northern Belize. This discussion draws on examples from other LAC nations and global policy reports to evaluate the potential for policy interventions in Belize and in other LAC nations. Hence, within a farm resilience framework, this discussion focusses mainly on response diversity and potential feedbacks.

6.1 AN INTEGRATED PERSPECTIVE OF LAND CHANGE HISTORY

Although the land change assessment in Chapter 4 provides key statistics regarding environmental change in the study area, there is limited reference to the human dimension that underlies major trends like deforestation and agricultural change. As a supplemental
lines of evidence, the farm survey provides insight into farm-level decisions relating to agricultural intensification and agricultural expansion through deforestation. The following discussion integrates major land cover change patterns from Chapter 4 with the farm groups discussed in Chapter 5 to present a more holistic understanding of the environmental impacts within each zone. Whereas the previous chapters defined landscape scale patterns and classified farms into six groups, this section quantifies the composition of farmers in each zone and their collective environmental impact. Three major sources of environmental impacts are discussed, namely expansion through deforestation, agricultural intensification, and conversion and/or expansion of livestock production.

6.1.1 Profile of Zone 1

About 81 percent of all farmers in Zone 1, the Mennonite area, are livestock producers (Figure 6.1). Of these farmers, about 35 percent exclusively produce livestock and over 46 percent operate a crop-livestock system. The next largest group of farmers are small-scale crop specialists at 12 percent followed by only two sugar cane producers. None of the farms surveyed fit into the “new farm” category, as defined in Chapter 5. Thus, the vast majority of farmers in this zone resemble typical frontier farmers in other LAC countries since they operate large, continually expanding farms that favour livestock and crop production.

Figure 6.1: Percent of farm types by zone.
6.1.1. Deforestation in Zone 1

Given the composition of farms within zone 1, deforestation is a major environmental concern. The farms in this zone are the largest within the study area, and they have the highest rate of expansion. Further, respondents report that expansion is likely to continue as the majority of farmers report a need for more pasture and/or cropland in the future. The deforestation rate in zone 1 was the highest in the study area with an annual decline of about -1.3 percent per year, which is equivalent to about 445 hectares per year. At this rate, the remaining 8,613 hectares could be cut within the next 20 years. The establishment of Indian Creek in the late 1980s and the ongoing expansion of Shipyard were the main drivers of deforestation. By 2010, zone 1 contained over 80 percent of total pastures and 52 percent of total cropland within the study area. This extensive expansion of both cropland and pastures left only 26 percent of the area covered with forest in 2010 (Figure 6.2). Thus, as observed throughout the LAC region, the combination of frontier expansion, domestic and feed crop production, and livestock production, contributed to the highest deforestation rate in the study area.

Figure 6.2: Land cover in 2010 by zone.

6.1.1.ii Agricultural intensification in Zone 1

Although crop production declined in this area since the 1990s in favour of livestock production, by 2010 cropland still covered 28 percent of the zone. Livestock specialists and
crop-livestock producers are among the few farmers who practice a range of sustainable agricultural techniques, such as fallowing, crop rotation, and the application of organic fertilizer. However, they still report a higher consumption of agrochemicals relative to other farmers in the area and few have adopted low or no tillage strategies, thus exposing themselves to risks relating land degradation (e.g. erosion). As discussed in previous chapters, agricultural intensification can cause many negative feedbacks in the form of water pollution, land degradation, and loss of biodiversity. Hence, although crop production is declining, the widespread use of unsustainable agricultural practices by the majority of farmers in this zone presents a number of environmental concerns.

6.1.1.iii Livestock expansion in Zone 1

Livestock production is among the greatest environmental concerns in zone 1. How the rapidly expanding livestock sector will impact the watershed's ecosystem services remains to be evaluated, and it is also unclear if the farmers in this area are using optimal and sustainable grazing and pasture management systems. What is clear from the preceding chapters is that livestock production relates to both higher rates of deforestation and higher rates of cropland conversion to pasture. As a consequence, less land is devoted to crop production and more is exposed to the environmental impacts associated with livestock production.

Hence, the majority of environmental concerns associated with the agriculture sector in zone 1 are attributable to large farms that practice specialized crop and livestock production. The two prominent environmental concerns relate to deforestation and the ongoing conversion of cropland to pasture. Policy interventions aiming to strengthen farm resilience must place limits on further expansion and offer alternatives to further expansion of cropland and pasture. Since livestock production has become the dominant activity in this zone, policies addressing sustainable pasture improvement are imperative.

6.1.2 Profile of Zone 2 and 3

The majority of farmers in these two zones produce sugarcane, of which there are two main types that were previously defined in Chapter 5 as groups 4 and 5 (Figure 6.1). In total, 63 percent of farmers in zone 2 and over 58 percent of farmers in zone 3 produce sugarcane while the remaining farmers produce domestic crops or livestock. Thus, given the specialized focus on sugar cane production, the main environmental threats in these zones relate to this activity.
6.1.2.i Deforestation in Zone 2 and 3

The deforestation rate in the zones is the lowest in the study area and zone 3 experienced a net forest transition from 1980 to 2010. However, by 2010, both zones contained the least amount of forest cover in the study area at just 23 percent in zone 2 and 25 percent in zone 3 (Figure 6.2). Since some of these communities have been in existence for over a hundred years, the majority of deforestation took place prior to 1980. Although widespread deforestation is considerably lower than in zone 1, competition for land in this area is high. With ongoing investments in the sugar industry in Northern Belize, it is likely that much of the remaining forest could be converted to sugar cane fields in the coming years. In addition, whereas frontier expansion drives deforestation in zone 1, on-farm deforestation (i.e. clearing land that is presently owned) is more frequent in this area. Any policies designed to combat deforestation in this area must therefore address issues relating to on-farm deforestation, such as the optimization of current agricultural land.

6.1.2.ii Agricultural intensification in Zone 2 and 3

In zones 2 and 3, 50 and 38 percent of land, respectively, was dedicated to crop production. These figures are higher than any other zone. Although in recent years some farmers have abandoned cropland, the land change assessment found that at least 26 percent of land in zone 2 and 17 percent of land in zones 3 was under crop continually from 1989 to 2010. When the land change assessment results are integrated with the farm survey results, it is evident that producing sugarcane, a nutrient demanding crop, on older cropland necessitates higher agrochemical inputs. As compared to other types of crop producers in the study area, the farmers in zones 2 and 3 are the most intensive through their use of agrochemicals and minimal use of sustainable agricultural practices. Although the sugar cane producers in zones 2 and 3 cleared very little forest since 1980, they used more agrochemicals than any other crop producers. Hence, as organizations like Fairtrade make sugarcane production more accessible to more farmers, it is expected that a greater amount of agrochemicals will be consumed in the study area. Thus, any policy interventions in this area aiming to address the deleterious effects of agricultural production must focus specifically on sugarcane production.

6.1.2.iii Livestock expansion in Zone 2 and 3

The number of livestock producers in these zones ranges from about 11 to 16 percent. Livestock production therefore represents a small portion of the farms in these zones and a
minimal environmental concern.

Hence, the primary environmental concern in zones 2 and 3 relate to the intensification of sugarcane production and to on-farm deforestation, which may relate to loss of productivity on existing land. To address both concerns, policy interventions that aim to strengthen farm resilience should be designed to support sustainable intensification strategies in the zones experiencing declining productivity.

6.1.3 Profile of Zone 4

The land change history and agricultural profile of zone 4 is distinct from the other zones in a number of ways. As shown in Figure 6.1, about 49 percent of farmers are engaged in sugarcane production, while the remaining farmers are a mix of livestock producers, small-scale crop producers, and new farms. Thus, the zone contains a larger diversity of farm types that practice varying forms of agricultural production.

6.1.3.i Deforestation in Zone 4

A higher percentage of land in zone 4 was under forest in 2010 than in any other zone (Figure 6.2). According to the farm survey, many farmers in this zone own forested areas that have not been brought into production. For example, some sugarcane producers held up to 10 hectares of forested land while new farms typically held an average of 30 hectares of forested land. Further, the land change assessment determined that the zone experienced the second highest deforestation rate of -0.8 percent per year, which is probably associated with on-farm deforestation. This is in contrast to zone 1, where deforestation was largely associated with frontier expansion and livestock production. Thus, as with zones 2 and 3, on-farm deforestation is a major environmental concern in zone 4.

6.1.3.ii Agricultural intensification in Zone 4

For half of the farmers in this zone who practice sugarcane production, the environmental concerns relating to agricultural intensification are similar to those in zones 2 and 3. However, for the other half of farmers in this zone, the survey found that they typically rely less on unsustainable agricultural practices and more on such practices as fallowing, crop rotation, and organic inputs. Conversely, those farmers who produce domestic crops alone report a lack of agricultural extension programs to help them increase productivity. Thus, from a policy intervention perspective, zone 4 would benefit from better management of sugarcane production and support for smallholders who produce crops for
domestic consumption.

6.1.3.iii Livestock expansion in Zone 4

Although pastures only covered about 13 percent of zone 4 in 2010, they have expanded consistently since 1989. Although greater environmental concerns exist within this zone relating to on-farm deforestation and agricultural intensification, there is a substantial amount of forest in which pastures could expand in the future. For this reason, livestock expansion is not considered an immediate environmental threat, but a potential future concern.

Thus, zone 4 presents a very different profile than the other zones. It contains the highest mix of farm types and this diversity helps to dilute many of the environmental concerns prevalent in the other zones. From a policy perspective, on-farm deforestation and agricultural intensification remain two of the primary sources of potential environmental impacts.

6.1.4 Revising the agricultural development narrative in Northern Belize

Chapter 3 presented multiple agricultural development narratives, first at the LAC scale, then in Latin America, the Caribbean, and finally in Belize. In many ways the agricultural sector in Belize resembles that of other Latin American countries, which experienced growth in export crop production, domestic crop production, and livestock production. However, given the findings from this thesis, the national narrative of agricultural development does not apply in the entire study area. Each zone has its own developmental trajectory, which may include its own period of growth, stagnation, and even decline. By adopting the language of resilience thinking, one can state that each zone occupied its own domain of attraction, wherein the actors demonstrate a certain amount of diversity, but ultimately are very similar. These different domains of attraction are maintained through different adaptive management systems, and as such follow very different historical trajectories. As this discussion turns to the topic of policy interventions, it is imperative to note that each domain of attraction will ultimately respond to different types of policy interventions. The key to mitigating the potential environmental impacts of agricultural expansion and intensification is to discern the best possible fit between policy and the specific type of agricultural community.
6.2 POLICY INTERVENTIONS

Policy interventions have the potential to strengthen farm resilience while protecting the natural resource base in Northern Belize. Specifically, policy interventions can address land use, the sustainable production of livestock, sugarcane production, food sovereignty and security, sustainable intensification, and the reduction of poverty by empowering rural communities. Based on knowledge gained about the study area through this study, these types of policy interventions are discussed by drawing on examples from other Latin American countries and global policy initiatives by international organizations, such as the FAO and IFAD.

6.2.1 Land use policy in Belize

The Government of Belize has invested greatly into the management of its natural resources, yet it faces increasing challenges with the concurrent growth of the agricultural sector and the tourism industry. In 2011, the government produced its first national land use policy (Meerman et al. 2011), a comprehensive document that outlines the current and future policy directions for the country. The document addresses a variety of land use issues relating to housing, urbanization, agriculture, infrastructure, tourism, mineral extraction, land allocation, and community development. Thus, as a summary of Belize’s policies towards agriculture and environmental change, the national land use policy is the starting point in this discussion on potential policy interventions to address the social-ecological impacts of agricultural expansion and intensification.

Recognizing the importance of rural areas, which contain 54 percent of the population in Belize, the document outlines a number of important priorities which target the agricultural sector. Specifically:

[t]he Land Use Policy and Planning Framework will enable the development of a sustainable rural settlement pattern along with improvements in the quality of life, the rural economy and the environment for the benefit of the rural population and the country of Belize (Meerman et al. 2011, p.23).

Hence, it is acknowledged that improving the lives of individuals living in rural areas requires a sustainable approach to land use and a decentralized policy that places more power in the hands of local governing bodies.

Concerning agricultural land use in particular, the current land use policy acknowledges that as “one of the main pillars of the Belizean economy”, agriculture has a number of
economic and social benefits (Meerman et al. 2011). The policy document cites a number of agricultural disturbances that farmers face, including recent shortages on the world market for a number of food products, plant diseases, future access to the beef market in Central America (to be discussed below), and the potential loss of “preferential export status for sugar and bananas” (Meerman et al. 2011, p.44). The document also acknowledges that a number of new farm responses, which include mechanization and irrigation, are emerging to deal with the realities of farming on marginal farmland and the effects of climate change. Hence, the policy framework includes a number of important policy strategies that relate directly to some of the main results from the thesis.

Many of the proposed strategies relate to directing future development onto land that is suitable for cultivation, which is defined according to King et al.’s (1992) land suitability index that was discussed in Chapter 3. The land change assessment revealed that expansion of agricultural production often occurs on marginal land. To address this issue, the policy document states that future expansion of agriculture should only occur on highly suitable land while expansion onto marginal or unsuitable land should be strongly discouraged. Both the land change assessment and field conversations with farmers confirmed that a small portion of the study area’s cropland was abandoned over the past 30 years. To address this issue, a policy strategy is proposed that will discourage further expansion until suitable abandoned land is brought back into production. Hence, Meerman et al. (2011) recognize the need for local government to direct future expansion onto suitable land in order to prevent future deforestation.

Another issue addressed by the policy framework concerns access to water within fields. It was observed through the farm survey that a large portion of cropland did not have access to either groundwater or surface water, which made many farmers more vulnerable to drought and less likely to adopt irrigation. To address this issue, the policy strategies prohibits the distribution of land that does not have adequate access to either groundwater or surface water. Thus, it is anticipated that this policy will encourage more irrigation, which is a land use practice that was rarely observed in the study area.

The farm survey also reported that the total area of some farms decreased since their establishment. Through open-ended discussions, many farmers reported that they sold their land due to crop failure or lack of labour. In many cases, land was sold as a response to various social or environmental disturbances. The policy document, however, seeks to discourage subdivision of suitable land into “parcels too small to allow meaningful
cultivation or pasture” (Meerman et al. 2011, p.45), a measure that would deny some farmers the ability to sell off land during times of crisis.

Domestic, export, and mixed crop producers in the study area all report that limited access to domestic and foreign markets is a major source of disturbance. Also, the exclusive dependence on a few individual products, namely citrus and sugarcane, exposes farmers to a number of market-related disturbances. The policy document rightly identifies the expansion of domestic and foreign markets as a priority. Specifically, policy strategies state that interventions need to attain “a sustainable price mechanism for farmers” and explore “feasible and profitable alternatives to principal export crops (citrus, sugarcane)” (Meerman et al. 2011, p.46). Thus, many of the socioeconomic disturbances experienced by the farmers in the study area could be minimized or eliminated with the creation of new markets and the diversification of the export sub-sector.

Finally, policy strategies were proposed to address two prominent environmental impacts of agricultural development, namely forest fires and the contamination of waterways from agricultural runoff. Forest fires are an annual problem in Belize, especially those that are started by farmers clearing fields for cultivation. These fires pose a risk to surrounding forest and established farmland. A number of respondents report that they have lost crops as a result of uncontrolled fires. Thus, the policy document suggests further enforcement of the Agricultural Fires Act, which governs such activities.

The second prominent environmental policy strategy seeks to reinforce the riparian buffer zone of 20m in Belize. The 30m spatial resolution of the LANDSAT sensors did not permit an assessment of land change in relation to riparian zones. However, the rate and extent of past expansion and the future plans of many farmers to expand their current farm area raise a number of concerns about the riparian zone in the study area. Further, casual discussions with river boat operators and farmers confirms that eutrophication is visible in the New River. Hence, further policy interventions to ensure that the buffer zone is not converted into agricultural land is justified.

Thus, the current land use policy strategies in Belize address many of the issues identified in the thesis, but several important areas still require policy interventions in the coming years. Specifically, very little reference was made to the expanding livestock sub-sector, the specific environmental impacts of the sugarcane industry, issues relating to food sovereignty and security in rural Belize, the possibility of sustainable intensification
techniques, and the issue of rural poverty. These five issues are discussed in the following sections as they relate to the findings of the thesis.

6.2.2 Livestock production

As discussed in Chapter 3, livestock production is the fastest growing agricultural sub-sector in the world, and in developing countries production has tripled since 1980 (Steinfeld & Wassenaar 2007). In Belize, as in much of Latin America, livestock production is among the most resilient farming systems since farmers report that it is one of the safest agricultural strategies to avoid market instability and environmental disturbances. However, livestock production is associated with a number of environmental risks that need to be addressed through future policy interventions in Belize.

6.2.2.i Environmental impacts of livestock production

The environmental impacts of livestock production are most severe in the developing world where production is in the hands of small, family-operated farms that have limited or no access to agricultural extension services (Nicholson et al. 2001). The most visible local environmental impacts include deforestation to expand pastures and cropland, land degradation, and water contamination (Ran et al. 2013; Thornton 2010). However, there are also global environmental impacts of livestock production that must be addressed through policy interventions.

Livestock production is a major contributor to greenhouse gas (GHG) emissions, specifically carbon dioxide (CO\textsubscript{2}), nitrous oxide (N\textsubscript{2}O), and methane (CH\textsubscript{4}). A comprehensive survey by Steinfeld and Wassanaar (2007) estimated that livestock production is responsible for 18 percent of the total GHG emissions. Specifically, at the global scale, the study found that inefficient livestock production strategies accounts for 9% of CO\textsubscript{2}, 37% of CH\textsubscript{4}, and 65% of N\textsubscript{2}O emissions. Both extensive and intensive livestock production contribute to carbon dioxide emissions through such practices as savannah burning, desertification of pastures, pasture/crop expansion into forest, the use of fossil fuels, fertilizer consumption, and carbon loss in soils used for fodder cultivation. Further, methane emissions are caused by enteric fermentation, which is associated with poorly managed livestock nutrition (Steinfeld and Wassanaar 2007). Lastly, nitrogen emissions are mainly from manure via ammonia volatilization, feed-related fertilizer applications, and nitrogen loss through leaching in fodder production. Thus, policy interventions must address local-scale livestock production practices in order to mitigate both local and global
environmental impacts.

6.2.2.ii Policy strategies

The current policy strategies in Belize with regard to livestock production are limited. First, Martin and Manzano's (2010) policy assessment of Belize makes a number of recommendations relating to livestock production. The authors cite the need to create an export market for beef and mutton, which is a complaint reported by a number of livestock producers in the study area who sometimes lack a market for their products. Their study also highlights a number of other priorities for the livestock sub-sector, such as herd improvement, the creation of surveillance programs for diseases, building the capacity to test meat products for residues and antibiotics, improving access to credit, and establishing a program for livestock traceability. To improve farm operations, they also recommend strengthening extension services to help improve feeding strategies, cattle and sheep breeds, and veterinary care. Hence, although these are all important components of a sustainable livestock sub-sector, more can be done to directly address the environmental impacts cited in the previous section.

Second, a CARICOM report by Singh et al. (2005) reviews the agricultural policies in Belize. It states that agriculture policy aims to continue “improving and conserving the natural and productive resource base to ensure long-term sustainable production and viability” (Singh et al. 2005, p.22). However, the policy strategies for the livestock sub-sector are not in line with these aims. Instead, the livestock policy strategies are to:

(i) improve competitiveness of the various sub-sectors; (ii) strengthen strong backward and forward linkages; (iii) promote value-added activities and diversification in processed meat products; (iv) increase levels of self-sufficiency and; (v) further exploitation of export market opportunities (Singh et al. 2005, pp.22–23).

In other words, the policy strategy for livestock production aims to improve the economic structure of the sub-sector, but there is no reference to strategies relating to long-term sustainability nor a mitigation strategy to deal with potential environmental impacts.

To address the current and future environmental impacts associated with the growing livestock sub-sector, it is imperative that environmental policy strategies are sub-sector specific. For livestock, this implies that policy strategies must not only address the direct impacts of livestock production, but also the indirect impacts associated with fodder crop production. First, a policy strategy would have to address the high deforestation rate
associated with the expansion of pastures and cropland. Policy strategies would also have to plan for eventual land and water shortages and to operate in a carbon-constrained economy (Thornton 2010). Thus, in resilience terminology, the period of expansion will have to give way to a period of reorganization during which the current resources would be used more efficiently without extensive expansion.

Second, the efficiency of livestock production will have to be improved while decreasing GHG emissions. A number of studies claim that these two objectives can be achieved by improving animal nutrition, waste storage and application, breeding and genetics, disease management, grazing management, and water management while strengthening supportive institutions, reducing the cost of inputs, and exploring alternatives to livestock intensification, such crop-livestock systems (see, for example, Ran et al. 2013; Tarawali et al. 2011; Nicholson et al. 1995; Thornton 2010; Ryschawy et al. 2012). In short, the current livestock production system that was identified in the study area will require many changes in the near future if the proposed economic changes are actualized.

Third, with almost 68 percent of livestock producers in the study area depending on supplemental feed, it is also imperative for policy strategies to address the sustainability of future fodder crop production. Steinfeld and Wassenaar (2007) suggest that through the adoption of sustainable intensification strategies, such as conservation tillage and organic farming, the environmental impacts associated with crop production can be minimized. In short, policies must also address the indirect environmental impacts associated with crop production.

In summary, the direct and indirect environmental impacts associated with livestock production need to be mitigated through innovative policy interventions. While the current economic policy strategy will likely help to improve the livelihoods of many smallholder producers, there is also a need for a comprehensive environmental policy strategy that addresses GHG emissions, land and water shortages, land degradation, and deforestation. Hence, policy interventions need to be designed to address specific issues that are endemic to each agricultural sub-sector.

6.2.3 Sugarcane production

As explained in Chapter 3, sugarcane is widely produced throughout Latin America, and the two northern districts of Belize are the chief producers of this primary export crop. Today, well over 6,000 smallholders depend on this crop for their livelihoods. Although the
thesis results indicate that high deforestation rates were not directly associated with sugarcane production, producers are the highest consumers of agrochemicals. Hence, the intensification of sugarcane production raises a number of specific environmental concerns that will eventually require policy interventions.

6.2.3.i Environmental impacts

Sugarcane production can have several negative impacts on natural resources. As with livestock production, Cheesman (2004) observes that the most obvious environmental impact associated with the expansion of sugarcane production is deforestation. Next, sugarcane production contributes to soil loss during harvesting (i.e. 1-15 percent of material delivered to the mill) and through erosion when it is cultivated on slopes. In addition, soil quality is often reduced through compaction, loss of soil organic matter, changes in nutrient levels, salinization, and acidification (Cheesman 2004; Pereira & Ortega 2010). Hence, given the propensity of farmers to cultivate marginal land in northern Belize, policy interventions may be needed to enforce the nation's new land use policies.

Sugarcane production can also have severe impacts on air quality, especially when fields are burned prior to harvesting (Cheesman 2004). This practice causes the release of GHG emissions, and it has also been linked to respiratory toxicity and higher incidences of asthma (Mazzoli-Rocha et al. 2008; Arbex et al. 2007; Cançado et al. 2006). Further research and investments will be required to find suitable alternatives to burning in Belize.

Lastly, sugarcane production is responsible for water contamination and excessive water consumption when crops are irrigated (Cheesman 2004; Arthington et al. 1997). Excessive water consumption is a minor concern in Belize because, as the thesis results indicate, very few sugarcane producers have adopted irrigation. However, water contamination through agrochemical runoff and leaching into groundwater is a major concern. In particular, nitrogen pollution is commonly associated with sugarcane production (Martinelli & Filoso 2008), especially considering that on average sugarcane producers in the study area consume more nitrogen fertilizer than domestic crop producers. Furthermore, in addition to water contamination caused by agrochemical runoff, sugarcane production is also associated with the discharge of waste. For example, in their environmental assessment of Belize, the UNEP report that “in 2002-2007, the sugar industry alone produced 5,074,261 to 5,950,123 gallons of liquid waste per year” (UNEP 2011, p.8). Thus, policy strategies for sugarcane production should address specifically the environmental issues relating to water
Thus, the environmental impacts that are associated with sugarcane production must be addressed in order to mitigate potential negative feedbacks. Doing so will help strengthen the resilience of sugarcane producers by managing the negative environmental feedbacks associated with their operations. Before proposing a number of policy strategies, the following section considers some of the recent policies in Belize targeting the sugarcane industry.

6.2.3.ii Policy strategies in Belize

In addition to the land use policies in Belize that were cited above, very little has been published concerning policy strategies relating to the sugarcane industry. CARICOM's review of agricultural policies in Belize states that, in regard to sugarcane, the objectives are to “improve its productivity and efficiency to enhance its competitiveness in the context of changes in the EU sugar regime” (Singh et al. 2005, p.22). The report goes on to list the following objectives:

(i) increasing the competitiveness of the sugar industry; (ii) stabilizing and increasing farm incomes and rural welfare; (iii) diversifying the agricultural production; (iv) supporting the industry's continued contribution to economic and social development in the northern region of Belize; and (v) ensuring the industry continues to make important contributions to economic and social development at the national level (Singh et al. 2005, p.22).

Hence, as with livestock production, these policy strategies make no direct reference to the environmental risks associated with the sugarcane industry.

In addition, policy strategies should aim to support agricultural practices that mitigate negative environmental impacts. Based on the farm survey results, it is evident that sugarcane production is the most intensive form of crop production in the study area. As Martinelli and Filoso (2008) and Cheesman (2004) observed, policy strategies must include both economic planning and the assessment of environmental risks. Suggested strategies include improving crop and land use practices, better nutrient management to minimize nitrogen pollution, more protection of riparian zones, banning sugarcane burning, and the creation of a more equable working environment for workers. Above all, the industry must plan on ways to mitigate the effects of climate change, which are likely to be more severe for sugarcane (Richardson 2009).

In summary, sugarcane production has various specific environmental impacts. Since
sugarcane farmers employ the most intense agricultural strategies, policy strategies must target the specific environmental impacts associated with this industry.

6.2.4 Domestic crop production and smallholder livelihoods

Poverty is widespread in the study area, especially among subsistence farmers who only grow domestic crops (Martin and Manzano 2010). These smallholders face the same environmental disturbances as export crop producers (e.g. soil infertility, erratic precipitation), yet they lack access to extension services, subsidized inputs, and centralized organization. Instead, the farm survey results indicate that smallholders rely heavily on agrochemical inputs to achieve optimal yields, many rely on off-farm wage labour to supplement their farm incomes, and only a few receive remittances from abroad. Further, conversations with former farmers in the study area and the results of the land change assessment both indicate that higher rates of forest transition occur in areas where domestic crop production is predominant. Hence, it was concluded that for many, agricultural production was their primary source of income and for some, the burden of expensive inputs and a lack of labour led to the abandonment of farmland.

To mitigate the environmental impacts associated with domestic crop production, it is imperative to improve the livelihoods of smallholders (IFAD 2013). After considering the existing policy strategies relating to domestic crop production in Belize, two policy strategies are proposed that could improve the livelihoods of rural farmers while mitigating the negative effects of intensive crop production, namely the adoption of sustainable agricultural practices and providing incentives through PES schemes.

6.2.4.i Current policy strategies for domestic crop production

The policy strategies for domestic crop production are similar to those for export crop production in that they focus mainly on economic development with little reference to environmental or social policy strategies. For example, CARICOM's review of agricultural policies states that the “policy objective for the domestic food production sub-sector is to improve efficiency and competitiveness in order to maintain market share locally” (Singh et al. 2005, p.13). Just as there is no reference to environmental policy, there is also no reference to the necessary social policy that is required to maintain the nation's food security. Such limited policy strategies prompted Martin and Manzano's (2010) critical view of agricultural policy in Belize. They state that:

environmental policy in Belize suffers from a number of substantial gaps. First,
national development policies fail to take environmental issues into account. Second, there are notable areas not covered by environmental policies and/or law. One of the major gaps is the lack of a National Land Use Policy and Plan that could act as the framework to guide development [this item has since been addressed]. Third, tools to ensure compliance with environmental laws are insufficient. Fourth, environmental regulations in Belize do not always reflect present-day realities... (Martin & Manzano 2010, p.183).

Given this critical view, it can also be argued that another significant gap in agricultural policy strategies is the lack of social polices to support the country's primary food producers.

A recent IFAD (2013) study discusses the relationship between smallholder production, food security, and the environment. The study notes that poor farmers often lack incentives to adopt sustainable agricultural strategies, so their focus is more on their immediate needs and less on the potential negative long-term environmental impacts associated with their practices. Policy strategies for smallholders must therefore address not only issues relating to long-term sustainability but also the immediate needs of poor, rural farmers and their households. IFAD recommends a number of potential policy interventions, including scaling up sustainability, removing policy barriers to sustainable agricultural growth, providing incentives to adopt sustainable intensification strategies, and removing subsidies for unsustainable agrochemicals (IFAD 2013). Based on the results from the farm survey and the land change assessment, the following section considers two such possible interventions, namely the adoption of sustainable intensification strategies and generating new or protecting existing sources of non-farm income.

6.2.4.ii Promote sustainable intensification

The thesis results indicate that smallholders have various responses to disturbances, which include expanding, intensifying, and seeking off-farm work. However, one important trend observed is the increasing dependence on external inputs. In Chapter 5, it was explained that as farmers move away from traditional forms of agriculture that includes such practices as crop rotations, fallowing, and the use of organic inputs, they become less autonomous and increasingly dependant on external markets. When these markets are not regulated, fluctuations in the price for inputs can have devastating results for smallholders. Thus, the key to the creation of a sustainable and resilient domestic agricultural sector is to strengthen the autonomy of rural farmers so that they are not dependant on foreign markets to maintain domestic food security. The question of how this can be achieved is complex,
but not impossible.

One important policy strategy to consider is the decentralization of the agricultural sector and the promotion of the concept of adaptive governance. This concept was discussed briefly in Chapter 2, and in an agricultural context it refers to the multiple levels of governance that exist within a social-ecological system (Folke et al. 2005). For domestic crop producers in Belize, their main contacts for support are Belize Agricultural Health Authority and Ministry of Agriculture officials who reside in Orange Walk. Many farmers report that they are rarely able to get advice regarding such practices as fertilizer application, so they apply an arbitrary amount to their fields, which likely explains the high usage of fertilizer in the study area. An adaptive governance model could help transform the agricultural sector by making communities more responsible for agricultural production since they are better able to respond to local-scale environmental and social disturbances. Indeed, this is one of the objectives proposed in the recent national land use policy (Meerman et al. 2011). Thus, an important step towards strengthening the domestic agriculture sector is to place more power in the hands of local communities, a step that must also include agricultural extension that targets the needs of local producers.

It is also imperative to decrease the costs of production for smallholders who are currently using an excessive amount of agrochemical inputs. One effective way to do this is to empower farmers with the knowledge to grow crops without a high dependence on external inputs. In Chapter 3, it was explained that there are two types of sustainable agricultural intensification. The first approach seeks to modify current agricultural practices by increasing such aspects as nutrient-use efficiency (see, for example, Tilman et a. 2002). The second approach seeks to alter the system completely through the adoption of agroecological practices (see, for example, Gliessman 2013). The latter is likely the better solution for the study area since it could provide smallholders with alternatives to costly and environmentally damaging agrochemical inputs. It could also help promote farm-level diversity, nutrient cycling, and improved water management. Hence, agroecology is a community-oriented approach that strives to empower local producers by building farm-level autonomy (Altieri & Toledo 2011).

In short, by decentralizing the governance of the agricultural sector and by adopting an agroecological approach that promotes farm autonomy, food security and food sovereignty will be enhanced in Belize. The farm survey results indicate that the current lack of agricultural extension to the most vulnerable smallholders likely contributes significantly to
environmental pollution and financial instability in rural Belize. Hence, the agricultural sector needs to refocus on the local-scale to find innovative ways to produce food for a rapidly growing population.

6.2.4.iii Protecting or generating sources of non-farm income

The rate of deforestation in the study area is high relative to the national average, which was calculated by Cherrington et al. (2010). Furthermore, the farm survey indicates that the majority of farmers, including domestic crop producers, expanded or intend to expand cropland to increase agricultural production. Consequently, there was only about 30 percent forest cover in the study area by 2010. Since this trend is likely occurring throughout the country, halting or even reversing deforestation is a priority in the national land use policy (Meerman et al. 2011). After considering the value of forests to rural farmers, two potential strategies are considered to help prevent deforestation by improving the livelihoods of domestic crop producers.

Better forest management is an integral part of poverty alleviation in the developing world, according to a recent study by the FAO (2011). Non-wood forest products contribute significantly to the total income of rural households. Forests provide non-cash income in the form of subsistence and cash income in the form of trade goods that can be used to support rural education, healthcare, and diet (FAO 2011). When this vital source of income is eliminated, the resilience of rural households will be further challenged. Hence, policy makers must face the difficult task of preventing deforestation without further contributing to the poverty crisis in rural areas of Belize.

As discussed in Chapter 3, PES schemes have been very effective throughout Latin America to help alleviate rural poverty and protect the environment. As Pagiola et al. (2005) observe, cash incentives not only help to prevent the loss of tropical forests throughout Latin America, but they also provide additional income to rural farmers. In Belize, several PES schemes have been effective at preventing forest loss and promoting sustainable development projects (Martin and Manzano 2010). With the current rate of expansion in the study area, the fact that 30 percent of the area remains forested, and the location of much farmland on or near the New River Lagoon (the largest freshwater body in Belize) or one of its tributaries, an argument can be made that a PES scheme could be implemented here to mitigate future environmental change.

Lastly, unemployment in Belize is a chronic socioeconomic problem affecting a large
portion of the population, though it is especially difficult for the young and women according to Martin and Manzano (2010). The unemployment rate increased through the 2000s, making the rate in Belize the fourth highest among Central American and Caribbean countries at around 14 percent in 2009 (Martin and Mazano 2010). It is therefore encouraging to note that the farm survey results indicate that about 55 percent of households generate non-farm income through either wage labour or through on-farm trades. These results are in line with the FAO estimate that 50-60 percent of households in Latin America generate non-farm income (FAO 2012). Further, it was observed that in Latin America “most rural households have one foot in farming and the other in the non-farm economy” (FAO 2012, p.34), so it is quite common in this region for over half of the farming population to seek non-farm income. The lack of employment opportunities, however, makes farmers even more dependent on agriculture, and will likely lead to further expansion of agricultural production. Thus, as Martin and Manzano (2010) stressed, it is imperative to lower the unemployment rate to eliminate it as a vulnerability throughout the country, and by doing so it will give rural farmers the ability to generate income without the need for further expansion.

In short, there is a significant knowledge gap in Belize regarding the relationship between environmental change and the livelihoods of rural farmers. If farmers are given better options with long-term solutions, they will be less likely to degrade the environment for immediate gains. Ultimately, policy strategies must look to the future for long-term sustainability but also focus on strengthening farm resilience.

6.2.5 Policy implications beyond Belize

The agricultural sector in Belize containing a mix of indigenous farmers, export crop producers, domestic crop producers, livestock producers, and frontier expansion is typical within most LAC nations. However, as a microcosm of broader LAC trajectories, the Belize experience demonstrates the need to balance policy initiatives to support the livelihoods of all rural farmers, not just those producing export crops. The case study presented in this thesis indicates that there has to be a balance between policies and initiatives that promote export production, livestock production, and domestic crop production. The experience of Belizean farmers illustrates how focusing too much on a single cash crop places farms at risk of collapse.

Next, investments into specific industries must weigh the environmental impacts of
such endeavours. For example, the continued expansion of Mennonite communities in Belize was a policy instituted at a time when forest cover was significantly higher than it is today. As the percentage of primary forest is declining rapidly throughout the LAC region, the Belize experience demonstrates that environmental policies must evolve alongside and as a response to economic and social changes. The policies and programs designed in 1950s may be outdated for the 2000's.

Lastly, with more farmers producing livestock and export crops throughout the LAC, this case study demonstrates that food security could emerge as a growing concern. This problem is enhanced when agricultural extension mainly targets export crop production and overlooks the flight of smallholders who produce for local consumption. Thus, the agricultural development process in Belize can help to frame policies that have application throughout the LAC region.

6.3 SUMMARY

In summary, by integrating the land change assessment with the farm survey results, it is evident that there is a relationship between the distribution of different farm types within each zone and local-scale environmental change. The results are comparable to major processes occurring throughout Latin America, such as high deforestation rates being associated with livestock production and the occurrence of forest transitions in areas experiencing economic hardships. Further, the farm survey provides additional insight that is not visible in the land cover change record, namely the level of intensification associated with domestic and export crop production and livestock operations. Although the farmers in these areas demonstrate resilience due to the longevity of their operations while managing a number of environmental and social disturbances, more must be done to strengthen farm resilience.

Policy strategies in Belize have improved over the past 5 years following Martin and Manzano's (2010) critical evaluation of environmental and social policy and with the recent publication of the recent national land use policy (Meerman et al. 2011). Based on the thesis results, it is argued that policy interventions must address the environmental impacts and social needs relating to specific agricultural sub-sectors. For the livestock industry, focus must be on the efficiency and environmental impacts associated with livestock and fodder production. For sugarcane, the high level of agricultural intensification must be re-evaluated.
since these farmers are using substantially more fertilizer and pesticides than domestic crop producers. Lastly, for subsistence farmers, environmental policy must decentralize the domestic crop production sub-sector and increase its efficiency and autonomy through the adoption of agroecological practices. In addition, social policy must fundamentally address the issue of rural poverty and its link to environmental change, which can be done through forest preservation, PES schemes, or by working to decrease the elevated unemployment rate.

In short, there are significant knowledge gaps between current policy strategies and cross-disciplinary research that must be narrowed in order to strengthen farm resilience. This must involve moving away from grand statements like aiming to make agriculture “fully sustainable” (Singh et al. 2005, p.22) and focus instead on specific ways to improve the efficiency, sustainability, and resilience of individual types of farm systems. Thus, policy interventions will require a local perspective that fosters greater interaction between rural farmers, their community, and agricultural extension officers.
7 CONCLUSION

This thesis integrated a land change assessment with a farm survey to evaluate the resilience of farms in Northern Belize to social and environmental disturbances (i.e. the disturbance regime). By addressing the three primary objectives of this thesis, insight was gained about the potential environmental and social impacts associated with deforestation and agricultural intensification in Northern Belize. Based on these findings, policy recommendations were made to address the particular needs of sugarcane, livestock, and domestic crop producers.

7.1 SUMMARY OF RESULTS

7.1.1 Resilience thinking as a theoretical framework

A theoretical framework was proposed in Chapter 2 that incorporates elements of land change science, resilience thinking, and agroecology. Fundamental to this framework is the notion that farmers face a wide range of social and environmental disturbances that must be managed through agricultural, socioeconomic, and/or environmental change. Just as the disturbance regime is diverse and complex, adaptive management includes both specific and general responses. For example, the use of pesticides can address a particular infestation while seeking non-farm employment (i.e. a general response) can help to supplement low earnings from agricultural production. Although it is possible to connect specific disturbances with specific responses, the adaptive management strategy of farms more often addresses numerous disturbances simultaneously. Hence, identifying the different types of farms holistically through their structure and function provides insight into their particular disturbance regime, response diversity, and the potential environmental and social feedbacks associated with their practices.

7.1.2 Land change assessment results

A LANDSAT time-series dating from 1980 to 2010 was used to evaluate land cover
change in the study area. These data were used to address the first objective of this thesis, namely to evaluate farm resilience to environmental and anthropogenic disturbances at the landscape level by evaluating proxy indicators derived from land cover change data. Two types of analyses were conducted, namely post-classification change detection and pixel-histories. The statistics derived from each analysis were used to evaluate how land cover in the four zones (1-4) changed during this time period.

Overall, relative to the national average, the study area experienced a higher rate of deforestation such that 154 square kilometres of forest were cleared over the 30 year period. This land was initially cleared mainly for cropland, but after 2000 the pasture area increased while cropland declined. However, at the zone-level, land cover change patterns were more complex.

In the Mennonite area, the major findings indicate that the establishment of Indian Creek in the late 1980s and the subsequent expansion of livestock production contributed most to deforestation. Further, the study also found that a large portion of pasture was located on marginal land. Hence, these results are consistent with major land cover change processes throughout Latin America where the expansion of livestock production is one of the major causes of deforestation.

It was known prior to this research that the Mestizo areas are used primarily for sugarcane production. However, prior to this study, it was not clear how or if sugarcane production impacts forest cover in Belize. The major findings from the land change assessment indicated that sugarcane production contributed very little to the total deforestation rate. Instead, it was observed that the area included a large amount of permanent cropland that is likely used primarily for sugarcane production.

Lastly, as discussed in Chapter 3, research has shown that forest transitions occur throughout Latin America and are associated with a variety of social, economic, and environmental conditions. It was therefore necessary to evaluate not only deforestation in the study area, but also the possibility that land was abandoned over time to revert back to either natural grasslands or forest. A major finding from the land change assessment was evidence of transitions to both forest and natural grassland in the Mestizo areas. Hence, these results are consistent with the recent land use policy strategy, which acknowledges that abandoned land must be brought back into production (Meerman et al. 2011).

Thus, the land change assessment identified a number of important patterns in the study
area, which are likely the result of complex land use decisions being made at the farm-level. These results were further investigated through a farm survey that was conducted from May to June of 2012.

### 7.1.3 Farm survey results

The farm survey was conducted to address the second objective of this thesis, namely to evaluate how different types of farms have demonstrated resilience to environmental and anthropogenic disturbances. The farm survey instrument was administered to 143 farmers throughout the study area. Using multivariate analysis, six types of farmers were identified and their household organization, cropping systems, and pasture systems were evaluated. The results help to explain the patterns observed in the land change assessment.

For livestock production, the grazing and pasture management strategies were evaluated, and it was determined that there were both intensive and extensive systems operating in the study area. Further, it was also found that livestock producers had the largest farms and expanded more than other types of farms. However, when the stocking rate was evaluated, it was determined that it did not differ significantly between extensive and intensive livestock producers. This fact indicates that there are considerable inefficiencies within the livestock industry. Instead, finding ways to increase the stocking rate on the current land would support increased demand for meat products.

It was also determined that sugarcane producers were the largest group of farmers in the study area. Although on-farm deforestation was low, the farm survey results indicated that sugarcane production employs a highly intensive agricultural strategy. In other parts of the LAC region, similar agricultural strategies are associated with negative environmental impacts. As compared to all other farmers in the area, sugarcane producers use more fertilizer and pesticides and the least amount of sustainable agricultural strategies, such as crop rotations, fallowing, and integrated pest management. Hence, it is quite likely that the Mestizo communities north of Shipyard face increased health risks from pesticide drift, nitrogen contamination of groundwater, and other types of environmental contamination.

Lastly, the farm survey found that domestic crop producers also intensified production through the use of fertilizer, pesticides, and mechanization. However, unlike sugarcane producers, many still relied on sustainable practices like crop rotation, fallowing, reduced tillage, crop-livestock rotations, and organic inputs. Another difference between domestic crop producers and sugarcane producers is that the former lack comparable access to
extension services, so they often operate with less knowledge about soil quality, fertilizer requirements, and pest management. Thus, the farm survey supported a point made by Martin and Manzano (2010) that there is a serious lack of administrative support for rural farmers in Belize and that cross-scale interactions are needed to strengthen farm resilience and ensure ongoing food security for the nation.

### 7.1.4 Integrated results and policy implications

To address the third objective of the thesis, namely to identify the relationship between environmental change and the types of farms within different zones within the study area, the land change assessment and farm survey results were integrated. The results revealed that specific types of farms were likely associated with certain environmental and social disturbances. The integration of the results stressed the need to evaluate the long-term environmental impacts of livestock and fodder production in Belize since this practice is associated with high rates of deforestation and creates the potential for increased water, air, and soil pollution. The environmental and potential social impacts of sugarcane production were also discussed since sugarcane producers are associated with higher rates of agrochemical consumption on permanent cropland. Finally, by integrating both lines of evidence, it became clear that the high rate of crop abandonment is likely related to the high rate of poverty among the area's marginalized domestic crop producers. Hence, it is suggested that policy interventions in Belize should seek to address both the social and environmental impacts associated with agricultural development in order to strengthen farm resilience, sustainably increase agricultural outputs, and protect the nation's natural resources.

### 7.1.5 The human dimension of environmental change in Belize

A new way of examining complex social-environmental systems was achieved by integrating land change science and resilience thinking approaches. Whereas the former places much importance on understanding the human dimension of environmental change, the latter provides a rich theoretical understanding of the structure, function, and identity of complex social-environmental systems. By adopting this integrated approach, this thesis not only examined long-term changes in land cover, but integrated such trajectories with farm-level data to enhance our understanding of agricultural and environmental change in Northern Belize. Although many important insights were gained by using this approach, perhaps the most significant finding was the variability that exists at the community or zone
level among smallholders. For instance, in areas where there was rapid and sustained deforestation, there were also pockets of stagnant growth, and in some cases there were even forest transitions amid rapid agricultural expansion. Ultimately, what this approach reveals is that the human dimension of environmental change is complex, near impossible to predict, and must therefore be understood from a bottom-up perspective. To be clear, this does not imply that top-down approaches (e.g. remote sensing of forest change) are inherently flawed or incomplete, but a holistic understanding of the processes of environmental change requires a closer look at those enacting such change, namely the smallholders that make up agricultural communities. Hence, when policies are being designed to address widespread processes of environmental change, it is also necessary to understand and address those processes operating at the local scale so that all farmers can benefit from carefully designed policy interventions.

7.2 STUDY LIMITATIONS

This study faced a number of limitations. The sample size of 143 farms was sufficient to address the thesis objectives, but a larger sample could have provided further insight into such practices as livestock production and domestic crop production. In the future, it may be helpful to gain access to the 2010 agricultural census data in order to better identify statistically significant farm typologies.

Another limiting factor was the inability to link the farm survey with specific fields. Time was a major limiting factor in this regard, but a lack of an adequate mobile data collection platform was a major limit. The use of a mobile mapping platform on a laptop or tablet would have enabled the surveyor to show informants high resolution aerial photographs (where available) to better link land use decisions with fields. By linking farm survey data with specific fields, it would have been possible to establish a more direct relationship between land cover change patterns and agricultural practices at the pixel level.

The type of individual that was included in the farm survey was also a source of bias. All farmers included in this study were resilient by the very fact that they were active agricultural producers. Further, to gain additional insight into farm vulnerability, it would have been informative to also interview individuals who recently abandoned agriculture.

One recurrent problem in this study was the lack of official boundaries in the rural areas of Belize. Zones were used in the study based on spatially generated boundaries, some
official boundaries (e.g. agricultural reserves), and expert knowledge of the area, but future studies should strive to use natural, hydrological boundaries to better link land use decisions with environmental impacts like phosphorus loading of waterways. To achieve this, it will be necessary to develop high resolution digital elevation models of the study area, which can be used to define the boundaries of subbasins. Hence, it would then be possible to link survey data with catchment areas.

Informal open-ended interviews were often conducted with farmers after the conclusion of the official survey. Many farmers, in particular older farmers who have operated in the study area for decades, were quite eager to discuss the challenges associated with agricultural production. Insight from these farmers was often recorded in note form, but in future studies it would be beneficial to conduct these discussions more systematically by devising a list of open-ended questions and recording the answers for future review. This would enhance the official survey and increase the amount of data on hand to help interpret land cover change processes. Further, it would also help to develop a more complete survey tool for future studies by identifying common concerns or practices among smallholders.

Finally, conducting research in Belize using satellite remote sensing is notoriously difficult due to frequent cloud cover. For example, since the launch of LANDSAT 8 on February 11, 2013, there has not been a single scene of Belize captured without clouds. For this reason, it was not possible to conduct any type of analysis that would require higher temporal resolution. Since this situation will not improve, it would be useful to explore the use of cloud-penetrating active radar remote sensing (e.g. RADARSAT-2) to monitor forest change, and the use of drones to monitor smaller areas of interest.

7.3 FUTURE RESEARCH DIRECTIONS

Several future research directions can develop from this thesis. For sugarcane production, representatives at BSCFA mentioned that more sustainable techniques are starting to be adopted, such as the planting of nitrogen-fixing cover crops during fallow periods. Given the high nutrient requirement for sugarcane, it would be useful to test if these new sustainable techniques help to decrease dependence on external inputs. Similarly, research on the possible agroecological techniques that could improve domestic crop production would also be beneficial.

Livestock production requires more research in Belize. This study indicated that a range
of techniques were employed by livestock producers without an obvious impact on stocking rate. Hence, a farm practice survey focusing on the resilience of livestock production would contribute to future policy strategies for this sub-sector.

This study has mainly examined changes in forest cover areas, but how rural inhabitants actually use forest resources has yet to be examined. Based on comparable studies, it is assumed that non-wood forest items are an integral part of rural household incomes. However, without quantitative data, it is difficult to assess the household value of forests in Belize. Further, since the study area has two main ethnic groups, it might be informative to compare how each group uses forest resources for such activities as hunting, wood harvesting, and the collection of fruit and nuts.

Forest transitions occur throughout the LAC region and this research found evidence that they also occur in the study area. Why they occur and what social and environmental factors contributed to this pattern are important questions that need to be addressed. This will require both a remote sensing assessment and field-based study to investigate abandoned sites. Further studies could also include innovative techniques like agent-based modelling (An 2012), which has already been used to evaluate the process of deforestation in Central America (see, for example, Manson & Evans 2007).

Environmental feedbacks from agricultural production in Belize are poorly understood because there is a nationwide lack of comprehensive environmental monitoring. Future studies should aim to collect baseline variables for the contamination of water, air, and soil in order to accurately evaluate the potential impacts of deforestation and agricultural intensification. Doing so will not only provide insight into the state of the environment, but also provide the opportunity to evaluate the impact of future policy interventions. It is hoped that in the coming years Belize will become a model of a truly sustainable nation in Central America as its farmers become increasingly resilient and aware of the long-term impacts of their actions.

Lastly, technological advances in the GIS sector provide the opportunity to improve such farm-based studies with more precise and detailed data collection. Specifically, mobile spatial data collection platforms, such as Fulcrum, ArcGIS Online, GIS Cloud, and Amigo Cloud, all have the capability to create forms that can be filled out in the field offline and synchronized to a server once Internet connectivity is gained. With concurrent advances in hardware such as tablets, smartphones, and high accuracy external GPS modules, it is
becoming increasingly easy to make the connection between pixels and people. Further, it is also increasingly easy to show respondents spatial data in the field, such as aerial photographs. In future studies, these technologies shall be used to gain additional insight into farm resilience and the process of environmental change at the farm-level.
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## APPENDIX 1: FARM SURVEY FORM

### SECTION 1: GENERAL FARM INFORMATION (May 14 version)

<table>
<thead>
<tr>
<th>Farm location (UTM WGS84)</th>
<th>N</th>
<th>E</th>
<th>Zone</th>
<th>16N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community name</td>
<td>Yo Creek</td>
<td>San Lazaro</td>
<td>Trinidad</td>
<td>Guinea Grass</td>
</tr>
<tr>
<td></td>
<td>Tacital</td>
<td>San Felipe</td>
<td>Shipyard</td>
<td>Indian Creek</td>
</tr>
<tr>
<td></td>
<td>San Carlos</td>
<td>Other:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marital status</td>
<td>Married</td>
<td>Widowed</td>
<td>Never married</td>
<td>Divorced</td>
</tr>
<tr>
<td>Gender</td>
<td>Male</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Where were you born?</td>
<td>Belize</td>
<td>Mexico</td>
<td>Guatemala</td>
<td>Honduras</td>
</tr>
</tbody>
</table>

If not Belize, what year did you migrate to Belize?

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Who established this farm?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operator</td>
<td>Father</td>
<td>Grandfather</td>
<td>Great grandfather</td>
<td>Other, specify:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specify year:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Spoken language (s) in household (click all that apply): | Spanish | English | German | Mayan, specify: | Other | specify |
|-------------|--------|--------|--------|-----------------|-------|
| 1.5 Ethnicity | | | | | |
| | Mennonite (Old Colony) | Mennonite (other) | | | | |
| | Mestizo | Creole | Maya | Other, specify: |
| 1.6 Household Demographics (include operator) | Age Group | Number of Males | Number of Females |
| 12 years and under | | | |
| 13+ | TOTAL PEOPLE: |

Are there any non-agriculture businesses on the farm (e.g. store, mechanic shop)? | NO | YES |

If yes, # people working:

How many people living in your house work for a wage off farm?

<table>
<thead>
<tr>
<th>Distance to land</th>
<th>Less than 2 miles</th>
<th>2-5 miles</th>
<th>5-10 Miles</th>
<th>10+ miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location:</td>
<td>Yo Creek</td>
<td>San Lazaro</td>
<td>Trinidad</td>
<td>Guinea Grass</td>
</tr>
<tr>
<td></td>
<td>Shipyard</td>
<td>Indian Creek</td>
<td>New Hope</td>
<td>Indian Church</td>
</tr>
<tr>
<td></td>
<td>Other:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total acres when established</th>
<th>Total acres today</th>
<th>Cropland 2011</th>
<th>Tree crops 2011</th>
<th>Pasture 2011</th>
<th>Fruit and Veg. 2011</th>
<th>Forest 2011</th>
<th>Fallow 2011</th>
<th>Idle 2011</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Land cover before farm was taken over:</th>
<th>Forest</th>
<th>Cropland</th>
<th>Pasture</th>
<th>Other, specify:</th>
</tr>
</thead>
<tbody>
<tr>
<td>What are the types and number of buildings on your farm?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Domestic Structure(s)</td>
<td>Workshop(s)</td>
<td>Barn(s), storage structure(s)</td>
<td>Tower silo(s)</td>
<td>Retail structure(s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What kind of water source does your farmland have?</td>
<td>NO WATER</td>
<td>Well</td>
<td>Pond</td>
<td>Creek</td>
</tr>
</tbody>
</table>
### SECTION 2: AGRICULTURAL CONVERSION AND EXPANSION (May 14 version)

Since establishing or taking over your farm:

<table>
<thead>
<tr>
<th>CONVERSION</th>
<th>YES/NO</th>
<th>YEAR(S)</th>
<th>TOTAL AREA (acres)</th>
<th>LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture to Cropland</td>
<td>[YES]</td>
<td>[NO]</td>
<td>[ ] Pre-1960</td>
<td>[ ] Yo Creek</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[ ] 1960s</td>
<td>[ ] San Lazaro</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[ ] 1970s</td>
<td>[ ] Trinidad</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[ ] 1980s</td>
<td>[ ] Guineas Grass</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>[ ] 1990s</td>
<td>[ ] August Pine</td>
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<td></td>
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<td></td>
<td></td>
<td>Ridge</td>
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<td></td>
<td></td>
<td>[ ] Chan Pine</td>
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<td>Ridge</td>
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<td>_______ acres</td>
<td>[ ] Tacital</td>
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<td></td>
<td></td>
<td>[ ] San Felipe</td>
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<td></td>
<td>[ ] Shipyand</td>
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<td>[ ] Indian Creek</td>
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<td>[ ] Indian Church</td>
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<td>[ ] San Carlos</td>
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<td></td>
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<td></td>
<td>[ ] Other:</td>
</tr>
<tr>
<td>Cropland to Pasture</td>
<td>[YES]</td>
<td>[NO]</td>
<td>[ ] Pre-1960</td>
<td>[ ] Yo Creek</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[ ] 1960s</td>
<td>[ ] San Lazaro</td>
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<td></td>
<td>[ ] Other:</td>
</tr>
<tr>
<td>Forest to Cropland</td>
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<td>[NO]</td>
<td>[ ] Pre-1960</td>
<td>[ ] Yo Creek</td>
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<td></td>
<td>[ ] 1980s</td>
<td>[ ] Guineas Grass</td>
</tr>
<tr>
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<td>[ ] August Pine</td>
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<td>Ridge</td>
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<td>[ ] Chan Pine</td>
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<td>Ridge</td>
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<td></td>
<td>[ ] Shipyand</td>
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<td></td>
<td>[ ] Indian Creek</td>
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<td></td>
<td>[ ] New Hope</td>
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<td>[ ] Other:</td>
</tr>
<tr>
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<td>[YES]</td>
<td>[NO]</td>
<td>[ ] Pre-1960</td>
<td>[ ] Yo Creek</td>
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<td>[ ] 1980s</td>
<td>[ ] Guineas Grass</td>
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<td></td>
<td>[ ] 1990s</td>
<td>[ ] August Pine</td>
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<td>[ ] San Felipe</td>
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<td>[ ] Other:</td>
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</tbody>
</table>

### FUTURE EXPANSION

- Do you plan to sell or rent any of your present land within the next five years?
  
  [ ] YES [ ] NO [ ] MAYBE [ ] Don't know

- If affordable land became available, would you expand your operation?
  
  [ ] YES [ ] NO [ ] MAYBE [ ] Don't know
  
  If yes, what would you expand? [ ] pastures [ ] cropland [ ] non-production property [ ] Other, specify: ____________

- Since establishing your farm, have you abandoned any land under cultivation or grazing?
  
  [ ] YES [ ] NO
  
  If yes, what reasons led you to abandon this land?
235


### Insecticides
**kills bugs**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Number of types used:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-1960</td>
<td></td>
</tr>
<tr>
<td>1960s</td>
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<td>1970s</td>
<td></td>
</tr>
<tr>
<td>1980s</td>
<td></td>
</tr>
<tr>
<td>2000s</td>
<td></td>
</tr>
</tbody>
</table>

**OR Specify:**

| [ ] Yes, always | [ ] No, never | [ ] Sometimes |

<table>
<thead>
<tr>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ ] Annually</td>
</tr>
<tr>
<td>[ ] Every 2 years</td>
</tr>
<tr>
<td>[ ] Every __ years</td>
</tr>
</tbody>
</table>

- [ ] INCREASED
- [ ] DECREASED
- [ ] NO CHANGE
- [ ] I HAVE STOPPED

### Herbicides
**kill weeds**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Number of types used:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-1960</td>
<td></td>
</tr>
<tr>
<td>1960s</td>
<td></td>
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<td>1970s</td>
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</tr>
<tr>
<td>1980s</td>
<td></td>
</tr>
<tr>
<td>2000s</td>
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</tr>
</tbody>
</table>

**OR Specify:**

<table>
<thead>
<tr>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ ] Annually</td>
</tr>
<tr>
<td>[ ] Every 2 years</td>
</tr>
<tr>
<td>[ ] Every __ years</td>
</tr>
</tbody>
</table>

- [ ] INCREASED
- [ ] DECREASED
- [ ] NO CHANGE
- [ ] I HAVE STOPPED

### Fungicides
**fungicida in spanish**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Number of types used:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-1960</td>
<td></td>
</tr>
<tr>
<td>1960s</td>
<td></td>
</tr>
<tr>
<td>1970s</td>
<td></td>
</tr>
<tr>
<td>1980s</td>
<td></td>
</tr>
<tr>
<td>2000s</td>
<td></td>
</tr>
</tbody>
</table>

**OR Specify:**

<table>
<thead>
<tr>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ ] Annually</td>
</tr>
<tr>
<td>[ ] Every 2 years</td>
</tr>
<tr>
<td>[ ] Every __ years</td>
</tr>
</tbody>
</table>

- [ ] INCREASED
- [ ] DECREASED
- [ ] NO CHANGE
- [ ] I HAVE STOPPED
<table>
<thead>
<tr>
<th>Tillage (plowing)</th>
<th>[ ] Yes, always</th>
<th>[ ] No, never</th>
<th>[ ] Sometimes</th>
<th>OR Specify:</th>
<th>[ ] PRIMARY [ ] ROUND PLOW (24&quot;)</th>
<th>[ ] Other:</th>
<th>PASSES [ ] All crops [ ] 1 [ ] 2 [ ] 3</th>
<th>Frequency</th>
<th>[ ] annually</th>
<th>[ ] every 2 years</th>
<th>[ ] I HAVE STOPPED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fallow (resting fields)</td>
<td>[ ] Yes, always</td>
<td>[ ] No, never</td>
<td>[ ] Sometimes</td>
<td>OR Specify:</td>
<td>Avg. fallow frequency: [ ] ANNUALLY [ ] OTHER:</td>
<td>Avg. length of fallow period: [ ] 1/2 YEAR [ ] 1 YEAR [ ] 2 YEARS [ ] OTHER:</td>
<td>Total area fallowed in 2011: [ ] All crops</td>
<td>Frequency</td>
<td>[ ] annually</td>
<td>[ ] every 2 years</td>
<td>[ ] I HAVE STOPPED</td>
</tr>
<tr>
<td>Manure (animal waste)</td>
<td>[ ] Yes, always</td>
<td>[ ] No, never</td>
<td>[ ] Sometimes</td>
<td>OR Specify:</td>
<td>[ ] chicken [ ] cow [ ] pig [ ] sheep [ ] Other, specify:</td>
<td>Total amount used in 2011: [ ] All crops</td>
<td>Frequency: [ ] annually</td>
<td>[ ] every 2 years</td>
<td>[ ] I HAVE STOPPED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop rotation</td>
<td>[ ] Yes, always</td>
<td>[ ] No, never</td>
<td>[ ] Sometimes</td>
<td>OR Specify:</td>
<td>[ ] Corn-Bean [ ] Various vegetables [ ] Other:</td>
<td>Frequency: [ ] annually</td>
<td>[ ] every 2 years</td>
<td>[ ] I HAVE STOPPED</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Liming (white powder applied to soil)</td>
<td>[ ] Yes, always</td>
<td>[ ] No, never</td>
<td>[ ] Sometimes</td>
<td>OR Specify:</td>
<td>Rate per acre in 2011: [ ] per acre.</td>
<td>Frequency</td>
<td>[ ] annually</td>
<td>[ ] every 2 years</td>
<td>[ ] I HAVE STOPPED</td>
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### SECTION 4: PASTURE MANAGEMENT (May 14 version)

<table>
<thead>
<tr>
<th>Pasture</th>
<th>Paddock and area</th>
<th>Stocking rate per paddock</th>
<th>Grazing time per paddock</th>
<th>Resting time per paddock</th>
<th>Water supply for animals</th>
<th>Feed</th>
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</thead>
<tbody>
<tr>
<td><strong>Pasture 1</strong></td>
<td>LOCATION</td>
<td>[ ] Home community</td>
<td>[ ] Other, specify:</td>
<td>YEAR first used as pasture:</td>
<td>[ ] Pre-1960</td>
<td>[ ] 1960s</td>
</tr>
<tr>
<td></td>
<td>Paddocks: Total area of pasture:</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Types and quantity:</td>
<td></td>
<td>[ ] Cows</td>
<td>[ ] Pigs</td>
<td>[ ] Sheep</td>
<td>[ ] Other:</td>
</tr>
<tr>
<td></td>
<td>[ ] INCREASED</td>
<td>[ ] DECREASED</td>
<td>[ ] NO CHANGE</td>
<td></td>
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<tr>
<td><strong>Pasture 2</strong></td>
<td>LOCATION</td>
<td>[ ] Home community</td>
<td>[ ] Other, specify:</td>
<td>YEAR first used as pasture:</td>
<td>[ ] Pre-1960</td>
<td>[ ] 1960s</td>
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<tr>
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<td>Paddocks: Total area of pasture:</td>
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<td>Types and quantity:</td>
<td></td>
<td>[ ] Cows</td>
<td>[ ] Pigs</td>
<td>[ ] Sheep</td>
<td>[ ] Other:</td>
</tr>
<tr>
<td></td>
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<td>[ ] DECREASED</td>
<td>[ ] NO CHANGE</td>
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<tr>
<td><strong>Pasture 3</strong></td>
<td>LOCATION</td>
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<td>[ ] Other, specify:</td>
<td>YEAR first used as pasture:</td>
<td>[ ] Pre-1960</td>
<td>[ ] 1960s</td>
</tr>
<tr>
<td></td>
<td>Paddocks: Total area of pasture:</td>
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</tr>
<tr>
<td></td>
<td>Types and quantity:</td>
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<td>[ ] Cows</td>
<td>[ ] Pigs</td>
<td>[ ] Sheep</td>
<td>[ ] Other:</td>
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<td></td>
<td>[ ] INCREASED</td>
<td>[ ] DECREASED</td>
<td>[ ] NO CHANGE</td>
<td></td>
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<tr>
<td>Field treatments</td>
<td>Year first used</td>
<td>Specifications</td>
<td>Frequency</td>
<td>Have you increased or decreased the frequency of this practice?</td>
<td>Pastures receiving treatment</td>
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<td>---------------------------------------------------------------</td>
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<tr>
<td>Seedling</td>
<td>[ ] pre-1960</td>
<td>[ ] 1960-70</td>
<td>[ ] Annually</td>
<td>[ ] INCREASED</td>
<td>[ ] All pastures</td>
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</tr>
<tr>
<td></td>
<td>[ ] 1970-80</td>
<td>[ ] 1980-90</td>
<td>[ ] Every 2 years</td>
<td>[ ] DECREASED</td>
<td>Some pastures</td>
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<tr>
<td></td>
<td>[ ] 1990-99</td>
<td>[ ] 2000-now</td>
<td>[ ] Every 2-5 years</td>
<td>[ ] NO CHANGE</td>
<td>[ ] 1 [ ] 2 [ ] 3</td>
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<tr>
<td></td>
<td>[ ] Specify:</td>
<td></td>
<td>[ ] Rarely</td>
<td>[ ] I HAVE STOPPED</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>[ ] Sometimes</td>
<td></td>
<td>[ ] Other.</td>
<td></td>
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<tr>
<td>Planting alfalfa or other legumes</td>
<td>[ ] Yes, always</td>
<td>[ ] 1960-70</td>
<td>[ ] Annually</td>
<td>[ ] INCREASED</td>
<td>[ ] All pastures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ ] No, never</td>
<td>[ ] 1970-80</td>
<td>[ ] Every 2 years</td>
<td>[ ] DECREASED</td>
<td>Some pastures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ ] Sometimes</td>
<td>[ ] 1980-90</td>
<td>[ ] Every 2-5 years</td>
<td>[ ] NO CHANGE</td>
<td>[ ] 1 [ ] 2 [ ] 3</td>
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<td></td>
<td>[ ] Specify:</td>
<td>[ ] 1990-99</td>
<td>[ ] Rarely</td>
<td>[ ] I HAVE STOPPED</td>
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<tr>
<td></td>
<td>[ ] 2000-now</td>
<td>[ ] 2000-now</td>
<td>[ ] Other.</td>
<td></td>
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<tr>
<td>Irrigation</td>
<td>[ ] Yes, always</td>
<td>[ ] 1960-70</td>
<td>[ ] &lt;5 hours per application</td>
<td>[ ] INCREASED</td>
<td>[ ] All pastures</td>
<td></td>
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<tr>
<td></td>
<td>[ ] No, never</td>
<td>[ ] 1970-80</td>
<td>[ ] 5-10 hours</td>
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<td>[ ] Sometimes</td>
<td>[ ] 1980-90</td>
<td>[ ] 10+ hours</td>
<td>[ ] NO CHANGE</td>
<td>[ ] 1 [ ] 2 [ ] 3</td>
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<tr>
<td></td>
<td>[ ] Specify:</td>
<td>[ ] 1990-99</td>
<td>[ ] Days/week</td>
<td>[ ] I HAVE STOPPED</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ ] 2000-now</td>
<td>[ ] 2000-now</td>
<td>Frequency:</td>
<td></td>
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<tr>
<td>Commercial Fertilizer</td>
<td>[ ] Yes, always</td>
<td>[ ] 1960-70</td>
<td>N P K (post)</td>
<td>[ ] INCREASED</td>
<td>[ ] All pastures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ ] No, never</td>
<td>[ ] 1970-80</td>
<td>______ per acre.</td>
<td>[ ] DECREASED</td>
<td>Some pastures</td>
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<tr>
<td></td>
<td>[ ] Sometimes</td>
<td>[ ] 1980-90</td>
<td>N P K (present)</td>
<td>[ ] NO CHANGE</td>
<td>[ ] 1 [ ] 2 [ ] 3</td>
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<td>[ ] Specify:</td>
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<td>______ per acre.</td>
<td>[ ] I HAVE STOPPED</td>
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<td>[ ] 2000-now</td>
<td>Frequency:</td>
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<tr>
<td>Rotate Crops onto Pasture</td>
<td>[ ] Yes, always</td>
<td>[ ] 1960-70</td>
<td>Crop type:</td>
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<td>[ ] All pastures</td>
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<td>[ ] 1970-80</td>
<td>[ ] every 2 years</td>
<td>[ ] DECREASED</td>
<td>Some pastures</td>
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</tr>
<tr>
<td></td>
<td>[ ] Sometimes</td>
<td>[ ] 1980-90</td>
<td>[ ] every 2-5 years</td>
<td>[ ] NO CHANGE</td>
<td>[ ] 1 [ ] 2 [ ] 3</td>
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<tr>
<td></td>
<td>[ ] Specify:</td>
<td>[ ] 1990-99</td>
<td>[ ] Rarely</td>
<td>[ ] I HAVE STOPPED</td>
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</tr>
<tr>
<td></td>
<td>[ ] 2000-now</td>
<td>[ ] 2000-now</td>
<td>[ ] Other.</td>
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<td>Other: specify:</td>
<td>[ ] Yes, always</td>
<td>[ ] 1960-70</td>
<td>[ ] Annually</td>
<td>[ ] INCREASED</td>
<td>[ ] All pastures</td>
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<td></td>
<td>[ ] No, never</td>
<td>[ ] 1970-80</td>
<td>[ ] Every 2 years</td>
<td>[ ] DECREASED</td>
<td>Some pastures</td>
<td></td>
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<td></td>
<td>[ ] Sometimes</td>
<td>[ ] 1980-90</td>
<td>[ ] Every 2-5 years</td>
<td>[ ] NO CHANGE</td>
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<tr>
<td></td>
<td>[ ] Specify:</td>
<td>[ ] 1990-99</td>
<td>[ ] Rarely</td>
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</tr>
<tr>
<td></td>
<td>[ ] 2000-now</td>
<td>[ ] 2000-now</td>
<td>[ ] Other.</td>
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