Assessing the Impact of Climate-Change-Induced Water Scarcity

Modeling Optimal Adaption Strategies for Maize and Bean Producing Smallholders in Chiquimula, Guatemala

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ABSTRACT

Climate change induced crop failure is becoming a more frequent phenomenon with large uncertainty as to the degree and character of future impacts. An overwhelming number of these impacts are projected to be within the tropical belt ; an already highly capital constrained region, where issues related to health, agriculture, and infrastructure are among the many perennial problems. With such limited capital, the opportunity cost of inefficient investments is massive. Thus, it is necessary to address the uncertainty of climate change and pinpoint which adaptation strategies are optimal for the region. This study focuses on maize and bean growing smallholders in the region of Chiquimula, Guatemala. A region which, over the past two decades, has proven to be among the world's most vulnerable ; as the frequency and intensity of drought has increased, the region has proven itself unable to provide sufficient disaster relief or food aid.

While climate impact and adaptation studies are not in short supply, the vast majority of these studies focus on a global or national scale and fail to address the farm level. The following research specifically assesses the uncertainty of climate change at the farm level. By modeling the economic impact of projected climate change and analyzing optimal adaptation strategies given economic constraints, this thesis will suggest that genotype mixes augmented with various degrees of fertilization and irrigation are the optimal strategies for smallholders in Chiquimula, Guatemala to counter the effects of climate change. This study draws on historical weather data and down-scaled General Circulation Model projections to simulate the meteorological effects of climate change in the region. The projections were considered given the IPCC A2 scenario, as well as a split between El Niño and La Niña years. These data were used to simulate the effects on maize and bean yields using DSSAT to determine the adaptation impact and principal constraints. Next, a linear programming model was employed to determine optimal irrigation, fertilizer, genotype, and intercropping combinations given the region's economic constraints.

The results suggest that without some form of adaptation, farmers within the region will continue to operate at subsistence with gradually worsening conditions over the next thirty years. The optimization indicates that smallholders in the region can increase overall income and guard against climatic impacts with investments in both novel genotypes and irrigation infrastructure. The study concludes that, although farmers can exploit the benefits of novel genotypes and irrigation infrastructure the opportunity cost of remaining in agriculture and farming maize and beans at a small scale is high relative to alternative options. For instance, shifting production to non-traditional export crops or shifting out of agriculture altogether.

RÉSUMÉ

Changement échec des cultures induite par le climat est en train de devenir un phénomène plus fréquent avec une grande incertitude quant au degré et la nature des impacts futurs. Un nombre écrasant de ces impacts sont projetées pour être dans la ceinture tropicale ; une région déjà très limitée capitale, où les questions liées à la santé, l'agriculture et les infrastructures sont parmi les nombreux problèmes vivaces. Avec un tel capital limité, le coût d'opportunité des investissements inefficaces est massive. Ainsi, il est nécessaire d'aborder l'incertitude du changement climatique et d'identifier les stratégies d'adaptation qui sont optimales pour la région. Cette étude se concentre sur les petits exploitants de culture de maïs et de haricots dans la région de Chiquimula, Guatemala. Une région qui, au cours des deux dernières décennies, a fait ses preuves pour être parmi le monde les plus vulnérables ; que la fréquence et l'intensité de la sécheresse a augmenté, la région a prouvé incapable de fournir des secours en cas de catastrophe suffisante ou l'aide alimentaire.

Alors que les études d'impact climatique et d'adaptation ne sont pas rares, la grande majorité de ces études portent sur une échelle mondiale ou nationale et ne parviennent pas à régler le niveau de la ferme. La recherche suivante évalue spécifiquement l'incertitude du changement climatique au niveau de la ferme. En modélisant l'impact économique des changements climatiques prévus et à l'analyse des stratégies d'adaptation optimales compte tenu des contraintes économiques, cette thèse va suggérer que le génotype mélanges à augmenté avec des degrés divers de la fertilisation et de l'irrigation sont les stratégies optimales pour les petits exploitants à Chiquimula, Guatemala pour contrer les effets du changement climatique . Cette étude se fonde sur des données météorologiques historiques et projections modèle de circulation générale vers le bas-échelle pour simuler les effets météorologiques du changement climatique dans la région. Les projections ont été examinées compte tenu du scénario A2 du GIEC, ainsi que scission entre El Niño et La Niña. Ces données ont été utilisées pour simuler les effets sur le maïs et les haricots rendements en utilisant DSSAT pour déterminer l'impact de l'adaptation et des contraintes principales. Ensuite, un modèle de programmation linéaire a été utilisée pour déterminer l'irrigation optimale, les engrais, le génotype, et les combinaisons de cultures intercalaires compte tenu des contraintes économiques de la région.

Les résultats suggèrent que, sans une certaine forme d'adaptation, les agriculteurs de la région continueront à fonctionner à la subsistance de l'aggravation des conditions progressivement au cours des trente prochaines années. L'optimisation indique que les petits exploitants de la région peuvent augmenter le revenu global et se prémunir contre les impacts climatiques avec des investissements dans les deux nouveaux génotypes et les infrastructures d'irrigation. L'étude conclut que, bien que les agriculteurs puissent exploiter les avantages de nouveaux génotypes et de l'infrastructure d'irrigation le coût d'opportunité de rester dans l'agriculture et l'élevage maïs et de haricots à petite échelle est élevé par rapport à d'autres options. Par exemple, en déplaçant la production des cultures d'exportation non traditionnels ou le déplacement hors de l'agriculture tout à fait.

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Chapter 1: Introduction

The intensity and frequency of natural disasters have accelerated over the past few decades to a point where our global food supply is impacted to an historically unparalleled degree (Spinoni et al. 2014). The food demands of a growing global population continue to pressure already strained hydrological systems, which necessitates farmers to go beyond rain fed systems. The demands of a growing global population will only exacerbate the pressures on our already strained hydrological systems (Cohen 2003). We will be confronted by the challenges that: global warming is expected to further drop already stagnating crop yields (Stern 2007; Foley et al. 2011); gross arable land is being depleted due to salinization and desertification; as well as the stresses of accelerating urbanization and changing diets. Unfortunately the bulk of this shift will primarily take place in the tropical zone where closing yield and infrastructure gaps are still among the region's many perennial problems (Vörösmarty et al. 2000; Solomon et al. 2007). Repeating the Malthusian thesis here will only echo the plethora of academic papers written on the subject (Stocker 2014). Consistently, all this literature emphasizes the point that there is a need for technological change to adapt to our changing climatic pressures.

Of these pressures water security is of utmost importance. The United Nations Development Report concluded that water scarcity, above all, will be the prime constraint to increased food production in the near future (Watkins 2006). Central America is cited as the world region most vulnerable to climate change in terms of both impact and ability to adapt (Kreft et al. 2013, p.6). The region has experienced mounting frequency of droughts in the last few decades causing hundreds of millions of dollars in damages and necessitating emergency aid (Guha-Sapir et al. 2015; Oxfam 2013; Philpott et al. 2008).

Collectively, climatic and demographic changes are pressuring our global food security to the extent that the developing world is pushed further below the subsistence threshold with each passing year (Vörösmarty et al. 2000). Reinvigorating the Green Revolution, and expanding it to these areas is not an easy option given the constraints faced by climate change. Since the onset of the Green Revolution, irrigation has been a key factor in meeting the greater water demands of intensified agriculture. Subsequently, over the last few decades water demands have surpassed surface water supplies to the extent that we have tapped into depletable groundwater to supply the growing demand (Gleick 2003). This situation will only intensify with climate change induced water scarcity. The high water demands of typical improved maize varieties make them inadequate for regions that lack capital to invest in irrigation infrastructure and already face future water scarcity. Although there has been advancement in the last few years with deep-rooting and drought-tolerant varieties, they are still in the development stage and are either lacking extension services or are expensive. Therefore, given the developing world's lack of capacity and future meteorological constraints there is a need to assess which adaptation strategy would optimize value.

1.1 Objective

The objective of this study is to model the economic impact of climate change and determine optimal adaptation strategies on maize and bean producing smallholders within the region of Chiquimula, Guatemala. Adaptation strategies will be optimized over a combination of seven maize and three bean genotypes, five irrigation systems, three fertilizer scenarios, as well as seeding rate over two seasons; and two climate scenarios representing El Niño and El Niña events given the region's economic constraints. Models that seek to consolidate agronomic and economic approaches are still quite novel and in their early stages of development. Thus, the bulk of the literature tends to be split between these two extremes. Agronomic models such as CropSyst (Stöckle et al. 2003) and ORYZA2000 (Bouman 2001) are built on a foundation of data derived from decades of experimental research. Though these models have been calibrated to be impressively accurate they are nonetheless highly hypothetical in that they propose adaptation of novel biotechnology and irrigation schemes without considering economic feasibility. The economic impact studies within the region have tended to assess dynamics only at a global or continental scale and thus have failed in relevance to farm-level decision making. Resulting adaptation suggestions are general and tend to not have quantitative comparisons made among them. These models cannot be used to assess a locality's particular changes, and thus which factors climate change is actually constraining. The resulting adaptation strategies are often inviable because they do not consider economic and regional particularities in their assessment. Investment in irrigation infrastructure or novel genotypes functions as a buffer against crop failure, thus limiting the risk and vulnerability to unforeseen climatic changes. However, as well as assessing the risk premium, there is a need to assess to what extent investment in irrigation equipment reduces risk. In regions of the world with such high capital constraints, such as rural Guatemala, the opportunity cost of ineffective investment is massive. It could very well be the case that there is an absolute shortage, or that the projected duration of dry periods is such that irrigation equipment and reservoirs are insufficient to guard against crop failure. It could also be the case that despite climatic constraints, such investments are desirable simply in terms of economic return. It is this relationship that needs to be assessed.

In order to go beyond the hypothetical impact models, there is a need to combine the biophysical elements with the economic specifics of the target area into the modeling procedure. There is also a need to refocus the objective of these models from simulation that deals with what-if scenarios, to optimization that revolves around what is best given the scenario and constraints. Optimization sets out to maximize net benefits given the stakeholder's capacity, alternatives, and opportunity costs. Incorporating the economic characteristics of a community into a climate-change impact projection will offer viable adaptation strategies.

This study focuses specifically on maize and bean farming in the Dry Corridor region of Guatemala. Maize and bean were considered for reasons that these are the two principal crops of the region in terms of consumption. Over the last decade almost yearly droughts have affected upwards of three million people with each event requiring some form of emergency food aid (Mora 2014). The region is considered one of the most vulnerable in the world and the effects of global warming are projected to worsen food insecurity. This study will try to pinpoint where weaknesses and potential blockages are, and suggest optimal adaptation strategies.

The following pages will attempt to aid in reconciling the uncertainty of which adaptation strategies would be most feasible given the region's projected climatic effects and economic constraints. This will be done by firstly gathering meteorological projections of daily precipitation, temperature extremes; and solar radiation was collected from averaging the results of six General Circulation Models (GCM) within the IPCC A2 scenario (See the overview in of the GCMs and IPCC scenarios in Appendix 6.3 and 6.3 respectively). A second weather data set was created by scaling the GCM temperature and precipitation data to create an El Niño-scenario data set. The associative El Niño and La Niña years were determined by a Holt-Winters seasonal projection of the last half-century of climatic data outlined in Appendix 6.3. Second, meteorological data were used in DSSAT to simulate annual maize and bean yields for the period of 2020 through 2050 over seven maize and five bean genotypes for each of six irrigation schemes and three fertilizer scenarios. Both crops were simulated for both seasons using DSSAT v4.6. Maize yields were simulated in two cases, either monocropped maize or intercropped with bean to account for the effects of bean's nitrogen fixation and residue on the maize crop. Third, future market prices and population (as a proxy for demand) were projected until 2050 using an autoregressive model. An optimization was conducted using a linear programming model over the irrigation systems, fertilizer, genotypes, and seeding rate. The objective function was specified as maximizing the net present value (NPV) of profits over the years 2020-2050. The model was constrained in three forms representing three scenarios, i.e., non-adaptation, fixed selection, and perfect information. Together these constrained models represent different assumptions concerning actions made to mitigate the effects of climate change as well as the availability of information and foresight. The results will be discussed within the context of the region and taking the opportunity cost of alternative resource allocation, employment, and lifestyle decisions into consideration. A flowchart detailing the methodology can be found in Figure 4.4.

Chapter 2: Global and Regional Context

2.1 Global

The opening statement of the FAO (2010) report *How to Feed the World in 2050* sets forth the dilemma clearly; "By 2050 the world's population will reach 9.1 billion, 34 percent higher than today. Nearly all of this population increase will occur in developing countries. Urbanization will continue at an accelerated pace, and about 70 percent of the world's population will be urban (compared to 49% today)." (FAO 2010, p.2). Changing population demographics will reconfigure global food demand. There are expected to be another 2.6 billion urban inhabitants, with this growth concentrated in the urban areas of developing countries (DESA 2011; Satterthwaite 2007). The implications are that not only will there be greater absolute demand, but also greater affluence will drive dietary demands away from starchy foods towards more resource-intensive diets of meat and vegetables (Godfray et al. 2010). This increase in demand further strains an agricultural system by pressuring our already over-exploited hydrological systems (Gleick 2003). By 2025, water withdrawals are predicted to increase by 50 and 18 percent in developing countries and developed countries respectively; two-thirds of the world population are expected to be under water stress conditions, with 1.8 billion living in regions with absolute water scarcity (IFAD 2011). The great misfortune is that both of these forces will have the hardest impact in the regions that are most vulnerable and least capable of adapting.

The scientific evidence of global warming, and its effects on the hydrological cycle and agriculture have been substantiated (Bates et al. 2008). Since 1980, annual global temperatures have increased on average by 0.4°C, with regions in the tropics witnessing larger changes

(McCarthy 2001). There is a direct positive relationship between CO_2 concentrations and temperature. [1] Multiple analyses predict that a doubling of CO_2 concentrations would correlate to a 5°C increase in global temperatures (NOAA 2014). Evidence shows that the concentration of greenhouse gases (GHG) in the atmosphere has been accelerating over the last century and is now the highest it has been in 420,000 years (Bárcena et al. 2010, p.14). For instance, during the industrial revolution CO_2 concentrations were just above 100 ppm whereas now they are over 400 ppm (NOAA 2010). Including carbon dioxide equivalent or CO_2e, [2] the jump in the same time period is as much as 430 ppm with a current 2 ppm annual increase (Stern 2007, p.169). Without mitigation, anthropogenic sources of GHGs are expected to rise with industrialization of the developing world; increased demand for meat with growing affluence (livestock is a huge source of methane, which has 20 times the impact of CO_2 per pound of emissions); as well as self reinforcing feedback from the melting of icecaps. Projections estimate that global CO_2 concentrations could reach as high as 550 ppm by 2050 and 650 ppm by the turn of the century. This will imply between a 2°C to 6°C increase in temperature by that time amplifying the already detrimental occurrence of extreme weather events (Stern 2007).

Global warming impacts agricultural production primarily by amplifying variability and magnitude of precipitation as well as increased evapotranspiration (Strzepek et al. 2010). The scientific basis behind this change relies on the Clausius-Clapeyron law which states that for every 1°C increase in the average air temperature the atmospheric water holding capacity increases by 7%. Hence, higher temperatures increase the atmospheric moisture holding capacity; thus the potential for heavier rainfall and extended periods between rainfalls is increased. Higher temperatures do not necessarily have an effect on absolute precipitation but instead affect the intensity and variability thereof (Trenberth et al. 2003).

1. Paleo data derived from glacial mapping has depicted that that over the last 500,000 years there has been a direct quadratic relation between CO_2 concentrations and temperature (NOAA 2014).

2. CO_2e includes methane, perfluorocarbons and nitrous oxide in their global warming equivalent to CO_2.

Globally, the IPCC has reported that since the 1970s, the frequency and severity of droughts have increased, with much of the impact being within the tropics (Alavian et al. 2009; Solomon et al. 2007). It is projected that the gross area and frequency of drought will increase in severity by ten to 30 fold by 2090 (Solomon et al. 2007; Kundzewicz et al. 2008). The impact of this climate projection is by no means globally homogeneous but rather is highly regionalised. For instance, various studies predict that Northern Europe will become wetter with more overall precipitation, while the tropical belt will follow trends as mentioned above (Beniston et al. 2007). Elevated evapotranspiration will make crops more susceptible to damages during longer dry periods associated with increased variability of precipitation. With more frequent crop failures it is evident that these stresses are beyond the biological resistance to drought of traditional varieties (Lesk et al. 2016). As well, heightened precipitation variability coupled with increased unpredictability compounds the stochastic risk of crop failure.

The intensity and frequency of droughts within the last decade have been unparalleled within the last two centuries. Between 2001 and 2012, moderate droughts consistently covered between 17–35% of the world annually, with 2-6% of those categorized as severe and requiring emergency assistance (Kogan et al. 2013). The 2012 U.S. Central Great Plains drought was the most severe since at least 1895, even surpassing in intensity the fabled Dust Bowl summers of 1934 and 1936 (Hoerling et al. 2014). The effects of the U.S drought resonated throughout the food system inflating prices on a global scale. Historically unparalleled droughts occurred in Russia 2010, East Africa 2011 and 2012, and Australia almost yearly throughout the last decade. The 2011 Horn of Africa drought caused severe malnutrition and fatalities as well as triggering massive migration that has yet to be reconciled (Kogan et al. 2014). Clearly, adaptation to climate change is a global issue with the most vulnerable needing the greatest attention.

2.2 Regional

For its size Guatemala has high spactial and temporal climatic variability. The country holds multiple ecosystems from tropical rain forest to dry highlands each with their distinct climatic conditions. This diversity is a product of the region being situated at the confluence between Pacific and Caribbean ocean currents interacting over irregular terrain. This complexity of influential weather phenomena makes the frequency, and thus prediction, of extreme weather events extremely difficult (Westerberg 2011; Amador et al. 2006). To compound the issue, besides global warming effects, the arrival and departure of the rainy season has high interannual variability which is subject to the fluctuations of the El Niño-Southern Oscillation (ENSO) (Waylen et al. 1996). El Niño consists of periods lasting approximately a year or two with temperatures 0.75-1.0°C above average, with opposing La Niña oscillations of the same degree below average temperature (Caffrey et al. 2014, p.vii). Coupled with global warming, the effects of ENSO will be far more severe to the point that traditional agriculture could be infeasible without costly adaptation measures (e.g., irrigation and novel genotypes). It is necessary to incorporate the effects of ENSO in the modeling procedure (Van Kooten 2012, p.53)

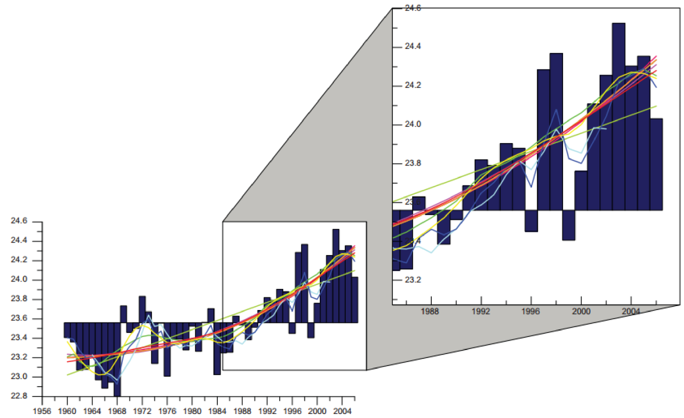

Figure 2.1: Long-Term Temperature Variations within Guatemala 1960-2006 (Degrees Centigrade) (Bárcena et al. 2010, p.20)

In the last few decades there have been observable increases in mean temperatures (Figure 2.1) as well as amplified precipitation variation and intensity (Table 2.1) within Central America (Hidalgo et al. 2013; Aguilar et al. 2005). Projections for Central America suggest a consistent reduction in future runoff. A 2009 hydrological modeling study of the Rio Lempa Basin (one of the largest basins in Central America covering Guatemala, Honduras and El Salvador) estimated that by the end of the 21st century changes in precipitation and evapotranspiration imply an average of a 13-24% reduction in inflows, with a peak decline of between 21-41% in the dry months of July and August (Maurer et al. 2009, p.190)

The region is experiencing an historically unparalleled number and intensity of natural disasters (Oxfam 2013). The 2001 drought affected 200,000 people with 41 deaths and US$14 million in loss. Similarly, the March 2009 drought affected 2.5 million people and caused severe malnutrition in Chiquimula and other areas along the Dry Corridor. The 2012 drought dropped maize yield by 90% in Chiquimula and the surrounding region (Oxfam 2013). In 2014, drought inflicted an estimated US$58 million in crop loss and other damages, necessitating emergency food aid (Guha-Sapir et al. 2015).

Table 2.1: Precipitation Events that Surpassed Accumulation Threshold (Bárcena et al. 2012)

Period	2 Days of Rain	5 Days of Rain	10 Days of Rain
1971-1980	1	1	9
1981-1990	5	14	25
1991-2000	6	8	17
2001-2011	10	30	56

Each threshold corresponds to 100, 150 and 200mm accumulated for 2, 5 and 10 consecutive days respectively. The data for 2011 are until Oct 31.

In 2005, Hurricane Stan caused more than 650 deaths, destroyed 35,000 homes and affected nearly 500,000 people with damages totaling close to US$100 million (Thomas 2007). In 1998, Hurricane Mitch caused landslides, flooding out of crops, destruction of coffee and cocoa plantations, and resulted in grain prices rising by 70% at a time of seasonal hunger (Philpott et al. 2008; Oxfam 2013). For Guatemala the number of tropical storms and hurricanes recorded in the two periods of 1971 to 1990 and 1991 to 2010 went from zero in the first two decades to 11 in the later two; while between 1970 and 1990 there were only five recorded floods compared with 13 in the 1991 to 2011 period (Bárcena et al. 2012, p.43). This trend is consistent with the effects of global warming, and is projected to get worse as a one degree increase in temperature will correlate to a 8%-12% increase in hurricane magnitude and duration (Emanuel 2005, p.688).

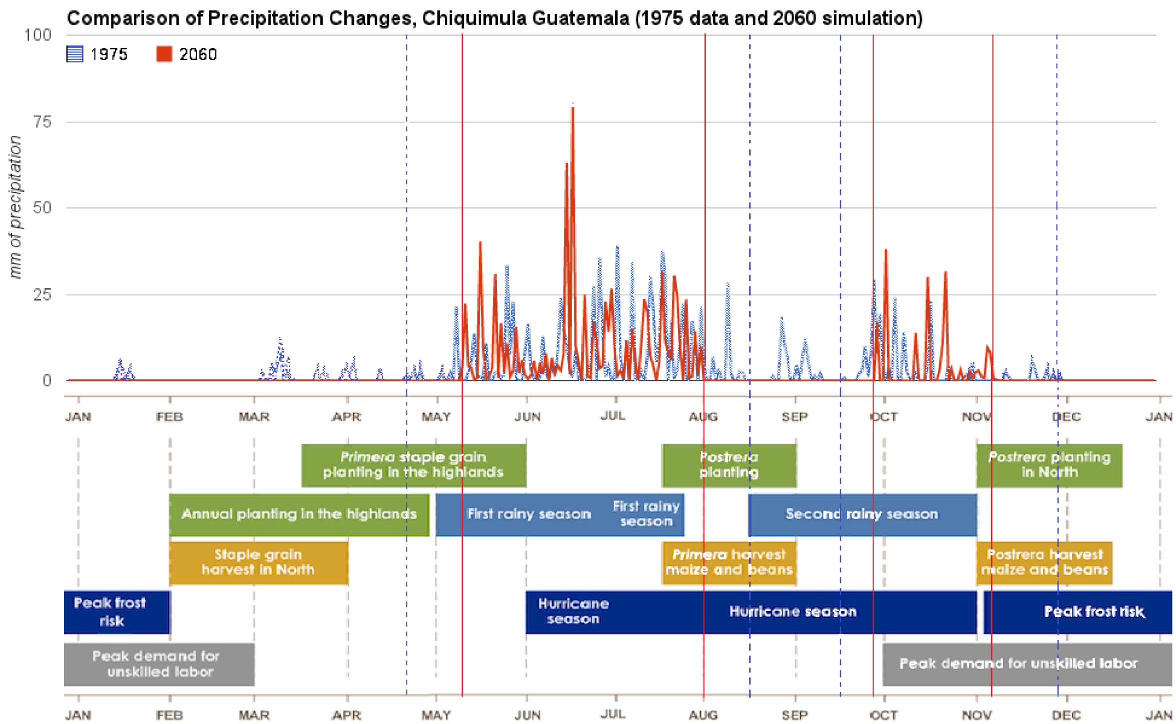

Figure 2.2: Comparison of Precipitation Variability 1975 data with 2060 simulation (ILRM 2014). Seasonal calender for Guatemala Planting and Harvesting (USAID 2012, p.2)

The upper half of Figure 2.2 depicts a comparison between 1975 observed precipitation data (the dotted line) and a 2060 simulation (the solid line) derived from the ECHam5 (Roeckner et al. 2003) General Circulation Model pattern scaled to the region of Chiquimula (for IPCC scenario A2 and without ENSO). 1975 was chosen as a representative year for reasons of it being between El Niño oscillations and without notable weather anomalies. The vertical solid and dotted lines represent the first and last rainfall of each season for 1975 and 2060 respectively. There is an evident increase in the intensity and variability of precipitation between the 1975 observations and the 2060 simulation. Both rainy seasons are contracted by about a month with the first rains arriving about two weeks later and stopping two weeks earlier. Compared to 1975, the *Primera* season not only begins much later but also with more intensity, and with almost no precipitation during the preceding months. The 1975 *Primera* season extended through August even into early September whereas with the 2050 simulation, the dispersion of the *Primera* season was far less and ended abruptly in late July followed by a long, dry and late summer despite the shorter span of the rainy season the absolute rainfall for each season only changes marginally according to the predictions. The bottom half of the figure displays the typical planting and harvesting seasons as well as demand for unskilled labor. As can be seen there are two rainy seasons that the two cropping seasons revolve around; i.e. the *Primera* season (May-August) and the The *Postera* season (August-December). Sowing is typically done after the first rains of the season, i.e., between mid April to mid May (Wellhausen 1957, p.15).

A shorter *Primera* season could affect the final stages of crop development as later arrival delays sowing dates and thus pushes the final stages of development later in the season and even past the last rains. Maize and beans are particularly vulnerable to water stress during these stages. Effects of the contracting *Primera* season have already been felt in the region. The last two years' sparse rains have resulted in below-average *Primera* maize and bean production which has limited smallholder income and food stocks (Caffrey et al. 2014, p.23). Unfortunately, during the summer of 2014, periodic warming due to natural ENSO anomalies resulted in no precipitation during the later half of the *Primera* rainfall. This resulted in a severe drought lasting a full 45-days without precipitation between July and August (Mora 2014).

2.2.1 Sources of Vulnerability and Constraints

It is important to remember that the effects of climate change exist within the social and economic context of the region. In the case of Guatemala, most of the rural population already lacks the means to cope with a multitude of pre-existing social and economic problems. Vulnerability and capacity to adapt are not simply functions of meteorological effects and available capital, rather it is dynamic and influenced by the overall socio-economic situation of a region; including natural and human resources, institutions, social networks, entitlements, property laws, governance and policies. Although capital constraints limit investment and access to improved varieties, the region is struggling with a plethora of other issues. Much of rural Guatemala has insufficient access to potable water, limited education and health care services, as well as undeveloped transportation infrastructure (FAO 2015a).

In the 2014 United Nations Health Development Index ratings, a collective measure of health, education, and standard of living indicators, Guatemala ranked 118^{th} out of 185 nations. Low literacy rates, unequal access to health care and education place the country closer to Namibia and Haiti on this list than their neighbor, Mexico (UNDP 2014, p.162). Poverty is concentrated in rural areas with the vast majority of this demographic dependent on subsistence agriculture. Food security and malnutrition in Guatemala are rated among the worst in all of Latin America. Childhood malnutrition was as high as 44% in the year 2000 (Marini et al. 2003), with 49% of stunting and 23% of low-weight-for-age in children under five years of age in 2002 (Lee et al. 2012, p.233). As well, Guatemala is the most food insecure country in the region with 30.4% of the population considered food insecure as of 2012 (World Food Program 2012, p.49). A recent report pointed out that in Chiquimula hunger fluctuates seasonally for the reasons that: firstly, families can only produce four to five months of grain; and secondly, during non-harvest time wholesalers within the department of Chiquimula have the price incentive and power to export grain to other areas of the country or international markets (Oxfam 2013).

Although substantial progress has been made since the ending of the 36-year civil war in 1996, the countryside still struggles with the archaic infrastructure left as its legacy. A 2013 market analysis of the Chiquimula region cited market access as the prime barrier to improving production (Oxfam 2013). Market access is costly as the study reported it typically takes a four-hour walk to access markets. Restricted market access inflates the cost of inputs, technical support, and financial services that can boost production. The study also emphasizes that small plot size and lack of expansion limits returns on investment (Oxfam 2013). Government institutions are still suffering from a democratic deficit perpetuated by corruption and inefficacy. Perpetually high crime rates compound the government's burden with limited funds to fight the problem. Inefficient and poorly functioning judicial institutions fail to secure credit and insurance markets (Brands 2010).

Within such conditions the economic cost of crop failure is extraordinary. Subsistence farmers do not have the means to weather crop failure. Crop insurance is often not available in many developing areas, and where it is available, inflated rates and high risk premiums destroy its viability. Without insurance, crop failure can force smallholders to sell off assets, ultimately diminishing their capital stock and further entrenching their vulnerability (Mahul et al. 2010).

Combined, these issues constrain the ability of the farmers to adapt and break the poverty cycle. A 2013 climate vulnerability index placed Guatemala in tenth place internationally with Honduras in first place and Nicaragua in fourth place (Kreft et al. 2013, p.6). With such restrictions the cost of marginal meteorological effects are drastic and affect the poorest sectors of the population by worsening their already inadequate food security and rates of chronic malnutrition. Smallholders, already living at the subsistence level do not have the capacity (financial or otherwise) to cope with such perennial problems without weather volatility compounding the issue (Bathfield et al. 2016).

2.2.2 Income and Socioeconomic Profile

The World Bank (2014b) estimates that 72% of Guatemala's rural inhabitants subsist on less than US$1.25 daily; with 87% depending on agriculture, either as small-scale farmers or laborers on coffee plantations (World Bank 2004, p.54). In the region, families can typically grow enough grain to last them four to five months while relying on income from unskilled labor, such as coffee picking, for the rest of the season. Due to the seasonality of agricultural production and labor demands, the poorest families experience chronic seasonal malnutrition between June and September, though in years of crisis this can extend until February (Oxfam 2013, p.6). Many rural households depend on a government social assistance program. *Mi Bono Seguro* gives regular cash support and is designed to provide each family with 300 Quetzales per quarter (approximately US$39). The program only reaches approximately 40% of the target population due to poor extension services (Oxfam 2013, p.6).

Land distribution has changed substantially over the past few decades. In 1964 the average farm size was 8.26 ha (11.8 Mz) with 20% of holdings less than 0.7 ha, whereas in 2003 the average farm size dropped to 4.4 ha (6.4 Mz) with over 45% of holdings less than 0.7 ha and over 68% less than 1.4 ha. The number of farms increased from 417,000 in 1964 to over 830,000 in 2003; 85% of farms are owned, with 11.4% rented (mainly for cash crops) (Instituto Nacional de Estadística Guatemala 2014, p.19). The GINI land holdings coefficient [3] of 0.84 suggesting massive inequality (Instituto Nacional de Estadística Guatemala 2004, p.22). These trends signify that land holdings are fragmented while large estate holdings are remaining constant or growing in number.

Coffee is still a mainstay of Guatemalan agricultural exports, with coffee picking employing a significant proportion of off-farm agricultural labour. However, over the last two decades many farmers have been shifting away from coffee production due to declining global prices (Haggar et al. 2013). Unfortunately, in the last few years coffee rust (a fungal infection similar to blight) has become a serious issue decimating crops and requiring millions of dollars in government assistance (Cressey 2013). This has unfortunately reduced labor demand for coffee picking with which many smallholders supplement their income. It is important to note that coffee and cocoa production is highly restrictive as the trees take upwards of seven years

3. The Gini coefficient is a statistical dispersion metric typically used to measure distribution of wealth within an economy. The metric is bound between zero and one, with zero being complete equality, i.e each person has an exactly equal share of the wealth, and one being complete inequality indicating one person holding all the wealth in an economy. Therefore, a larger land Gini coefficient indicates that holdings are distributed unequally with presence larger farms, which in the case of Guatemala are plantations. Research has shown that there is a strong negative correlation between the land holding Gini coefficient of a country and long-term growth (Deininger et al. 1998)

until the first harvest, and once such an investment has been made it is difficult to (economically) shift out of production. As well, within Central America a study by the International Center for Tropical Agriculture (CIAT) has indicated that within the region coffee is among the most vulnerable to climate change because of its sensitivity to temperature and water stress (Rahn et al. 2014). Prior to these impacts there has been a production shift away from coffee and cocoa towards alternative plantation crops. For instance, palm oil production has increased by 154% and cardamom has increased by 76% in the last decade (Instituto Nacional de Estadística Guatemala 2014, p.20).

2.2.3 Demand and Demographic Dynamics

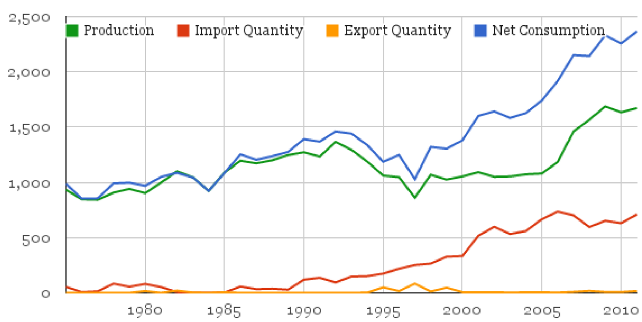

Figure 2.3: Annual Maize Production, Import and Export (1,000 Ton) (FAO 2015a)

Production of maize has been unable to keep pace with demand. Since the mid 1970s Guatemala's population has more than doubled (237%) from 6.2 million to almost 15 million today with total demand (production+imports-exports) just outpacing population (247%) (Table 8.5 in Appendix 6.3) (World Bank 2014a). This growing deficit is not solely attributable to climate impacts; there are two other factors which explain this divergence. Firstly, agricultural productivity has stagnated. Falling land fertility, lack of investment in, and access to improved varieties and technology have failed to boost yields beyond what they were almost half a century ago. According to FAO data, from 1993 to 2013, national maize yields fluctuated between 1.25 to 2.5 ton/ ha, with a country average of 2.03±0.29 t ha^{-1} (FAO 2015a). Within Chiquimula, average yields were 0.97 ton/ha (19.3 q/mz) (Ramirez et al. 2013, p.8). This can be compared with potential yields in the United

States under ideal conditions of as high as 17 ton/ha for late-maturing maize cultivars. Though this is the ideal,under full irrigation and fertility yields of between 10 to 12 ton/ha have been reported for similar varieties in Mexico (Steduto et al. 2012, p.119).

Secondly, the urban population of Guatemala grew by 322% since 1975 leading to a growing production deficit. National maize production has only increased by 186% since 1975, keeping pace with rural population growth that increased by 188% in the same period (DESA 2014). Figure 2.3 illustrates the deficit caused by the divergence between domestic production and demand; necessitating imports to fill the gap. Currently, the Guatemalan population is almost evenly split between rural and urban inhabitants. However, over the last three decades they have exhibited a steady 1% yearly decrease in rural/urban ratio (DESA 2014). Projections show that by 2050 the rural/urban ratio will be the inverse to what it was in 1975, i.e., 69%/31% as compared 36%/63% respectively. Over the last three decades, a tripling in population coupled with stagnant yields have dramatically diminished per capita production (FAO 2015a). In Guatemala, approximately 90% of agricultural production destined for internal consumption is comprised of maize (70%), beans (25%), and rice (6%)(CEPAL 2011, p.48).

For Chiquimula, consumption has not kept up with local demand. In 2003, a typical production year, maize production totaled 684,379 tons out of the 734,911 tons that region has consumed (Ramirez et al. 2013, p.6). For an agricultural community, not only is it disconcerting that a deficit of over 50,000 tons is typical, but during drought years upwards of 90% of consumption comes from imports and food aid (Guha-Sapir et al. 2015). In terms of trade, maize is now the largest agricultural import in terms of both quantity and value. Figure 2.3 illustrates the production deficit that has grown over the last few decades because sluggish domestic production has been unable to keep pace with demand. There is clearly a yield gap given how far local yields are below biological potential reached elsewhere in the world. This implies not only that there is an issue, but that technology exists to raise local production standards.

CHAPTER 3: LITERATURE REVIEW

Navigating through the plethora of climate impact studies reveals how contentious the topic is. Overwhelmingly, scientists agree that there are, and will be, substantial climate change impacts on the agricultural sector (Solomon et al. 2007; Kurukulasuriya et al. 2013), however there is considerable debate over the utility of multitude of models and methods used as they often reach contradictory conclusions (Nordhaus 2007; Marengo et al. 2014). The following pages summarize the literature in terms of methodology and scale of analysis.

3.1 Global and Regional Impact Studies

The controversial Stern (2007) Review which forecasted daunting global impacts on global crop yields and water resources. The Review was widely criticized for its overly-generalized approach (Nordhaus 2007). Parry et al. (2004) employed General circulation Model (GCM) projections and estimated that given a continued rate of growth in clean and more efficient technologies the effects of climate change in the developing regions could be offset by a shift in production to developed countries. Another GCM study of Latin America and Africa predicted that, although aggregate yields would decrease by only 10%, there is large geographic variation with certain areas completely unsuitable for continued maize and bean production (Jones et al. 2003). Due to the enormous geographical variation, the previous studies all concluded that they only give general trends and fail in relevance to local conditions.

In terms of regional studies, the 2014 IPCC report for Central America emphasized the regional variability and concluded only with general observations of increasing temperatures and late onset of the rainy season (Margrin et al. 2014, p.40). In another regional report, Marengo et al. (2014) echoed this generality and highlighted the lack of impact studies within Central America compared with other developing regions. Regional studies consistently predict large variances in impacts and yield reductions due to geographic variability. One recent impact study in Guatemala predicted that of the regional crops, maize yield showed the highest impact of between 39% to 107% of current yields with the greatest impact in the Dry Corridor region (Díaz-Ambrona et al. 2013, p.18). Bárcena et al. (2010, p.50) used GCM output and past yields to estimate that an average 3.5°C rise in temperature coupled with a 30% reduction in rainfall could result in total yield reductions as high as 34% for maize and 66% for beans.

The International Center for Tropical Agriculture (CIAT) conducted the most recent study, entitled *Tortillas on the Roaster*, which is probably the most rigorous regional study to date. The work utilized various GCM over the whole of Central America and identified the most vulnerable and prone areas for maize and bean production. The study's climate projections for the Dry Corridor estimated that rainfall during June (end of the *Primera* season) will be greatly reduced leading into an extended dry period (A. Eitzinger et al. 2013, p.33). As well they predicted significant, though minor decreases in absolute precipitation as well as an increased probability in the number of cumulative dry months from four to five months (A. Eitzinger et al. 2013, p.38). Within Guatemala, they pinpointed the most vulnerable regions as the Dry Corridor, Northern Highlands as well as the tropical lowland region of Petén with losses up to a third of production. However, in the regions around Guatemala City, Quetzaltenango, San Marcos, and Totonicapán the study predicted production increase of between 20% to 40% (A. Eitzinger et al. 2013, p.57). Although the study did suggest intensification, diversification, increasing off-farm income, and discontinuance of agriculture as adaptation options, there was no statistical assessment or modeling of these options (A. Eitzinger et al. 2013, p.107). It is important to recognize that the aforementioned studies have all been at a regional scale, and due to their generality, fail to offer locality-specific effects. Therefore they can only broadly suggest adaptation strategies.

3.2 Economic Impact Assessment of Water Scarcity

3.2.1 Cost-Benefit Analysis

Although not often used for climate change impact studies, cost benefit analysis (CBA) is by far the most common means of evaluating investments in limited water resources scenarios. Boardman et al. (2010) and Mishan et al. (2007) are two of the primary sources that cover the methods of CBA for optimal management of environmental resources. As well, the influential NOAA report by Arrow et al. (1993) established a standard for methods of contingent valuation. The strengths of CBA are that it is project specific and can easily incorporate discounting, sensitivity and scenario analysis. Compared to linear programming (LP) and regression analysis, CBA can better deal with risk and stochastic elements such as in the case of climate change where uncertainty must be managed. This can be done by converting uncertainty into expected risk by attaching probabilities to data according to historical observations, albeit with limitations; that is, following the seminal work of Knight (1921) who established the distinction between risk and uncertainty, projections will always be uncertain since future probability distributions will never be known and thus risk can only be expected. However, CBA does not have the same capacity that LP models have in dealing with the complexity of environmental systems. For instance, CBA often relies on only a single decision rule of a positive net present value after a sensitivity analysis has been performed, whereas with other modeling methods (such as those that incorporate systems theory) there is the ability to work with the dynamics of the system and their relationships.

The few CBA studies of climate change are at a national scale and tend to estimate in terms of impact on GDP against the cost of GHG abatement. Climate change CBAs of this type tend to be limited due to their generality. For instance, there is a high degree of uncertainty among almost all variables; such as the effects of GHG in the atmosphere and on plant growth;

and economic effects such as future demand, prices, technology on social welfare (Munasinghe et al. 1996, p.159). Shindell et al. (2012) drew on estimated pollution effects on human health and the market value impact on the yields of the four principal cereals to estimate that by 2050 abatement benefits range from US$700 to US$5000 per ton with a cost of US$250 per ton. West et al. (2005) drew on past studies and employed CBA to estimate the benefit of methane abatement on ozone depletion in terms of global grain yields and forestry. Conde et al. (1997) conducted a CBA on maize production in Mexico. The authors assumed a province-wide cost of adapting and performed a sensitivity analysis given potential price changes from liberalization of the maize market.

3.2.2 Linear and Mathematical Programming

Positive Mathematical Programming (PMP) calibrates non-linear yield or cost functions given resource allocation and farmers' optimization, satisfying Hicksian conditions for competitive firms (Howitt 1995). Over the past three decades this method has been used to optimize economy-wide impacts of climate change on agriculture in California (Medellín-Azuara et al. 2011) and Chile (Ponce et al. 2014). Labriet et al. (2003) optimized abatement measures by coupling damage functions of the costs of climate change with GHG abatement costs in an LP model. Farquharson et al. (2013) applied a LP model in Australia to evaluate substitution to perennial crops given land, labour, and water constraints. R. Kingwell et al. (1991) developed a discrete stochastic programming model which accounts for carry-over effects of costs and responses in yield to inputs in subsequent seasons. The model was used for dryland wheat-sheep farms in Western Australia to identify and calculate the value of optimal adjustments to climate change (R. S. Kingwell et al. 1993). Henry et al. (1981) combined input-output and linear programming models to determine how water constraints limit economic activity on an economy wide scale. The early models outlined an objective function with each agent maximising profit with respect to water as its limiting resource until production becomes infeasible. Another study by Liu et al. (2009) used an LP model to determine the shadow price of water restrictions in agriculture; they concluded that this technique is limited to economic phenomena and does not properly incorporate environmental variables. An earlier study by Chakravorty et al. (1995) used a Hamiltonian model to derive the shadow value of water for adoption of more efficient water conveyance systems, i.e. they modeled the cost of water lost in conveyance. Other studies employed a Lagrangian-Euler constrained optimization approach, such as with the case of measuring willingness to pay for improvements in irrigation technology (Haimes et al. 1974; Yoram 2003). Ward (2009) analyzed the value of water conservation that resulted from farmers converting to drip irrigation in the Rio Grande area. They accounted for incentives and water rights regimes, choice of technology, crop mix, water application and depletion. The analysis interpreted the shadow price of water as a change in the value of the irrigation districts' total net income that can be attributed to adding an additional acre-foot to the deletable water supply. They constructed a profit function derived from a linear production function of yield on land and water then they aggregated it and maximized by means of solving for the first order necessary conditions of the profit function with respect to water. Schmitz et al. (2013) identified global hot-spots of water demand and scarcity based on demand for irrigation technology. Their model starts with a nonlinear dynamic optimization model that analyses the impact of aggregate agricultural production on the environment. They linked this with a previously developed systems model that simulates land and water use patterns. Their model integrated over biophysical and economic constraints and was able to optimize and derive a shadow value for each constraint.

3.2.3 Hydro-Economic Models

There has been a burgeoning literature within the last two decades which incorporates economic elements into hydrological systems models used in engineering. Unlike hydrological systems analysis, hydro-economic models build around the objective of optimizing economic ends. The first models date to the late 1960s and early 1970s when economists developed optimal groundwater extraction models (Burt 1966; Rogers et al. 1970). These models typically consist of mapping supply as water flows and stocks in relation to estimated demand curves based on crop yield functions, dependent on factors such as irrigation technology and evapotranspiration. In general these models are based on an optimization algorithm subject to the constraint of water flow rates and stocks. Modular models function on the transfer of information from hydrological-state variables to economic variables although the two models operate independently of each other. With integrated models, as the name implies, the economic and hydrological models are joined. Cai and McKinney (2003) integrated hydrologic, agronomic and economic elements and optimized the draws of irrigation on a river basin subject to the effect of irrigation-induced soil salinity. Jones (2000) analyzed the risk of climate change by means of a Monte Carlo Simulation of water stress on an irrigation demand model. Varela-Ortega et al. (2011) developed an integrated hydro-economic model that would optimize water balance rates and ecosystem conservation of the *La Mancha* reservoir in Spain's central arid region. This was done by integrating flow rates with socioeconomic and projected climatic constraints then optimized given a variety of possible conservation policies. Santos et al. (2014) combined a dynamic input–output model with event tree analysis to analyze strategies to manage drought risk. The authors applied the model to a hypothetical drought in the United States National Capital region evaluating three risk management strategies with the objective of minimizing economic loss.

3.2.4 Agronomic Approach and Crop Simulation

Crop Simulation

Early crop simulation models were primarily regressions of national-scale yield and meteorological data on time (Thompson 1969). Regressions of this type suffered from omitted variable bias as results are dependent on a particular region and time and cannot account for changes in soil, land and other variables. What these models lose in accuracy they gain in simplicity. The National Agricultural Statistics Service still provides forecasting models and data sets to be used in the United States and Central America (NASS 2012). The limited predictive capacity is offset by the minimal data requirements and expertise needed to run the model.

Process-based models which rely on biological processes to simulate outcomes are the foundation of modern crop simulation models. Developments in computer science have allowed these models to incorporate photosynthetic processes, light interception, root uptake and CO_2 effects. Crop specific process models are numerous and can be divided into regional or farm level models. Regional models such as the General Large Area Model (GLAM) (Challinor et al. 2004) and FAO's Agro-Ecological Zone Model (Fischer et al. 2002) are used for national assessment and policy options, however, are unable to be scaled down to a farm or local level.

There are crop-specific models such as the Sirius Wheat Simulation Model (Semenov et al. 2007), the rice specific ORYZA2000 (Bouman 2001), as well as the CERESMaize (Ritchie et al. 1998) model developed by CIMMYT and used to simulate maize yields. Conde et al. (1997) applied GFDL climate predictions to the CERES maize model to analyze impact and specific points of vulnerability on rain-fed maize in a country-wide assessment of Mexico. Crop-specific models have been consolidated into multi-crop models to better represent management options. A CGIAR article found that few studies evaluated adaptation at the farm level and thus concluded with emphasizing the need for "more explicit farm level analysis with a focus on adaptation, vulnerability and risk."(vanWijk et al. 2012, p.3) . Another review covered 221 crop simulation models and found there was a clear deficit of accounting for risk at the farm level (White et al. 2011, p.357).

Popular simulation models include the Australian APSIM v4.2 (Keating et al. 2003) which simulates the response of agricultural systems to economic and biological outcomes. For instance APSIM was used to evaluate the performance of two maize varieties under different water stress conditions in Australia (Song et al. 2010). The INFOCROP model (Aggarwal et al. 2006) has been utilized in studies of rice (Krishnan et al. 2007), wheat (Kumar et al. 2014), and maize (Byjesh et al. 2010). INFOCROP has the capacity to model impacts on a variety of crops and has been specifically used to model pest damage; however it is largely used only in India and calibrated to the South Asian environment and cultivars. The STICS model has been developed and used extensively in France to model agro-environmental impacts on multiple crops (Brisson et al. 1998). STICS is particularly well suited to optimizing crop choice given climatic change, although use and studies of the model have been mostly within France. WOFOST was developed in the Netherlands as a tool to calculate attainable yield and water given soil type, crop type, weather data and crop management factors (Diepen et al. 1989). WOFOST has been used to simulate the impacts of drought at low temperatures in northeastern China with an estimated 34% drop in yield given low temperatures and drought (Chen et al. 2007) .

CropSyst and CERES-Maize (the predecessor of DSSAT maize) are the most widely used in maize yield simulation. The two models surpass others in terms of available data and calibration to multiple climatic environments. CropSyst focuses primarily on cropping systems management and has incorporated GIS to analyze optimal land management strategies (Stöckle et al. 2003). In one Argentinian study, CropSyst was found to have had higher statistically predictive ability than the CERES-Maize model. The difference is that DSSAT tends to marginally underestimate yield (Monzon et al. 2012). CropSyst results have been found to be less sensitive to drought and temperature fluctuation compared to DSSAT and others (J. Eitzinger et al. 2013). DSSAT was produced in Mexico under the International Maize and Wheat Improvement Center, and compared to CropSyst, DSSAT has been applied more frequently in North and South America.

The limitations of each model are found in their parameterization. Each model emphasizes different biophysical phenomena and disregards others such as pests, flooding, disease, soil effects and so on. Moreover, each model is calibrated for a certain region and crops. Soil characteristics, humidity levels, regional specific cultivars, and cropping practices are all regionally specific. Therefore, using the model for studies in the region it was calibrated in is important. Moving a model outside of its geographic region introduces endogeneity by means of the nuanced effects of the non-parameterized variables. Thus model performance and specification is regionally dependent.

DSSAT is more appropriate than other models for studies within Guatemala since it has been calibrated and applied more frequently in the region. Its high sensitivity to climatic changes must be taken into account in order to avoid Type-two errors; i.e., rejecting the null hypothesis of no impact when there is an impact. However, having this sensitivity the model is more conservative and cautious than a potential for a Type-one error in the case of lower sensitivity.

Elevated CO_2 and Temperature Effects

There is little response of maize yield, total leaf area, silking or anthesis date to elevated CO_2 levels. One study did reveal statistically significant effects on yields, though the increase was marginal in magnitude, i.e., 370 ppm CO_2 = 140 ± 6 g per plant compared with 550 ppm CO_2 = 142 ± 6 g per plant (Leakey et al. 2006, p.786). The reason for the minimal effect is that CO_2 affects growth in two counteracting ways; firstly CO_2 induces stomatal closure, thus lowering transpiration rate (TR); as well, CO_2 stimulates photosynthesis which increases the TR (Maurer et al. 2009, p.190). Kergoat et al. (2002) have shown that in tropical regions the magnitude of each effect is near equal thus canceling each other out.

Maize is a C_4 crop and is remarkably tolerant of high temperatures. C_4 fixation is more efficient than C_3 crops because the presence of the C_4 molecule overcomes the tendency of the enzyme RuBisCo to wastefully fix oxygen rather than carbon dioxide (Ehleringer et al. 1977). Therefore, as far as temperature stress is concerned maize is far more tolerant than C_3

crops such as beans and rice. In the case of beans (which constitute a substantial protein source for all of Latin America) there is a temperature optimum of between 21°C to 26°C, beyond which, in early stages, germination is substantially slowed and in later development, pollen sterility is possible (Goldsworthy et al. 1984, p.346). Due to the importance of beans in the Latin American diet, of heat stress which lowers bean yields might have a greater nutritional impact than on maize (Jones et al. 2003, p.56).

Maximum temperatures above 35°C have a negative impact on biomass, however temperatures up to this point have increasing marginal developmental effect for both anthesis and maturity time. When exposed to short temperature shock treatments of 30 minutes at 45°C, maize had permanent damage to photosynthetic rate and did not recover. At 40°C treatments, it took over 48 hours to recover to normal photosynthesis. The photosynthesis of leaves grown at optimal temperature decreased considerably when exposed to 35°C or higher (Sinsawat et al. 2004, p.128). Bannayan et al. (2004) conducted a study of nine maize cultivars over nine temperature minimums and maximums ranging from minimums of 5°C-35°C to maximums of 15°C-45°C. They found that the development rate increased until 35°C maximum temperatures, beyond which there was a negative impact on biomass. However the highest potential yields were found at rather low temperature combinations of maximum and minimum temperatures of 20°C and 10°C respectively, mostly for reasons of lengthened growing season at lower temperatures. Overall yields varied between 10.0 t/ha to 23.2 t/ha (Bannayan et al. 2004, p.283). A faster development rate at higher temperatures (below 35°C) might shorten the growing season enough to mitigate the impact of the contracted rainy season, as long as the crops reach full development before the end of the rains. Importantly, these data are used in the calibration of the DSSAT crop simulation model.

Crafts-Brandner et al. (2002) reported that at temperatures above 38°C net photosynthesis was drastically inhibited. The study concluded that the inactivation of the RuBisCo enzyme at temperatures above 30°C was the prime constraint on photosynthesis. They also found that rapid increases in temperature inhibited photosynthesis by greater than 95% at 45°C, whereas gradual increases inhibited photosynthesis by just over 50%. An earlier study at 38°C /32°C day/night temperature with relative humidity 55%/75% respectively (this translates to a VPD of 2.98/1.19 day/night[4]) showed a 48%, 72%, and 85% yield reduction for treatments of water stress, heat stress, and heat and water stress combined (Schoper et al. 1986). A study by Dupuis et al. (1990) on pollen sterility and fertilization, showed that the fertilization rate is nearly unaffected at temperatures up to 32°C during anthesis with marginal reductions up to 36°C. However, beyond 36°C the fertility of pollinated spikelets dropped substantially with almost complete sterilization above 40°C during anthesis. These findings are relatively consistent, and together they illustrate that maize spikelet sterility is almost certain around 38°C with minimal variance among varieties. In the case of maize, since the sterility threshold is so high, and the low probability of temperatures of this degree being reached during the flowering period (June-July for Chiquimula region), the direct effect of temperature is of minor concern compared with the indirect effects it has on evapotranspiration and overall water requirements which will be discussed later.

Water Stress

Various studies have shown that sensitivity to water stress is dependent on developmental stage. The stages can be split into four periods: vegetative stage, 5-50 DAS (days after sowing); flowering and fertilization stage, 65-70 DAS; grain filling/milking stage, 70-90 DAS; and maturity, 90-135 DAS. There is some temporal variation among varieties with short season cultivars flowering 10 to 15 days earlier (Steduto et al. 2012, p.117). Robins et al. (1953) reported that during anthesis (approximately 57 DAS) a two and seven day long water stress resulted in 22% and 50% grain yield reduction respectively . Doorenbos et al. (1979, p.176) reported that maize is relatively tolerant to water stress during the vegetative stage and is most

4. Calculations done using Excel using Murray (1967).

susceptible during the flowering and fertilization. The FAO used a Yield Response Factor (yield water elasticity) which is a percent reduction in yield given a percent reduction in water. Their results showed that overall maize is “very sensitive” to water deficits with an overall yield response to water deficit coefficient of 1.25, and a coefficient as high as 2.3 for the flowering and yield formation stages (Steduto et al. 2012, p.8). NeSmith et al. (1992, p.107) showed that 18 and 21 days without water during anthesis resulted in yield losses of 15–25% respectively at time of maturity. Çakir (2004, p.12) found that short periods of water omission of as few as 15 days during anthesis resulted in as much as a 40% yield reduction in high Vapor Pressure Deficit (VPD) conditions, with yield losses as high as 66%–93% if water was omitted during tasseling. The same study observed only minor losses with similar stresses during the vegetative stage (Çakir 2004, p.9). Collectively, the literature highlights the high sensitivity of water stress during the flowering stage (65-70 DAS); therefore emphasis needs to be put on timing this stage to coincide with rains by means of early planting or quick maturing cultivars, or maintaining water reserves for irrigation.

The Water Use Efficiency metric was the earliest, and most widely used metric to determine growth with limited water supply. It is simply a ratio of the water used in plant metabolism over water loss through transpiration (Briggs et al. 1913). Since higher TR correlates to higher yield and a lower water use efficiency, the metric cannot represent optimal yield given water restrictions (Bacon 2009, p.204). Over the last few decades crop water requirements have been determined with the VPD which is a general representation of the drying force of the ambient air, or the ’pull’ on plant transpiration. VPD and temperature are the two primary factors influencing a plant’s minimum water requirements and thus drought tolerance (Crafts-Brandner et al. 2002, p.1774).

In a study of multiple genotypes, Yang et al. (2012) showed that there is a substantial difference in the marginal TR at higher temperatures. Each genotype consistently exhibited a break point around a VPD of 2.0 kPa. Below this pressure, TR increased with VPD at a rate of 19.0 mg H_2O m^{-2}, whereas above the 2.0 kPa point the slope of transpiration response to VPD decreased from 19.0 to 9.4 mg H_2O m^{-2} kPa^{-1}. As well, the response of plants to water stress in the soil has been found in various studies (Sadras et al. 1996; Ray et al. 1998, 2002) to not affect the TR, i.e., soil water levels do not have an effect on stromal closure in a variety of crops and genotypes. As well, TRs have been found to be independent of soil types, although minimum water requirements are correlated to soils that have drainage and poor water extraction ability, such as with highly sandy soils (Sinclair et al. 1998). Consistently throughout the literature TRs are marginally decreasing with VPD. There is minor variation among genotypes and soil type, although minimum water requirements are dependent on soil type. [5]

3.2.5 Gap in the Literature

Climate change impact and adaptation studies are split between the two extremes, that of agronomic models at the field level and economic impact models which are of low resolution, i.e., at a national or even international scale. Although crop simulation and economic impact studies are based on the biological phenomena there are only a few studies, such as An (2015), that have analyzed the impact and adaptation strategies at the farm level. An (2015)

5. Calculating the expected VPD during each growth stage can determine if water stress will be a constraining factor given climatic predictions. Relative humidity for Chiquimula ranges between summer highs of 95-99% with lows around 40% in April and 60% from June-December (refer to Table 8.6 in Appendix 6.3) (Cedar Lake Inc. 2014). Using Murray (1967) formula calculations showed that VPD is highest during the early *Primera* season with a daytime VPD of 2.67. Using the TR model from Yang et al. (2012) this correlates to a TR of 40 mg H_2O m^{-2}. Considering global warming projections, if ambient temperatures were to rise by around 2°C to 35°C this would suggest a TR ratio of 45 mg H_2O m^{-2}. With the marginal effects mentioned this signifies a 10% increase in water demands for the first six weeks of the season. Since the marginal impact of VPD on the TR is higher below the 2.0 kPa point, with a comparable increase in temperature during the late season the impact would be greater, i.e. from 1.24 to 1.65 VPD which correlates to a 8mg H_2O m^{-2} increase (assuming a slope of 19mg H_2O m^{-2}) in TR from 25mg H_2O m^{-2}. Although marginal effects are less during the planting and vegetative stages the absolute effects are higher due to high temperatures and high VPD over 3 kPa (refer to Table 8.6 in Appendix 6.3). Since higher temperatures and a shorter rainy season will have the greatest impact in the late season (i.e., late flowering through the grain filling stage) this is the point where irrigation infrastructure will have its greatest benefit. Thus these calculations signify that maize and bean are vulnerable to the predicted effects of climate change in the region.

her study focused on Ontario and Quebec, a region characterised by large scale farms and functioning credit markets; this study will be focusing on smallholders within Chiquimula, Guatemala, living near the subsistence level. National impact studies are useful for informing policy makers, however they fail to inform the smallholder as to what optimal investments they can make given their particular socioeconomic reality and constraints. On the other side, agronomic experiments do provide specific results to particular phenomena with a tested degree of significance. However, they are nonetheless hypothetical as they exist in a *ceteris paribus* world void of socio-economic constraints.

CHAPTER 4: METHODOLOGY

4.1 Methodology

1. First, the meteorological effects of the changing climate were assessed. Climate projections of daily precipitation, maximum and minimum temperatures, as well as solar radiation, were compiled from averaging the results of six GCMs (See the overview in appendix A.2.3) given the IPCC A2 scenario. A second weather data set was created by scaling the temperature and precipitation data to represent an El Niño-scenario. In the LP model, a Holt-Winters seasonal model was used to determine which years are El Niño and La Niña.

2. Second, the meteorological data were used in DSSAT to simulate annual maize and bean yields for the periods of 2020 through 2050 over seven maize and five bean genotypes for each of six irrigation schemes and three fertilizer scenarios. Maize yields for both seasons were simulated using DSSAT's sequence analysis with residue to simulate intercropping and without for monocropped maize. Bean yields were simulated for both seasons.

3. Third, future input and output market prices as well as population were projected using an autoregressive model. A linear programming model was used to optimize the NPV of profit for each irrigation system for the period of 2020-2050. Each irrigation system was optimised over three different constraint scenarios of non-adaptation, fixed genotype, and perfect information. Each model was optimised for the fertilizer and genotype combination subject to both capital and intercropping rates.

4.2 Data Requirements and Assumptions

4.2.1 Meteorological

Data requirements for the climate projections are straightforward since DSSAT simulations require daily precipitation, minimum and maximum temperatures and solar radiation. Unfortunately, Chiquimula, as in most developing regions, has almost no historical weather data. The closest weather station with consistent data is in Guatemala City which is almost 200 km away and has a different climate since its located at a lower elevation and closer to the Pacific coast. Without substantial regional meteorological records robust projections are not possible, therefore, this study must rely on GCM-generated climate data.

The International Panel on Climate Change (IPCC) climate scenarios were used as predictions of future trends. The scenarios are composite measures of both natural and anthropogenic drivers of climate change. Each follows a theme of best and worst case scenarios of the spread and rate of efficient technological progress combined with degrees of reliance on fossil fuels; both serve as metrics for projected adaptation to and intensification of climatic changes. Drawing on these scenarios, the global warming effects are calculated for each year until the end of the century given the life-cycle and feedback effects of their respective expected levels of GHG emissions; such as CO_2 , CH_4 (Methane), and O_3 (Ozone) (Solomon et al. 2007, p.14). Each model specifies: trends of an economically diverging or converging world based on ease of trade and transfer of technology; rates of technological change; rates of population growth and demographics; and degree of emphasis on coal and petroleum versus alternative energy sources (Van Kooten 2012, p.103). There are four base models spanning from B1 to A2; the prior assumes fast technological growth, convergence, and emphasis on sustainable energy sources; while the latter assumes a heterogeneous world, market restrictions, and population growth continuing at current rates. A synopsis of the scenarios are outlined in Appendix 6.3.

For the purposes of this research, scenario A2 will be the only scenario considered for four reasons: First, outside of Guatemala City, the economy is largely insular for reasons of lack of integration into international markets and trade barriers [6] (World Trade Organization 2009). Second, unlike most developed countries where a shrinking manufacturing sector leads to a service based economy, Guatemala is experiencing a shift from the agricultural sector towards manufacturing. The country will likely be export-oriented for agricultural, natural resource and manufacturing goods for years to come. Third, it can be expected that funds for investment in novel and efficient technologies will be limited for a considerable time as addressing the country's infrastructure gap takes precedence. Lastly, Guatemala's population growth rate is among the world's fastest at 2.5% annual (33^{rd} highest out of 188 countries) (World Bank 2014a).

4.2.2 General Circulation Models and Downscaling

There are four typical forms of climate models that differ primarily in degree of complexity. Firstly, although Energy Balance Models (EBMs) are the simplest they do allow for isolating effects such as the effect of CO_2 on temperature. The model is a simple function of the balance of solar radiation on the Earth and its effect on the atmosphere (including clouds, CO_2 and humidity). The model allows for energy exchanges across latitudes that are caused by melted snow or ice-caps. Secondly, Radiative-Convective (RC) models include elevation but do not allow for horizontal exchanges of energy. It divides the Earth into grid cells with particular conductive capacity depending on type of vegetation (e.g., desert or jungle). They calculate the conductive potential given the atmosphere's conductive capacity. RC models operate under the assumption that "at the top of the atmosphere there must be a balance of shortwave and long-wave fluxes, and that surface energy gained by radiation equals that lost by convection"

6. Since the Uruguay Round, Guatemala has made commitments towards liberalization and lowering of tariffs. Though import tariffs still exist for many agricultural goods, including maize, the government has committed to phasing them out without a determined deadline (World Trade Organization 2009).

(McGuffie et al. 2005, p.53). Thirdly, Earth Modeling with Intermediate Complexity (EMIC) are similar in function to EBMs in that they allow for energy diffusion across latitudes but instead are governed by an eddy diffusion process. In the last level of complexity are the General Circulation Models (GCM). These models are one step beyond EMIC models in that they exist in three dimensional space, as opposed to EMIC or EBM models which are restricted to two or less dimensions. GCMs have resolutions as fine as 2° X 2° latitude by longitude with each grid cell having a corresponding vertical column; each column having between 6 to 50 layers depending on the model. Energy diffusion between cells revolves according to observable atmospheric currents. As well, time is separated into 20-30 minute periods (17,000 to 26,000 periods per year) (Van Kooten 2012, p.126-129).

When considering model choice, complexity does not imply higher predictability. It has been shown that in many cases GCMs perform only marginally better than simpler models (Van Kooten 2012). Even though the modeling process takes far more effects into account, bulky models suffer from over-fitting and over-specification of the model as well as high data demands. Even if climate models accurately depict ocean and atmospheric currents they are very poor at describing clouds, dust, and the biology of fields and farmlands (Dyson 2007). It is important to mention that the above GCMs run off of a third order Markov Chain, and thus over time have a tendency to estimate towards a mean as opposed to diverging from the mean. Although divergence and sensitivity to initial conditions will render the model useless in long term studies, for this study the smoothing effect does impose this limitation, and understanding this limitation is crucial. The objective of this study is to access not only the impact of water scarcity in absolute terms, but also the cost in terms of increasing variability. Therefore when interpreting the results this characteristic must be taken into account.

This study will use an average of the six GCMs that can be down-scaled with MarkSim, namely; BCCR_BCM2.0, CNRM-CM3, CSIRO-Mk3.5, ECHam5, INMCM3.0 and MIROC3.2 (also named Medres). For a synopsis of each model including their place of origin and function refer to Appendix 6.3. There are two primary downscaling techniques. Firstly, statistical downscaling which is based on the Delta Method which assumes consistency, or asymptotic convergence to a given probability distribution (Greene 2012, p.70). The method downscales climate model data with the distribution of local weather variance. The ClimGen and MarkSim both follow the pattern-scaling approach. This approach scales down GCM data by coupling it to a third-order Markov Chain fitted to daily weather data from local stations. Secondly, dynamic downscaling, which uses the output of the GCM to drive a regional model at higher resolution that has been calibrated to a region's particularities; examples include the ETA model and RCMS Precis model. The characteristics of the above models are detailed in Appendix 6.3.

4.2.3 El Niño and La Niña

To account for the effects of the El Niño southern oscillation, monthly data for the past 65 years (1950-2015) of the above and below average temperatures were collected from the National Weather Service Climate Prediction Center (2015). These data were then projected until 2050 in Stata (StataCorp 2013, p.590) using the Holt-Winters seasonal multiplicative model because of its ability to capture seasonal effects and oscillations around a mean (Holt 2004; Winters 1960). The Holt-Winters model is a composite of three nested parts, firstly, a level equation with ℓ_t as the estimated level of the series at time t. The smoothing parameter $\alpha(0 \leqslant \alpha \leqslant 1)$ for the level is a convex combination spanning the previous value y_t with the next step forecast as $\ell_{t-1} + b_{t-1}$ with b_t as the slope coefficient of the series at time t. Secondly, a trend equation is estimated with a similar convex combination but over the changing levels of the equation, i.e., $(\ell_t - \ell_{t-1})$. Third, a seasonal equation, differentiating the model from Holt's linear trend, estimates a weighted average of the current seasonal index i.e., $(y_t - \ell_{t-1} - b_{t-1})$ with the same season last year. Lastly, all three models are nested into a forecast equation with level, trend, and seasonal parameters (Hyndman et al. 2014, p.180).

Holt-Winters Seasonal Method

$$
\begin{aligned}
\text{Forecast Equation} \qquad & \hat{Y}_{t+h|t} = \ell_t + hb_t + s_{t-m+h_m^+} \\
\text{Level Equation} \qquad & \ell_t = \alpha y_t + (1-\alpha)(\ell_{t-1} + b_{t-1}) \\
\text{Trend Equation} \qquad & b_t = \beta^*(\ell_t - \ell_{t-1}) + (1-\beta^*)b_{t-1} \\
\text{Seasonal Equation} \qquad & s_t = \gamma(y_t - \ell_{t-1} - b_{t-1}) + (1-\gamma)s_{t-m}
\end{aligned}
$$

To accommodate for the inability of the Holt-Winters model to allow for negative values, projected points were readjusted around their mean. That is, the mean for the points past 2015 was equated with the zero, or an average temperature line, of the observed data. Essentially this resulted in a projection that indicates years that would have above average temperatures, i.e., El Niño, and years below average temperatures, i.e La Niña. Years containing at least four consecutive months with 0.5°C above or below mean temperatures, thus representing El Niño and La Niña years, respectively. To import the data into the model dummy variables were created to classify a year as either falling into the El Niño or La Niña scenario, with the model drawing from each data source depending on the dummy variable. A time series of the observed and forecasted data is in Appendix 6.3. Figure 4.4 details the role which the Holt-Winters results play in determining which years the final linear programming model will select as El Niño or La Niña.

4.3 DSSAT Data and Local Characteristics

4.3.1 Soil

Entisols and inceptisols are the most common soils in the Guatemalan highlands (IICAs 1992, p.11-23). The province of Chiquimula is mainly covered in Entisols derived from volcanic ash with a high silt and sand content (IARNA 2006, p.8). Land depletion in the area is high due to overuse, soil erosion, as well as lack of organic and inorganic amendments (IARNA

2006, p.25). Given the sandy and silty nature of the Entisols in the region this study will use the *generic medium sandy loam* soil in DSSAT. This generic soil profile is a conservative choice as it tends to have a high drainage coefficient which suits the sandy nature of the soil in the region. As well, a slope coefficient of 20% will be used to account for the mountainous nature of the region, where a reported majority of crops are planted on slopes.

Since DSSAT is not suited to accommodate the complex symbiosis of inter-cropping, the effects were simulated with periodic sub-surface (10cm below surface) bean residue applications. Four applications were automated for every 15-day interval over the second season. Each of the residue applications equated to 10, 12, 14 and 16 kg N/ha (20, 40, and 60 kg N/ha over the season) for genotypes Rabina de Gato, ICTA-Oustra, Turbo III, Porrillo Sintético and San Cristóbal 83 respectively. Choice was based on each variety's expected performance, as well as the ability to simulate a range of performances. The values were deduced from studies on the common bean of high performing varieties that have nitrogen fixation rates that are equivalent to 80-120 kg N/ha for the season (Wortmann 2006). Lower values were chosen since none of the varieties used are considered to have specifically high fixation rates, with Rabina de Gato being closest to a traditional variety and Turbo III being a high-performance novel strain.

4.3.2 Planting Date

Throughout Central America there are two planting seasons for maize and bean producers which coincide with the two rainy seasons. The *Primera* which runs from May through August (4-5months) and the *Postera* season which runs from September to December (3-4 months). For smallholders the *Primera* season is predominantly mono-crop white maize, while the *Postera* season is white maize intercropped with black bean. *Primera* maize is sown following the first rains of the season, which commence from late April until mid May and continue until about May 1st to July 15th. The *Postera* season is planted within the first few weeks of September and harvested in early December. A quick overview of the GCM weather projections place early May and September as a key time frame of the first rains. Therefore, this analysis will consider May 1st and September 5th as the mean business-as-usual planting dates for the *Primera* and *Postera* seasons respectively.

4.3.3 Genotypes and Production

Maize and bean production in the region is traditionally split 66/34% respectively; with the *Primera* season consisting almost completely of maize monocultue and *Postera* intercropped (Instituto Nacional de Estadística Guatemala 2014, p.18). The majority of maize is produced during the *Primera* season, which accounts for two thirds of the national maize area harvested and about 75% of production. The remainder of maize production is typically intercropped with beans during the *Postera* or late summer season (Barreto et al. 1999, p.3-4). Local estimates place maize yields as low as 0.97 t/ha for traditional varieties to about 3.3 t/ha for improved varieties (Ramirez et al. 2013, p.8). FAO estimates that national yields fluctuate between 1.25 to 2.5 t/ha, with a country average of 2.03 ± 0.29 t/ha (FAO 2015a). Returns on improved varieties for the neighboring region Jutiapa, were estimated at between 35% to 70% over the same set of available cultivars (Sain et al. 1999, p.22).

In terms of maize, the local Arriquín and Tuza y Olote Morado varieties are the most popular non-improved genotypes which are planted at least in part by 50% of the farms (Ramirez et al. 2013, p.31). The improved and hybrid varieties used in the region are HB-83, H-5, DK357, HB-64, and Pionner 304X (Ramirez et al. 2013, p.30). Experimental data, and thus parameterization in DSSAT of any of the local traditional seeds is non-existent. Therefore, for the non-adaptation scenario a similar performing tropical hybrid with comparable biological characteristics has been chosen as a proxy. The vegetative cycle and max biological potentials are known for Arriquín, B-1 and B-5 which are; 3.68 , 3.94 , and 3.61 t/ha respectively, with B-1 and B-5 having water stress tolerance as low as 1000 mm of precipitation per year (Soria 1993). The non-adaptation proxy genotype will be ND108 (also referred to as DEA) for reasons of its comparable yield and time to maturity (Cao et al. 2009; Hoogenboom et al. 2015). Dekalb (2015) XL 71 and Pioneer (2015) 304X will be chosen as the improved varieties. Although neither of them carry the title of "drought tolerant" both are considered to have a higher resistance to water stress and a shorter duration until harvest (65-70 DAS) than traditional varieties. This gives them improved resilience in conditions of a contracting rainy season.

Cost of maize seed is quite variable and dependent on suppliers' and purchasers' economies of scale as well as regional specifics. According to Iowa State University (2011), seed prices in the last decade range from US$1.00 to US$2.50 per 1000 seeds. Seed volumes range between 2,500 to 4,000 seeds per kilogram. A desired plant population per hectare of 15,000, results in a sowing rate of 5.5 kilograms per hectare. Assuming a mean of 3,250 seeds per kilo, a seed sowing rate of 5.5 kg/ha results in 17,875 seeds per hectare; with a price range of US$1-$2.5 per 1,000, or US$17.87-$44.69 per hectare. Thus, the average cost is US$31.28 per hectare. The cost of seeds has been projected given an average economic growth rate from the World Bank (2014b) for 1950-2015 (short of outliers $\mu \pm \sigma^2$), as well as with a coefficient of production technology to mimic the effect of increases in efficiency and technology on price. Technological growth coefficients for both maize and bean were determined with a time-series regression over average annual yield data for the years 1961 until 2014 from Mexico collected from the World Bank (2014b). The analysis resulted in slope coefficients of $\beta = 0.047$ and $\beta = 0.056$ for maize and bean respectively in terms of tons per hectare per year. Due to an unavailability of prices for specific genotypes based on performance, the model will assume all genotypes as being equivalent in cost. While this is a limiting assumption, given the minimal cost of seed relative to other inputs, and the probability that many seeds will be recycled, this restriction does not have a great influence on the calculation.

In terms of bean genotypes there is much less diversity in the region. The common black bean constitutes the majority of production with ICTA-Ostua and Rabia de Gato varieties most widely used. Nitrogen fixation of black beans is highly dependent on the variety selection.

Bliss (1993, p.76) studied the mean nitrogen fixation rates of 12 black bean varieties in enriched and depleted soils. The results showed an average fixation rate of 375.27 mg of nitrogen per plant in non-enriched soil[7]. Of particular note, the Mexican genotype *Puebla 152* that is common throughout the region has a high nitrogen fixation rate of 688 mg of nitrogen per plant. Herridge (2003) likewise reported similar findings with a mean of 674 mg/plant for *Puebla 152*. With a seeding density of 25-30 plants per meter squared this correlates to fixation rates of 17.20-20.64 kg N/ha.[8] The variety uses 62.2% of its nitrogen from fixation (Kabahuma 2013, p.27). Achieng et al. (2011) observed that the symbiotic effect of intercropping contributes a 37.5% higher overall yield given a 30/70 maize/bean mix one season, followed by maize monoculture. The additional yield is primarily in the following *Primera* season with yields reported to be as high as 50% greater compared to no intercropping the previous season, given nitrogen depleted soil without additional amendments. Five bean genotypes that are either available in the region, or suited to the tropical climate are used. Three of which, i.e., Rabina de Gato, ICTA-Ostua, and TURBO III were calibrated at the Instituto de Ciencia y Tecnología Agrícolas (ICTA) research facility in Guatemala. The other two bean genotypes, Porrillo Sintético and San Cristóbal 83, were calibrated at the Centro Internacional de Agricultura Tropical (CIAT) bean research facility (Zuluaga et al. 1989).

The linear programming model will determine an optimal seeding ratio for both seasons, that is allowing for bean to be intercropped with maize during both seasons. The unconstrained model will choose between five intercropping bean to maize ratios (α), namely; $\alpha = [0, 0.3, 0.5, 0.7, 1]$, with $\alpha = 0$ being monoculture maize and $\alpha = 1$ as monoculture bean. The model will be run in two scenarios: Firstly unconstrained allowing for $\alpha \in [0, 1]$ and secondly constrained such that $\alpha \in [0.3, 0.7]$. The latter assumes that the smallholders will be devoting at least 30% ($\alpha = 0.3$) of their land to bean production for personal consumption as

7. This is excluding the outliers *Sanilac* which showed a mean of 19 mg of nitrogen per plant

8. The Gov. of Canada (2012) suggests an optimum density of 30 plants per meter squared for black beans in irrigated conditions

well as at least 70% ($1 - \alpha = 0.7$) to maize production. The latter scenario mimics current practices. The symbiotic effects of bean nitrogen fixation on maize will be calculated by applying a convex combination between the yields of maize given that it is intercropped with 70% bean as the maximum level of symbiosis and monoculture maize. Unfortunately this method is limited in that it does not capture the complex symbiosis of intercropping effects. Moreover it assumes that the relation is linear and purely a function of proportion, which multiple studies have shown is not the case (Giller et al. 1991). To avoid over-specification and preserve a parsimonious model the linear assumption will be maintained. To account for the potential benefit of advances in biotechnology over the projected thirty year period both maize and bean yields will be scaled by a biotechnology coefficient. This coefficient was estimated as a linear time-series of average maize and bean yields in Mexico from the year 1960 to 2015 projected until 2050. The yield projections used to estimate the biotechnology coefficients are in Appendix 6.3

4.3.4 Fertilizer

The region has been predominately using granular urea as its inorganic fertilizer source for many years making up nearly 85% of fertiliser used (FAO 2015a). By international standards the country does consume a significant amount of fertiliser considering its degree of economic development. As of 2015 Guatemala was consuming an average of 98 kilograms of nitrogen per hectare, not far behind the global average of 124 kilograms per hectare (FAO 2015b, p.97). This figure is not representative of the entire population as the bulk of consumption is for large scale plantation agriculture, such as sugar and bananas, whereas smallholders who have less access to credit tend to use much less, if any. This figure does indicate that fertiliser, specifically granular urea, is readily available through established markets.

The crop simulation will consider three distinct inorganic fertilizer scenarios. The first being none, to simulate a 'business-as-usual' scenario since little or no inorganic fertilizer is used among smallholders (Ramirez et al. 2013). The second and third scenarios will be that of 100 and 200 kilograms of nitrogen per hectare respectively. Each treatment is applied in the form of granular urea with two scheduled amendments at 25 and 45 days after planting. The three fertiliser scenarios will give a range for the model to optimize, given the constraints of cost. Future urea prices were predicted using a standard OLS ($R^2 = 0.57$) regressed on crude oil prices in terms of US dollars per barrel from the World Bank (2014b) and national population from FAO (2015a) data for the years of 1961 until 2015. Both crude oil and population are specified as proxies for supply and demand, respectively. Future fertiliser prices were predicted by fitting the model coefficients with projected prices for oil and population that were determined by projecting the 1961-2015 data to 2050 with an ARIMA(2,3,2) model.

4.3.5 Irrigation

There has been a variety of studies that have shown an increase in demand for water-efficient production technologies due to strained supplies and increased competition for resources (Cai, Rosegrant, et al. 2003). The literature on irrigation techniques and ground cover is extensive, and the results are largely dependent on environmental conditions as well as crop type (Burton 2010; Laycock 2007; Walker 1989). The literature indicates that both drip irrigation and plastic mulching (i.e., ground cover) substantially increase the water use efficiency of crops by typically between two to three times, but without any significant increase in yield (Zwart et al. 2004; He et al. 2013). Water-efficient technology is viable only in situations where water is a sufficient constraint on production (Kay 2001).

There has been a variety of low input irrigation systems developed to service smallholders. Mostly these systems are gravity fed and consist of a 50-gallon drum or larger reservoir connected to irrigation conveyance systems such as sprinklers, drip tape, or furrows, each with their respective cost and efficiencies. Trickle irrigation systems function at an efficiency of $\geqslant 90\%$. Chapin Watermatics bucket irrigation kit is a much smaller kit that covers 15m^2 at a subsidized cost of US$7. The kit consists of a 5-gallon bucket raised 1 metre above field height with two 16-metre long drip lines. The kit can be multiplied depending on how many rows need to be irrigated (Jain inc. 2015). The Netafim Family Drip System is a trickle irrigation system which covers 1,000 m^2 for US$160-240 (or US$1,500-$2,400 per hectare) (NETAFIM 2015). International Development Enterprises's (IDE no date) drum kits can irrigate 125 m^2 at a cost of $25 USD (or US$2000/ha). The kits are gravity-fed by raised 200-liter drums which can be added to depending on the plot size and storage needs. The irrigation system emits water from perforations made in the irrigation hose. The system functions similar to a sprinkler system though with more accuracy and efficiencies between $75\% - 85\%$.

Due to the small capacity of fifty-gallon reservoirs the aforementioned kits are limited typically to smaller fields and vegetable gardens. Expanding such kits to cover one hectare would be economically inefficient since larger reservoirs are much cheaper per capacity than fifty-gallon drums. There are two kits that can be scaled up or down to meet smallholders' demands. The Drip Works drip irrigation tape kit, US$460, covers forty 100-foot rows. At 1-meter row spacing, this kit covers one hectare at a cost of US$3,772 (Drip Works Inc 2015). Secondly, the Huntop Agricultural Drip Irrigation System is a medium scale system produced in China that covers 500 m^2 and costs US$128.20 per kit. Scaling this kit up to one hectare would cost US$2,564 plus the reservoir cost (Huntop inc. 2015). Lastly there are gated pipe-furrow irrigation systems. Although not a particular kit, furrow irrigation consists simply of diverting water from a stream or reservoir into furrows. Prices range around US$600 for a reservoir and conveyance to furrows. Irrigation efficiency is as low as 50% (Wichelns et al. 1996)

Each system will be considered in terms of initial cost, holding capacity, and application efficiency. Irrigation Efficiency E_i is a metric determined by $E_i = ET_i/W_g - P_e$ with ET_i as the water consumed by evapotranspiration, with W_g as gross supply and P_e the amount of effective precipitation that reduces the amount of irrigation water needed (Jensen 2007). Field application efficiency ranges from 60% for border and furrow, to 75% for sprinkler, to drip with between 85-95% depending on technology (Mostafa et al. 2013; Brouwer et al. 1989). Below are the five irrigation schemes that will be considered in the analysis. They consist of two drip systems with two sizes of reservoirs, as well as a furrow system with the largest reservoir. The lifespan of a typical irrigation system is near indefinite, water tanks and hoses can last for upwards of 50 years (Fischer et al. 2007).

Two reservoirs

— 1. 6600 Gal (25,000 l) water tank. = US$2750

— 2. 2100 Gal (7,950 l) water tank = US$999

Irrigation treatments

1. Rain fed
2. Gated-Pipe-Furrow Irrigation System with Reservoir A:
   (a) Cost: US$2750 + US$150 (ABS to transfer water into furrows) ,
   (b) Irrigation efficiency: 50%
3. The Huntop Agricultural Drip Irrigation System with water tank B. The kit comes with one 200 l drum and covers 500m^2.
   (a) Cost: US$999 + US$2564 /ha ($128.2 USD per 500m^2 per kit)
   (b) Irrigation Efficiency: 95%
4. The Huntop Agricultural Drip Irrigation System with water tank A.
   (a) Cost: US$2750 + US$2564
   (b) Irrigation Efficiency: 95%
5. Netafim Family Drip System trickle irrigation system;
   (a) Cost: US$2000
   (b) Irrigation Efficiency: 75%

4.4 DSSAT Simulation

To interpret the symbiotic effect of intercropping maize and bean, DSSAT's sequence analysis was used with six bean scenarios; that is, the yield of each maize variety in the first season given that it is followed by a second season of one of the five beans varieties monocropped. The resulting yields represent the extremes of the second season being either all bean or none, therefore this captures the effect of nitrogen residue at both extremes. To capture the effect of intercropping along a spectrum of crop mixes between the two extremes a convex combination was applied between the yield matrices of all maize intercropped at a

$\alpha = 0.7$ ratio of bean followed by all bean for both seasons. Since DSSAT does not allow for intercropping effects, the effects were simulated with sub-surface bean residue applications every 15 days for a total of four applications. The residue applications equated to 10, 12, 14, and 16 kg N/ha for Rabina de Gato, ICTA-Oustra, Turbo III, Porrillo Sintético and San Cristóbal 83 respectively, with both Porrillo Sintético and San Cristóbal 83 at 16 kg N/ha. Choice was based on each variety's expected performance. For instance Rabina de Gato being closest to a traditional variety and Porrillo Sintético and San Cristóbal 83 being high performance novel strains. Depicted below, resulting maize yields are a convex combination of maize intercropped with bean ($\mathbf{Y_{S1M_m \cap S1M_b}}$), and maize monoculture ($\mathbf{Y_{S1M_m | S2M_m}}$) for each variety combination. [9]

It should be noted that the seeding ratio α is not double counted in the model, but rather used to represent two dimensions of scaling. As explained above, it is used in a convex combination to determine the intercropping effects on maize, however there is also a secondary scaling needed to determine the final proportion of the area devoted to each crop. Therefore the yield of maize per hectare after intercropping effects are calculated, so that final output is a function of what proportion of that hectare was devoted to either crop. Formally:

$$\mathbf{Y^m_{S2}} = \Big[(1-\alpha)\big[\alpha\mathbf{Y_{S1M_m \cap S1B_b}} + (1-\alpha)\mathbf{Y_{S1M_m|S1M}}\big]\Big]$$
$$\mathbf{Y^b_{S1}} = \Big[\alpha\mathbf{Y_{S1B_b}}\Big]$$
$$\mathbf{Y^m_{S2}} = \Big[(1-\alpha)\big[\alpha\mathbf{Y_{S2M_m \cap S2B_b}} + (1-\alpha)\mathbf{Y_{S2M_m|S1M}}\big]\Big]$$
$$\mathbf{Y^b_{S2}} = \Big[\alpha\mathbf{Y_{S2B_b}}\Big]$$

Combined for each season there are seven maize genotypes, five bean genotypes, six irrigation schemes, three fertilizer scenarios, with five possible intercropping combinations; for both seasons over the 30 years accounting for both as well as for both El Niño and La Niña years this comes to an optimization over a total of 378,000 data points.

9. Here, for lack of a better symbol, the set-theoretic term "∩" is used to represent intercropping as opposed to its typical notation of intersection. As well the term "|" is used to signify "given" or "such that" as in its set-theoretic understanding and not in the probabilistic interpretation.

4.5 Markets: Demand and Price Dynamics

4.5.1 Land and Holdings

Available land is limited in the whole region of Chiquimula with the area surrounding Chiquimula City as the most limited. There are very few areas for expansion with forested land being already sparse (IARNA 2006, p.18). Hernandez et al. (2010, p.26) reported that land ownership is relatively consistent across rural Guatemala with an average of four hectares (cropped land averaging 3.6 hectares) across all quartiles except for the poorest which have less than 2.2 hectares. The irrigation rate is extremely low with less than one percent of all farms utilizing some form of irrigation technique; this includes furrow and canal systems. In the national survey, Guatemala's Instituto Nacional de Estadística Guatemala (2014, p.18-22) found the average farm size to be 4.4 ha (6.4 Mz). This number is hardly representative as the concentration of landholdings is severe even by Latin American standards. The country maintains a land Gini coefficient of 0.84 which has steadily increased over the last three decades due to the amalgamation of smaller farms into the holdings of large plantations (Gauster et al. 2013, p.105).

The importance of land distribution to the livelihoods of rural Guatemalans cannot be over emphasized. The severity of land inequality and the politics surrounding it was the principal force driving the 36-year civil war. Large agri-business firms and local landed oligarchs have far more agency in government decision making than local smallholders leading to further imbalances of rights. Despite official efforts of land tenure reform, smallholders are still at risk of being pushed off their land to make way for cash crops with little to no compensation (Alonso-Fradejas 2012). Although beyond the scope of this study it is nonetheless important to recognize the frailty of land tenure and pressures that smallholders in Guatemala face. Over 45% of holdings are less than 0.7 ha and over 68% less than 1.4 ha, split between 85% family owned and 11.4% rented. Land is typically rented from large landholders for cash crop production (e.g., coffee, cardamom and rubber). The higher quartile of landholders were not included in this study because their farm structure and crop selection are substantially different from the smallholder farmers who tend to be subsistence farmers. The larger landholders do provide off-farm income opportunities for the smallholder farmers, which is included in the model as off-farm income. Out of the lower 68%; 66% hold $\leqslant$ 0.7 ha and 34% hold $\leqslant$ 1.4 ha, thus a weighted average shows that 68% of the farms are $\leqslant$ 0.90 ha. This study will be considering all inputs, costs and yields per hectare, and for convenience since the mean farm size of smallholders is approximately one hectare, results will be reported in single hectare terms.

4.5.2 Population

As mentioned in Section 2.2.3 the national population growth rate is constant at 2.5% annually (World Bank 2014a) with a marked divergence between urban and rural demographics. Projections show that due to migration, by 2050 the rural/urban ratio within Guatemala will be 31%/69%, an almost complete inverse of the 63%/36% of today.

To capture this trend, domestic demand characteristics are forecasted using a non-seasonal autoregressive Integrated Moving Average Model, or ARIMA, in Stata (Greene 2012; StataCorp 2013, p.983). An ARIMA model was chosen over a more parsimonious ARMA model for its ability to interpret non-stationary stochastic processes; i.e., the tendency of the series not to return to the mean. [10] This characteristic fits well with strictly increasing population projections, as well as the price projections for maize, bean, and oil which will be addressed in Section 4.5.3. The order of the ARIMA model was specified according to the degree to which the moving average captures the curvature of exponential population growth. Moreover, the model selection criteria of choosing an ARIMA(2,3,2) over a single or even simple second-order model was in minimizing the RMSE, or Root-Mean-Squared-Error. Specifically, ARIMA(1,1,1)

10. Formally, consider the time series $X_t = \rho X_{t-1} + \varepsilon_t$, if $|\rho| \in [0,1]$ this would signify a tendency for the model to return to the mean, or a weakly stationary stochastic process. While if $|\rho| = 1$ this specifies a non-stationary series, or one without a tendency to return to the meal(Greene 2012, p.982).

and ARIMA(2,2,2) had RMSE of 6,152 and 445 respectively, with ARIMA(2,3,2) minimized RMSE at 324 (Durbin-Watson = 2, AIC: 11.72). Population growth trends from 1960 until 2015 were collected from the FAO (2015a) and projected with the ARIMA(2,3,2) until 2050. The resulting projections are graphed in Appendix 6.3. Figure 4.4 details each data base used corresponding to each model used which resulted in the final values over which the linear programming model optimizes.

Autoregressive Integrated Moving Average Model ARIMA(p,d,q)

$AR(p) \equiv X_t = c + \sum_{i=1}^{p} \phi_i X_t + \varepsilon_t$ p- order of the auto-regression

$I(d) \equiv X_t = c + X_{t-1} + \varepsilon_t$ d- order of the differencing of variables

$MA(q) \equiv \mu + (1 + \theta_1 L + \cdots + \theta_q L^q) e_t$ q- order of the moving average on error term

Within the AR(p) model Parameters ϕ are indexed p. μ in the MA(q) model is the mean of the series. Collectively the three models create the ARIMA(p,d,q) model with L as the lag-operator. (Hyndman et al. 2014, p.214)

$$\equiv \underset{\text{AR}(p)}{\underset{\uparrow}{(1 - \phi_1 L - \cdots - \phi_p L^p)}} \quad \underset{\text{I}(d)\text{ differences}}{\underset{\uparrow}{(1-L)^d y_t}} \quad = \quad \underset{\text{MA}(q)}{\underset{\uparrow}{c + (1 + \theta_1 L + \cdots + \theta_q L^q) e_t}}$$

$$\equiv \left(1 - \sum_{i=1}^{p} \phi_i L^i\right) (1-L)^d Y_t = \left(1 + \sum_{i=1}^{q} \theta_i L^i\right) \varepsilon_t$$

4.5.3 Output-Input Markets and Prices

There are two primary market prices that need to be considered; namely the local and national/international, which *de facto* consists solely of prices in markets in Guatemala City. Rural markets tend to be insulated from the urban commercial sectors because of poor transportation infrastructure and the high cost of transportation. Insulated rural markets work against national interests in that it makes local production uncompetitive internationally, diminishing both aggregate consumer and producer surplus. As mentioned in chapter three, urban consumption is almost entirely fulfilled by imports; therefore they are insulated from the shocks of local droughts. In years of drought, the price in rural markets is many times higher than that in the city. Overall, both rural Guatemala and Guatemala City have had average maize prices of US$320 per ton over the last two decades. This does not entirely reveal price dynamics since the overall trend is of rural prices being slightly lower than urban until a drought hits and spikes rural prices (FAO 2015a).

Statistical tests show that there is a significant $\beta = 0.81,\ S.E. = 0.03\ (p > 0.000)$ difference between rural and urban prices within Guatemala. However, between January 2000 and January 2015, rural Guatemalan prices were only one percent higher than that of Guatemala City. However, this figure is influenced by high rural prices during times of crisis (e.g., periods of drought) pulling up the average to above the urban market price. For instance during November 2013 rural grain prices were 63% higher than urban centers. Doing the same analysis but removing outliers greater than one standard deviation (representing crisis values) rural prices are almost ten percent less than urban prices, i.e., US$295-US$320 rural-urban respectively. It should be expected that continuing infrastructure projects will further the integration of rural and urban markets. Therefore, this study will assume there to be near no rural-urban price difference and thus only one output market.

Moreover, there is no statistically significant relation between rural prices and harvest time or month of the year.[11] As well, there is no statistically significant difference between Guatemala City prices compared with San Salvador, Mexico City, Panama City, and San Jose. This suggests that Guatemala City is linked to the international maize market, and thus prices reflect international trends. In terms of bean production the same dynamic exists. The average rural price is about 10% less than the urban price, i.e., US$893 per ton compared to US$813 for rural areas if outliers are removed (FAO 2015a).

11. Results from a regression of Guatemala City and Rural Guatemala Prices on dummies for each month.

Farm-gate prices for both maize and beans were compiled from the FAO (2015a) archive data for the period of 1961 until 2014. These data were projected for both crops using an OLS indexed over thirty years. The national population was used as a proxy for demand, and production quantity in metric tons as a proxy for supply. As well, real urea prices, again from FAO (2015a), paid by farmers were determined with a separate OLS with global population and crude oil price per barrel from TheWorld Bank (2014b) as independent variables. Below are the price OLS regressions with the two ARIMA(2,3,2) projections for crude and population.

$$
\begin{aligned}
BeanPrice_t &= \alpha + \beta Production_t + \gamma Population_t + \delta UreaPrice_t + \varepsilon_t \\
MaizePrice_t &= \alpha + \beta Production_t + \gamma Population_t + \delta UreaPrice_t + \varepsilon_t \\
UreaPrice_t &= \alpha + \beta Crude_t + \gamma Population_t + \varepsilon_i
\end{aligned}
$$

Autoregressive Integrated Moving Average Model ARIMA$(2,3,2)$

$$
\begin{aligned}
Crude_t \equiv \left(1 - \sum_{i=1}^{2} \phi_i L^i\right)(1-L)^3 Crude_t = \left(1 + \sum_{i=1}^{2} \theta_i L^i\right) \varepsilon_t \\
Population_t \equiv \left(1 - \sum_{i=1}^{2} \phi_i L^i\right)(1-L)^3 Population_t = \left(1 + \sum_{i=1}^{2} \theta_i L^i\right) \varepsilon_t
\end{aligned}
$$

4.6 Model Specifics and Constraints

A few specifics of the linear programming model (detailed in Section 4.7) should be clarified. Firstly, it is arranged according to a typical profit function. The objective is specified as maximizing NPV profit $\prod_{\forall t \in T}$ which is a function of revenue, calculated as the output price of maize and bean by their respective yields for each season, minus costs in terms of quantity of granular urea and seed used in each season. The cost of the irrigation is at the end. Here, the cost vectors of seed prices, $\mathbf{p}^t_{MS}$ for maize and $\mathbf{p}^t_{BS}$ for bean, are based on data from Iowa State

University (2011) of the average seeding cost per hectare as in Section 4.3.3. As mentioned earlier the model is run separately for each of the six irrigation systems, also for each of these system the model is run over three different groups of constraints for the non-adaptation model, the fixed genotype model, and the perfect information model. Each of these constraints are detailed in Section 4.7. Lastly, the six separate irrigation system models over the three groups of constraints are run at prices representing the predicted values, as well as a worst and best case scenario.

4.6.1 Credit and Capital Market Constraints

One primary agricultural bank in the country, offers loans to farmers, namely Banrural S.A.. For this bank the average loan size is US$2,839 at an average annual interest rate of 16%. In total they have an agricultural portfolio of US$81.7 million over 28,810 loans (Trivelli et al. 2007). They do require a formal credit history for farmers to apply. There is also the NGO FUNDEA (Fundacion para el Desarrollo Empresarial y Agricola) which operates in 19 locations throughout rural Guatemala with substantial representation in the highlands. They offer loans and micro-credit to farmers with a minimum holding of 0.4 ha. Their average loan size is US$694 at an average annual interest rate of 28%. Their credit check consists of proof of previously paid bills, such as phone or electricity bills (FUNDEA 2015).

As such, credit is generally available in the region, and thus for the purposes of this study investment in a specific irrigation system can be made on credit, as well the expense can be amortized over a period. Considering the size of the irrigation investment, being between $2,030 and $4,565 for furrow and DripWorks 1 respectively, this entails that borrowing from a credit source such as Banrural S.A. is possible. For this study, the initial investment in each irrigation system will be at an interest rate of 16% amortized over five years.

4.7 Linear Programming Model

$$Max \prod_{\forall t \in T} = \sum_{t=2020}^{2050} \frac{1}{(1+r)^t} \Big[(\mathbf{p}^t_M((1-\alpha_{S1})\mathbf{Y}^t_{S1m} + (1-\alpha_{S2})\mathbf{Y}^t_{S2m}) + \mathbf{p}^t_B(\alpha_{S1}\mathbf{Y}^t_{S1b} + \alpha_{S2}\mathbf{Y}^t_{S2b})) - (\mathbf{p}^t_U(\mathbf{u}^t_{S1} + \mathbf{u}^t_{S2}) + \mathbf{p}^t_{MS}(2-\alpha_{S1}-\alpha_{S2}) + \mathbf{p}^t_{BS}(\alpha_{S1}+\alpha_{S2}) + \mathbf{p}^t_i) \Big]$$

$$\mathbf{Y}^m_{S1} = (1-\alpha_{S1})\left[\alpha_{S1}\mathbf{Y}_{\mathbf{S1M_m \cap S1B_b}} + (1-\alpha_{S1})\mathbf{Y}_{\mathbf{S1M_m|S1M}}\right]$$

$$\mathbf{Y}^b_{S1} = \alpha_{S1}\mathbf{Y}_{\mathbf{S1B_b}}$$

$$\mathbf{Y}^m_{S2} = (1-\alpha_{S2})\left[\alpha_{S2}\mathbf{Y}_{\mathbf{S2M_m \cap S2B_b}} + (1-\alpha_{S2})\mathbf{Y}_{\mathbf{S2M_m|S1M}}\right]$$

$$\mathbf{Y}^b_{S2} = \alpha_{S2}\mathbf{Y}_{\mathbf{S2B_b}}$$

Business As Usual Model

$$S.T.\ \ \forall\, t \in T: \ \ VC_{t+1} \leqslant \pi_t + of_t - c_t,\ \ m = \text{DEA}\ \forall t,\ \ b = \text{Rabina de Gato}\ \forall t,\ \ I = \text{Rainfed},$$
$$N = 0\ \&\ N = 100,\ \ \alpha_{S1} = 1, \alpha_{S2} \in [0.3, 0.7]$$

Fixed Genotype Model

$$S.T.\ \ \forall\, t \in T: \ \ VC_{t+1} \leqslant \pi_t + of_t - c_t - P^t_i,\ \ m_t = m_{\forall t \in T},\ \ b_t = b_{\forall t \in T},\ \ \alpha \in [0.3, 0.7]\ \&\ \alpha \in [0, 1]$$

Perfect Information Model

$$S.T.\ \ \forall\, t \in T: \ \ VC_{t+1} \leqslant \pi_t + of_t - c_t - P^t_i,\ \ \alpha \in [0.3, 0.7]\ \&\ \alpha \in [0, 1]$$

$\mathbf{Y}_{S1M_m \cap S1B_b}$ $\equiv$ S1 yield matrix of maize m intercropped with bean b

$\mathbf{Y}_{S2M_m \cap S2B_b}$ $\equiv$ S2 yield matrix of maize m intercropped with bean b

$\mathbf{Y}_{S1B_b}$ $\equiv$ S1 yield matrix of bean b

$\mathbf{Y}_{S2B_b}$ $\equiv$ S2 yield matrix of bean b

$\mathbf{p}^t_M$ $\equiv$ Maize price vector indexed over time t

$\mathbf{p}^t_B$ $\equiv$ Bean price vector indexed over time t

$\mathbf{p}^t_U$ $\equiv$ Urea price vector indexed over time t

$\mathbf{p}^t_S$ $\equiv$ Maize seed price vector indexed over time t

$\mathbf{p}^t_{BS}$ $\equiv$ Bean seed price vector indexed over time t

$\mathbf{u}^t_{S1}$ $\equiv$ Urea usage season one indexed time t

$\mathbf{u}^t_{S2}$ $\equiv$ Urea usage season two indexed time t

$\mathbf{p^t_i}$ $\equiv$ Annual payment on irrigation at time t

r $\equiv$ Discount rate of 6%.

VC_t $\equiv$ Variable cost of inputs at time t.

π_t $\equiv$ Profit from crop at time t.

of_t $\equiv$ Off-farm earnings at time t.

c_t $\equiv$ Consumption at $2 per day.

α^t_{S1} $\equiv$ Bean seeding rate for season one at time t

4.8 Capital constraints

Each model is constrained such that annual payments according to the amortization will only be made after minimum living expenses are covered. The rational behind this constraint is that for subsistence farmers, capital is a principal constraint limiting not only access to improved varieties but livelihood in general. Even though an investment might be profitable, i.e., returning a greater NPV, it might be infeasible given the reality that these farmers depend on their yearly production to cover basic living expenses and feed themselves. Unlike a situation with larger farms, such as plantations or industrialised farms, a year of minimal profits cannot be offset by either crop insurance or savings, rather a year of minimal earnings means a lack of basic necessities and impoverishment. The region is already struggling with food security and malnutrition, and has been dependent on aid during droughts between 2010-2015 (Marini et al. 2003; Lee et al. 2012).

According to World Bank (2014a) the mean daily consumption of the lower 40% of income earners in the country is US$2.0 as of 2011, down from US$2.4 in 2006. At $2.00 this translates to an annual minimum of US$730. The last recorded average household size was 4.2 in 2002. For a family of four this translates into $2,920 of annual consumption. This amount is hypothetical but also includes the value of household consumption of the crops that they produce and consume outside of the market. For most Guatemalan smallholders daily consumption of maize and beans comes from a proportion of what they produce rather than through market channels. According to Lmmink (1991) on average farmers consume 38.36kg of maize and 4.46kg of bean per capita per year. Since there are no transaction costs included in the model, the proportion of the crop set aside for personal consumption will be considered at its market value, thus the model includes the opportunity cost of not selling that proportion of the crop on the market.

Off-farm income is a substantial source of income for most rural Guatemalans. Coffee picking is the most prominent source, however plantation work in cocoa and cardamom also constitutes a substantial labour demand. For coffee picking the harvest season lasts from a month to six weeks followed by about another month of processing the beans, e.g., sorting and shucking. Typically a coffee picker will make between Q60($7.57) - Q75($9.46) a day during this time. For two months of off-farm work, at 6 days per week, this would translate to between US$363 and US$454 income per worker. If the employment is close to the farm most members of the family will pick, otherwise the men of the family will travel away from the home to pick (Schuit 2012). Since off-farm income is substantial it will be included within the model as a source of income. Specifically the model will be constrained subject to the variable cost of inputs at year t+1 being less than or equal to profit from production and off-farm labour combined minus yearly consumption at $2 per person per day, formally; $VC_{t+1} \leqslant \pi_t + of_t - c_t$. Also, for each irrigation system the model is constrained so that variable cost in the following season is less than or equal to profit plus off-farm income minus consumption and annual payments on the irrigation investment. Formally the above constraint becomes; $VC_{t+1} \leqslant \pi_t + of_t - c_t - P_i^t$ with P_i^t being the annual payment for the irrigation system i at time t.

Each irrigation system, as well as the rainfed system, are separate, albeit identical models. Each of these models was run in three forms over three price scenarios. The three price scenarios being the mean projected prices from the autoregressive models as well as a best and worst case scenarios which are the input prices scaled down and output prices scaled up by one standard deviation and vice versa, respectively. In effect, and assuming that the prices are normally distributed, the best and worst case scenarios depict a 68% ($\pm 1\sigma$) confidence interval around the mean results. Uncertainty for both climatic effects and prices is one of the main costs that climate change will have on farmers. Though crude, interpreting the results over a span of best and worst cases does help endogenize some of this uncertainty. The first of the three forms is the non-adaptation, or 'business-as-usual' model which is constrained to emulate current practices. The non-adaptation model is constrained to allow for only the rainfed and the traditional varieties DEA and Rabina de Gato. As well, the intercropping ratio is constrained to simulate current planting practices, that is, monoculture maize in the first season with between 30% to 70% bean in the second season. The model is run in two nitrogen scenarios, with nitrogen constrained to zero kilograms per hectare and unconstrained. The second model is the fixed genotype model which assumes that genotype selection is made at the time of planting. Thus, the model is constrained to allow for only one choice of genotype for all years. This emulates a case where farmers will choose one variety in the first cycle and recycle the seed in following seasons and years. Unlike the non-adaptation model, higher performing genotypes are available, although once chosen they are set for all years. This also mimics the case that farmers do not have the foresight of seasonal weather and output prices at the time of planting, thus they are constrained by available knowledge. Fertilizer application is unconstrained because fertilizer purchases are typically made during the early stages of planting, and the availability of novel genotypes in the unconstrained model also assumes that nitrogen is readily available at the market price. For each irrigation system, including the rainfed system, the model was run for both the intercropping ratio unconstrained, i.e., 0/1, as well as with the intercropping ratio constrained to 30% to 70% bean in each season. The latter case follows the assumption that farmers will always plant some portion of bean for their own consumption. Lastly, within the perfect information model genotype and fertiliser selection are unconstrained allowing for differences in yearly choice. This situation mimics the case in which farmers have perfect foresight into yearly weather patterns and output prices at the time of planting, as well as unrestricted market access, and thus have the ability to select optimal genotype and fertilizer combinations best suited to these conditions. As for the fixed genotype model the model is run with both intercropping scenarios, i.e., unconstrained allowing for monoculture maize or bean and constrained at 30%/70% bean. The only other constraints in the model are the capital constraints.

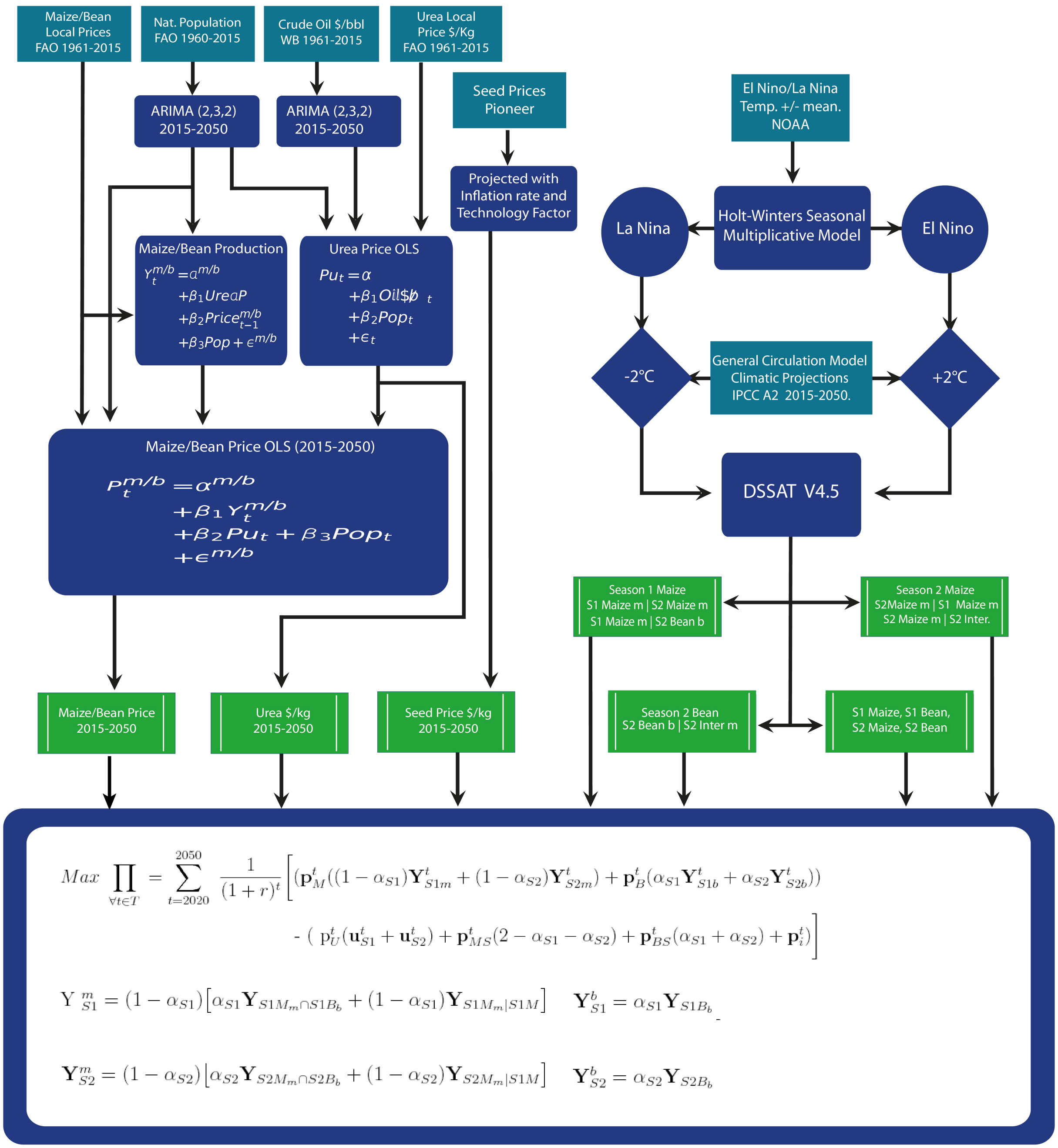

Figure 4.4: Methodological flowchart. Data Banks (Teal), Processes (Navy), and Results (Green)

Chapter 5: Results and Discussion

5.1 Results

5.1.1 Non-adaptation Model

The results of the non-adaptation model displayed in Table 5.1 indicate that some form of adaptation is needed in order to adjust to changing weather patterns. If no adaptation is taken, farmers will probably be living below the subsistence level at which they currently operate. This signifies that a continued reliance on precipitation and traditional varieties will not suffice given changing climatic conditions. The model was unable to find a feasible solution given the constraints under all scenarios except for the best case scenario (where output and input prices are scaled up and down respectively) with nitrogen application being unconstrained. When the model was run at mean prices with nitrogen application being constrained the consumption constraint of $VC_{t+1} \leqslant \pi_t + of_t - c_t$ was violated twelve times, most of which were in the later years. This implies that during these years the hypothetical family was unable to cover the following years' planting costs after the minimal amount of household consumption was covered. Note that this constraint is less binding than in other models since it does not include covering the annual payment on the irrigation infrastructure, and in effect is reduced to cover only consumption. With the minimum consumption constraint relaxed the model was able to optimise at a NPV [12] of \$20,924 for the thirty years combined at mean prices with \$27,549 and \$12,901 as the best and worst case scenarios. These results refer to the first, third, and fifth rows of Table 5.1. For a family of four this translates to \$0.47 daily with \$0.29-\$0.62 as the worst and best case scenarios which is substantially below the \$2 per day mark for consumption expenditures, as well as being below the international poverty line of US\$1.90 per day (Ferreira

12. This is with a constant 6% discount rate over the 30-year period. A 6% discount rate was chosen for the reasons of the higher risk and opportunity cost of investment in developing countries

et al. 2015). Even including expected off-farm income of $425.70 per person, assuming a rate of $9.46 per day for 45 days of labour yearly, the results come to $1.63 ($1.45-$1.78). Not only is this still below subsistence but it indicates that the majority of the family income is from off-farm labour. It should also be noted that these values are for a farm size of one hectare which is representative of 68% of the smallholders with less than 1.4 hectares. However for the 45% of landholders with less than 0.7 ha this translates to less than $0.33 daily ($0.20-$0.43 in the worst and best cases) (Instituto Nacional de Estadística Guatemala 2014, p.18-22). This can be compared to $0.66 daily ($0.40 -$0.86 in the worst and best cases) for smallholders with 1.4 ha. For both farm sizes, these amounts are substantially below the subsistence level of $2 per person per day.

Table 5.1: Non-adaptation Model

		Primera (First Season)				Postera (Second Season)				Totals		
	Bounds	Maize	Bean	Ratio	N[1]	Maize	Bean	Ratio	N	NPV	ANPV[2]	DNPV[3]
Rainfed	1 & 0.3/0.7	DEA[4]	-	0	0	DEA	Gato[4]	0.7	0	\$20,924[5]	\$169	\$0.46
Rainfed	1 & 0.3/0.7	DEA	-	0	100	DEA	Gato	0.7	0	\$26,452[5]	\$213	\$0.58
Rainfed (Best)	1 & 0.3/0.7	DEA	-	0	0	DEA	Gato	0.7	0	\$27,549[5]	\$222	\$0.61
Rainfed (Best)	1 & 0.3/0.7	DEA	-	0	100	DEA	Gato	0.7	100	\$36,514	\$295	\$0.81
Rainfed (Worst)	1 & 0.3/0.7	DEA	-	0	0	DEA	Gato	0.7	0	\$12,901[5]	\$104	\$0.28
Rainfed (Worst)	1 & 0.3/0.7	DEA	-	0	100	DEA	Gato	0.7	0	\$15,498[5]	\$125	\$0.34

1. N refers to the nitrogen application in kilograms per hectare.
2. ANPV refers to the annual net present value per capita, assuming an average family size of four persons
3. DNPV refers to the daily net present value per capita, assuming an average family size of four persons
4. DEA and Gato refer to the maize and bean genotypes ND108/DEA and Rabina de Gato respectively.
5. The model was infeasible given $VC_{t+1} \leqslant \pi_t - C_t$. The value represents this constraint loosened to $VC_{t+1} \leqslant \pi_t$.

The non-adaptation model is constrained to allow for only rainfed farming of the traditional varieties DEA and Rabina de Gato. As well, the intercropping ratio is constrained to simulate current planting practices, that is, monoculture maize in the first season with between 30% to 70% bean in the second season. The model is run in two nitrogen scenarios. For the first, third and fifth rows nitrogen application is constrained to zero kg N/ha, whereas the results in the second, forth and sixth rows nitrogen is unconstrained. The best and worst cases represent the optimisation results with output prices scaled up and input prices scaled down by one standard deviation and vice versa respectively.

With nitrogen application being unconstrained (referring to the second, fourth and sixth rows of Table 5.1) the results are not much better. The mean model returns a NPV of \$26,452 translating into \$0.60 (\$0.35 - \$0.83) daily. It is only in the best case price scenario with nitrogen unconstrained that the livelihood consumption constraint was satisfied, which equals just over \$2 per day. For the case of the lower 45% of smallholders with less than 0.7 hectares mean daily earnings would be less than \$0.42. The results specified by the model output are representative of the current situation, albeit with a gradual worsening with weather restrictions. DSSAT yield estimates, in the worst case scenario of depleted soil and no fertilizer amendments (inorganic or otherwise), are mostly below 1,000 kg/ha degrading down to less than 800 kg/ha in the later years; granted that this is not much lower than the recent 970 kg/ha as reported by (Ramirez et al. 2013, p.8). However, both the simulated and reported statistics are far lower than American cultivars that have reported a maximum biological potential upwards of 10,000 kg/ha (Steduto et al. 2012, p.119). It is this yield gap that needs to be addressed. As it is, smallholders earn very little, if anything, from their harvest and need to supplement their income from alternative sources. The model does not indicate any specific inflection point where sowing any amount is unprofitable, that is, the marginal revenue is always above the marginal cost curve. This is to be expected since yields are always positive and the model does not include any opportunity cost of holding land.

Our results clearly indicate that current farming practices will not be sufficient to keep smallholders above the poverty line. As was detailed in Chapter 1.1 the effects of climate change do not happen in a vacuum, rather the severity is dependent on the socio-economic situation of the region, which in this case is dire. The population suffers from low literacy rates with unequal access to health care and other services (UNDP 2014, p.162). As well, food security and childhood malnutrition in the region are among the worst in all of Latin America (Marini et al. 2003; World Food Program 2012). Income levels predicted in the results will be insufficient to improve the socio-economic situation of smallholders in the region, but they forecast worsening conditions in the future. Hunger and food insecurity in the region follow seasonal trends because families can only produce four to five months of grain and during non-harvest time wholesalers within the department of Chiquimula have the price incentive and power to export grain to other areas of the country or international markets (Oxfam 2013). The clustering of the capital constraint violations in the later years suggests that seasonal food insecurity and vulnerability trend will worsen in the future. In a scenario such as this, where farmers do not have access to means of intensifying production with improved varieties or irrigation, leaving agriculture seems like the most viable option.

5.1.2 Fixed Genotype Model

In contrasting the results of the non-adaptation model, the findings of the fixed genotype model in Table 5.2 indicate that biotechnology offers a substantial possibility for improvement. With the rainfed model unconstrained to allow for improved genotypes and any fertilizer combination, NPV jumps from \$20,924 to \$64,218 (\$86,329 - \$39,910), which equates to \$1.42 (\$1.91 - \$0.88) daily per person (DPP) for a family of four. The optimal result only differs slightly from current planting practices with the intercropping ratio of the first season being an all maize (XL71) corner solution with 100 kg of nitrogen per hectare followed by monoculture bean with no nitrogen application in the second season. Including off-farm income, this comes to \$2.59 daily per person, which is still near the subsistence level but nearly twice the earnings without access to improved biotechnology. The average yield of the best performing maize variety DEKALB XL71 comes to 3,088 kg/ha over all irrigation systems and fertilizer scenarios. This is is slightly more than estimates of current maize yields in the region, given current planting practices, of 970 kg/ha (Ramirez et al. 2013, p.8), and almost three times the average of the traditional variety, DEA, used in the model over all conditions at 1,319 kg/ha. Dekalb XL71 is a high performance variety that is specified as moderately drought tolerant and has a maximum biological potential of 8,000 Kg/ha in optimal conditions

(Ritchie et al. 1989; Espaillat et al. 1989). This result implies that without the longer term commitment of investment in an irrigation system, substantial benefits can be achieved with access to biotechnology. Within neighboring Mexico, average maize yields between 2012 to 2014 were comparable to the DEKALB XL71 results at 3226 kg/ha (FAO 2015a). Considering that restricted market access in the region has been cited as a source of limiting access and inflating the cost of inputs (Oxfam 2013), this suggests that, in terms of policy implications, the issue can be addressed by improving market extension, as opposed to subsidies for improved varieties. It should be remembered that Guatemala's 36-year civil war left in its legacy a debilitated transportation infrastructure, which is a prime barrier to market access (Oxfam 2013). Therefore, smallholders could substantially benefit from positive externalises of public investment in infrastructure.

Table 5.2: Fixed Genotype Model

		Primera (First Season)				Postera (Second Season)				Totals		
	Bounds	**Maize**	**Bean**	**Ratio**	**N**	**Maize**	**Bean**	**Ratio**	**N**	**NPV**	**ANPV**	**DNPV**
Rainfed	0/1	XL71	-	0	100	-	Turbo	1	0	$64,218	$518	$1.42
	0.3/0.7	XL71	Crist	0.3	100	XL71	Sint	0.7	100	$57,584	$465	$1.27
Rainfed (Best)	0/1	XL71	-	0	100	-	Turbo	1	0	$86,329	$696	$1.91
	0.3/0.7	XL71	Crist	0.3	100	XL71	Sint	0.7	100	$78,067	$630	$1.73
Rainfed (Worst)	0/1	XL71	-	0	100	-	Turbo	1	0	$39,910	$322	$0.88
	0.3/0.7	XL71	Crist	0.3	100	XL71	Turbo	0.7	0	$35,453	$286	$0.78
DripWorks 1	0/1	-	ICTA	1	100	33B	Sint	0.7	100	$79,449	$641	$1.76
	0.3/0.7	XL71	ICTA	0.7	100	33B	Sint	0.7	100	$74,969	$604	$1.65
DripWorks 1 (Best)	0/1	-	Crist	1	100	-	Sint	1	200	$107,501	$866	$2.37
	0.3/0.7	XL71	Crist	0.7	100	33B	Sint	0.7	100	$101,712	$820	$2.25
DripWorks 1 (Worst)	0/1	-	Crist	1	100		Sint	1	100	$46,506	$375	$1.03
	0.3/0.7	XL71	Crist	0.7	100	33B	Sint	0.7	100	$43,331	$349	$0.96
Huntop 1	0/1	XL71	-	0	100	-	Sint	1	100	$84,635	$682	$1.87
	0.3/0.7	XL71	ICTA	0.7	100	33B	Sint	0.7	100	$78,462	$632	$1.73
Huntop 1 (Best)	0/1	XL71	-	0	100		Sint	1	200	$115,956	$936	$2.56
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	200	$107,402	$866	$2.37
Huntop 1 (Worst)	0/1	XL71		0	100	-	Sint	1	100	$50,117	$404	$1.11
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$46,189	$372	$1.02
Furrow	0/1	XL71	-	0	100	-	Sint	1	100	$86,738	$699	$1.92
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$80,230	$647	$1.77
Furrow (Best)	0/1	XL71	-	0	100	33B	Sint	1	200	$118,001	$952	$2.61
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$108,523	$876	$2.40
Furrow (Worst)	0/1	XL71		0	100		Sint	1	100	$52,331	$422	$1.16
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$48,186	$388	$1.06
DripWorks 2	0/1	XL71	-	0	100	-	SInt	1	100	$70,630	$569	$1.56
	0.3/0.7	XL71	Sint	0.3	100	33B	Crist	0.7	100	$65,590	$529	$1.45
DripWorks 2 (Best)	0/1	XL71	-	0	100	33B	Sint	1	100	$96,987	$783	$2.15
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$90,597	$731	$2.00
DripWorks 2 (Worst)	0/1	XL71		0	100		Sint	1	0	$41,867	$337	$0.92
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$37,106	$300	$0.82
Huntop 2	0/1	XL71	-	0	100	-	Sint	1	100	$69,054	$557	$1.53
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$64,801	$522	$1.43
Huntop 2 (Best)	0/1	XL71	-	0	100		Sint	1	100	$94,525	$762	$2.09
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$88,920	$717	$1.96
Huntop 2 (Worst)	0/1	XL71					Sint	1	0	$41,526	$335	$0.92
	0.3/0.7	XL71	Crist	0.3	100	33B	Sint	0.7	100	$38,062	$307	$0.84

1. DripWorks 1 and Huntop 1 refer to each system with the first reservoir 6600 Gal (25,000l). With DripWorks 2 and Huntop 2 referring to 2100 Gal (7,950l).

The fixed genotype model assumes that genotype selection is made at the time of planting. Thus, the model is constrained to allow for only one choice of genotype for all years. This emulates a case where farmers will choose one variety in the first cycle and recycle the seed in following seasons and years. Fertilizer application is unconstrained in the model so that there is a seasonal element of input choice based on fertilizer price and expected output. For each irrigation system, including rainfed, the model is run with the intercropping ratio unconstrained, i.e. 0/1, as well as with the intercropping ratio constrained to 30% to 70% bean in each season. The latter case follows the assumption that farmers will always plant some portion of bean for their own consumption. The best and worst cases represent the optimisation results with output prices scaled up and input prices scaled down by one standard deviation and vice versa respectively.

All irrigation systems within the fixed genotype model had NPVs greater than simple rainfed agriculture. At mean prices with intercropping being unconstrained this spanned from \$86,738 to \$69,054, or \$1.92 to \$1.53 DPP, for furrow to the Huntop system with the smaller reservoir. In the best and worst cases, price values for each system range from \$118,000 - \$52,331 (\$2.61-\$1.16 DPP) for furrow and \$94,525 - \$41,526 (\$2.09-\$0.92 DPP) for Huntop (Table 5.2). Notice that the worst case scenario for the furrow irrigation system is less than the mean price scenario of the rainfed model with improved biotechnology, i.e. \$1.16 versus \$1.42 DPP respectively. Although all irrigation systems do have a greater NPV than rainfed, even given a conservative capital market of 16% on the loan, the investment might not be worth the risk given the uncertainty of future prices and conditions. That is, the relatively marginal increase in profitability and overlap of NPV through different price scenarios of the lesser performing irrigation systems suggests that investment in irrigation infrastructure might not be an outright best choice. This entails that investment profitability is dependent on future prices, and that the uncertainty might make the investment unprofitable.

The added profitability of investing in the most profitable irrigation system is substantial, i.e., the furrow system at \$86,738, is 25% greater than the rainfed solution of \$64,218 with intercropping unconstrained. This added \$22,520 of value for a one hectare farm or an added \$0.51 NPV DPP. However, comparing this to the relative gains in profit from simply taking advantage of higher performing genotypes it is clear that, though gains in irrigation are substantial they are less than that of investing in biotechnology. That is, the rainfed model constrained to traditional varieties output a NPV of \$26,452, while the rainfed model with genotype selection unconstrained jumped by 58% to \$64,218. This means that access to biotechnology coupled with irrigation investments could potentially increase returns upwards of 70% at mean prices.

5.1.3 Perfect Information Model

Lastly, the perfect information model displayed in Table 5.3 simulates a case where farmers have perfect insight into both seasonal climatic conditions and expected output prices at the time of planting, and can thus adjust planting practices accordingly. A comparison between the results of the fixed genotype model in Table 5.2 reveals the value of information into future conditions. At mean prices with intercropping unconstrained NPV of each irrigation system ranges from $89,368 ($2.04 DPP) for furrow to $71,566 ($1.63 DPP) for Huntop with rainfed at $66,691 ($1.52 DPP). Compared to the fixed genotype model, the same systems give $86,738 ($1.98 DPP) for furrow to $69,054 ($1.58 DPP) for Huntop with rainfed at $64,218 ($1.47 DPP). This is 2.9%, 3.5% and 3.7% increase in profits respectively. Unsurprisingly, the genotype and fertilizer combinations used for the majority of years in the perfect information model were the same as those selected in the fixed genotype model. However, none of the crop combinations represented a clear majority with each combination being used for between 45% to 58% of the seasons. This result, combined with the relatively minimal increases in profit of around 3% suggests that although there are clearly specific varieties and fertilizer combinations that outperform the rest, switching planting practices seasonally has minimal impact on profits.

Table 5.3: Perfect Information Model

		Primera (First Season)					Postera (Second Season)					Totals		
	Bounds	**Percent**[1]	**Maize**	**Bean**	**Ratio**	**N**	**Percent**	**Maize**	**Bean**	**Ratio**	**N**	**NPV**	**ANPV**	**DNPV**
Rainfed	0/1	45%	XL71	-	0	100	58%	-	Turbo	1	0	$66,691	$538	$1.47
	0.3/0.7	58%	XL71	Crist	0.3	100	23%	XL71	Turbo	0.7	0	$58,736	$473	$1.30
Rainfed (Best)	0/1	68%	XL71	-	0	100	65%	-	Turbo	1	0	$87,838	$708	$1.94
	0.3/0.7	71%	XL71	Crist	0.3	100	26%	XL71	Turbo	0.7	100	$78,861	$636	$1.74
Rainfed (Worst)	0/1	61%	XL71	-	0	100	65%	33B	-	1	0	$40,766	$329	$0.90
	0.3/0.7	59%	XL71	Crist	0.3	100	46%	XL71	Turbo	0.7	0	$35,914	$289	$0.79
DripWorks 1	0/1	45%	-	Crist	1	200	29%	-	Sint	1	100	$85,001	$685	$1.88
	0.3/0.7	39%	XL71	Crist	0.3	100	39%	33B	Sint	0.7	100	$77,145	$622	$1.70
DripWorks 1 (Best)	0/1	45%	33B	Crist	1	200	29%	-	Sint	1	100	$113,853	$918	$2.52
	0.3/0.7	35%	XL71	Crist	0.3	100	35%	33B	Sint	0.7	100	$104,834	$846	$2.32
DripWorks 1 (Worst)	0/1	35%	-	Crist	1	100	42%	-	Sint	1	100	$48,426	$391	$1.07
	0.3/0.7	35%	33B	Crist	0.7	100	42%	33B	Crist	0.7	100	$44,406	$358	$0.98
Huntop 1	0/1	71%	XL71	-	0	100	42%	-	Sint	1	100	$86,850	$700	$1.92
	0.3/0.7	52%	XL71	Crist	0.3	100	35%	33B	Sint	0.7	100	$79,560	$642	$1.76
Huntop 1 (Best)	0/1	84%	XL71	-	0	100	26%	XL71	-	0	100	$117,599	$949	$2.60
	0.3/0.7	87%	XL71	Crist	0.3	100	35%	33B	Sint	0.7	100	$108,558	$876	$2.40
Huntop 1 (Worst)	0/1	84%	XL71	-	0	100	52%	-	Sint	1	100	$50,644	$408	$1.12
	0.3/0.7	81%	XL71	Crist	0.3	100	39%	33B	Sint	0.7	100	$46,599	$376	$1.03
Furrow	0/1	52%	XL71	-	0	100	45%	-	Sint	1	100	$89,368	$721	$1.98
	0.3/0.7	29%	XL71	Sint	0.7	100	71%	XL71	Sint	0.7	0	$81,577	$658	$1.80
Furrow (Best)	0/1	65%	XL71		0	100	45%	-	Sint	1	200	$119,395	$963	$2.64
	0.3/0.7	65%	XL71	Crist	0.3	100	42%	33B	Sint	0.7	100	$109,821	$885	$2.42
Furrow (Worst)	0/1	61%	XL71	-	0	100	45%	-	Sint	1	100	$53,333	$430	$1.18
	0.3/0.7	61%	XL71	Crist	0.3	100	42%	33B	Sint	0.7	100	$48,933	$395	$1.08
DripWorks 2	0/1	58%	XL71	-	0	100	26%	-	SInt	1	100	$73,316	$592	$1.62
	0.3/0.7	65%	XL71	Crist	0.3	100	26%	33B	Crist	0.7	100	$66,991	$540	$1.48
DripWorks 2 (Best)	0/1	81%	XL71	-	0	100	23%	XL71	-	0	100	$99,464	$802	$2.20
	0.3/0.7	81%	XL71	Crist	0.3	100	23%	33B	Crist	0.7	100	$91,863	$740	$2.03
DripWorks 2 (Worst)	0/1	77%	XL71	-	0	100	32%	-	Sint	1	0	$42,533	$343	$0.94
	0.3/0.7	74%	XL71	Crist	0.3	100	19%	33B	Crist	0.7	100	$38,782	$313	$0.86
Huntop 2	0/1	58%	XL71	Crist	0.3	100	26%	-	Turbo	1	100	$71,566	$577	$1.58
	0.3/0.7	65%	33B	Turbo	0.7	100	26%	33B	Crist	0.7	100	$65,748	$530	$1.45
Huntop 2 (Best)	0/1	81%	XL71	-	0	100	23%	XL71	-	0	100	$96,821	$781	$2.14
	0.3/0.7	81%	XL71	Crist	0.3	100	23%	33B	Crist	0.7	100	$88,861	$716	$1.96
Huntop 2 (Worst)	0/1	77%	XL71	-	0	100	32%	-	Sint	1	0	$42,083	$340	$0.93
	0.3/0.7	74%	XL71	Crist	0.3	100	19%	33B	Crist	0.7	100	$38,460	$310	$0.85

1. Percent refers to the percentage of optimal solutions which the listed genotype and fertilizer combinations occupy.

The perfect information model assumes that farmers have perfect foresight into seasonal weather patterns and prices as well as have knowledge of which genotype and fertilizer combination is best suited for such conditions. The model thus allows for seasonal variation of genotype and fertilizer choice. The listed solutions, in terms of genotype and fertilizer combinations represent the combinations that are most often chosen over the sixty seasons in the model, with the percent representing their respective frequency of choice. For each irrigation system, including rainfed, the model is run with the intercropping ratio unconstrained, i.e. 0/1, as well as with the intercropping ratio constrained to 30% to 70% bean in each season. The latter case follows the assumption that farmers will always plant some portion of bean for their own consumption. The best and worst cases represent the optimisation results with output prices scaled up and input prices scaled down by one standard deviation and vice versa respectively.

The significance of the furrow irrigation system having a higher NPV than more efficient systems, such as the Dripworks or Huntop suggests that, although the other systems did output higher yields, their added efficiency did not make up for the added cost of the system. For almost all cases, the second best solutions differed not by intercropping ratio but by genotype and fertilizer selection. For maize, second best solutions were occupied either by the same genotype, i.e., XL71, with a different fertilizer application in certain years, or by DEKALB 333B. However, it was not the case that DEKALB 333B was more profitable with different levels of nitrogen application than compared to XL71. Rather in years where 100 kg N/ha was optimal, this rate of fertilizer application was optimal for both the first and second best solutions. This suggests that the optimal level of nitrogen application might be independent of genotype selection, but could rather be dependent on the projected price of urea during a given year.

The results of both the fixed genotype and perfect information models imply that the price of nitrogen is a constraining factor on production. That is, it is only in the best case scenario, where urea prices are scaled down by one standard deviation that 200 kg/ha is profitable. The results do show that more nitrogen, at least up to 200 kg/ha, does produce more yield but when scaled by prices there is a diminishing return on investment after 100 kg/ha. As well, with the intercropping ratio unconstrained the model overwhelmingly optimises at monoculture maize in the first season and bean in the second. After intercropping is constrained to a 30%/70% seeding ratio, the model again optimises towards monoculture but stopped at the corner solution imposed by the constraint. This, combined with optimal solutions paired with some amount of nitrogen application suggests that the symbiotic effect of intercropping [13] on maize yields is less than that of a rotational monoculture with synthetic nitrogen amendments.

In almost all cases, for both the fixed genotype and perfect information model, running the model with the intercropping ratio constrained to 30%/70% is binding. That is, with

13. It should be noted that this result is limited to the ability of applying a convex combination to DSSAT results to mimic the relationship. Research on the effect of maize and bean intercropping and rotational systems is substantial and beyond the scope of this study.

intercropping unconstrained to allow for monoculture, the model tended to optimise towards the extremes. As well, with the model constrained, results tended to optimize at the limit imposed by the constraint rather than an alternative mixture. That is, if the unconstrained model optimised with a monocropped maize solution in the first season, the constrained optimal solution was at 70% maize rather than another intercropping ratio. It should also be noted that the model never chose a 50%/50% intercropping ratio. Results of this type tend to be expected in linear programming models that choose optimal crop selections, since the model will find the most profitable crop from that season and plant the entire field with it. However, our model interprets a trade off between intercropping with bean with their respective nitrogen fixation rates and the use of synthetic nitrogen. This result implies that the symbiotic effect of nitrogen fixation from bean, though positive, is less profitable than monocropping with synthetic nitrogen. It should be noted that while the model does not include an opportunity cost of labour, monocropping might have a higher relative return on labour because planting, harvesting, and general management of one crop is simpler than managing intercropping.

CHAPTER 6: CONCLUSION

6.1 Conclusion

The objective of this study was to incorporate agronomic and economic models in such a way as to assess the economic impact of climate change and determine optimal adaptation strategies for maize- and bean-producing smallholders within Chiquimula, Guatemala. The findings indicate that climatic stress is a significant constraint, and therefore adaptation is necessary. As witnessed in the last decade, traditional farming practices and technology are outdated, as they have been incapable of coping with increasing frequency and severity of droughts. Given the results of this study, the situation is expected to worsen, our model indicated that without adaptation smallholders will be pushed further below the poverty line; nonetheless, this study has been able to pinpoint a few viable adaptation options.

The results suggest that outright water scarcity is not the critical issue. This was expected because it is not that absolute precipitation is decreasing, but that the rainy season is contracting, i.e., increasing intensity over a shorter duration. [14] The results show that the contracting rainy season does have a negative effect on yields, but will not lead to outright crop failure. Therefore, the benefits of investment in an irrigation system are not so much for reasons of guarding against crop failure but mitigating negative effects and increasing overall potential yield.

The minimal earnings from traditional crops compared to alternative sources of income denote that smallholders in the region are at a threshold where crucial decisions have to be made. Smallholder farming, even with supplementary income from alternative sources does not bring farmers much above the poverty line. Although it is clear that adaptation is necessary

14. This is according to the results of the GCMs, which have to be interpreted in the way that the predictions are achieved with a Markov Chain. Therefore, as described in the limitations section, there is a tendency for values to cluster around the mean as opposed to diverge as would be the case in stochastic predictions.

in order to remain in agriculture there are few options. The results of this study point not to irrigation infrastructure, but novel biotechnology as the optimal path. Either shifting to cash crops or scaling up production in both an extensive and intensive way will be necessary to boost income above the international poverty level and guard against the financial impact of crop failure. Average yields within the region have been reported at 970 kg per hectare (Ramirez et al. 2013, p.8) which is substantially below international standards. In the United States yields under ideal conditions have been reported to be as high as 17 tonne/ha for late-maturing cultivars and between 10,000 to 12,000 kg per hectare for similar varieties in Mexico (Steduto et al. 2012, p.119). Though these yields do represent the maximum biological potential, it still does indicate that there is plenty of room for improvement.

The maximum daily profit at mean prices of $2.94 reported in the perfect information model does seem substantial compared to the non-adaption scenario at $0.48, however the opportunity cost of remaining in agriculture still has to be considered. Weighing this against the national minimum wage of just below US$9/day (OECD 2014, p.124) with an unemployment rate of 2.8% (World Bank 2014a) (suggesting some availability of employment and ease of transfer into the labor market) reveals different options. Abandoning agriculture for off-farm employment does provide a degree of wage stability without the risk of extreme weather events. Income is not the sole driving force behind a family's life decisions. Although rural standards of living might not be higher in terms of actual affluence, the lifestyle offers much above the urban minimum-wage worker's lifestyle. Size of living space, flexibility of work hours, clean air, and sense of accomplishment of working for yourself all have value. This is not to mention the non-quantifiable value of living outside of a congested city center. With these values considered, even for some of the smallest land holding families of below 0.7 ha, staying on the farm may be worthwhile. However, if this is the case, income support would be necessary.

This study is in agreement with so many others in suggesting that the only certainty of remaining in agriculture is the uncertainty of future events. The risk of extreme weather events, variable weather patterns and contraction of the rainy season are significant and they have to be incorporated into decision making. Unfortunately abandonment of farming does seem to be a practical option; and given the demographic trends of the last decade, it is a choice that many have already made, or have been forced to make given the harsh political realities. Land devoted to plantation and cash crop agriculture (e.g., palm oil, coffee, cardamom, sugar and rubber) has increased in the last decade (Hernandez et al. 2010; Instituto Nacional de Estadística Guatemala 2014), and with the stresses on smallholders this trend will likely continue. If anything, the opportunity cost of staying in farming, given the choices of shifting production or migrating, is the largest constraint. Needless to say the situation is dire.

There are two forces at play, beyond that of optimizing a mere profit margin. At the mundane level there is the perennial cycle of small scale farmers, unable to compete with the prices of those with greater economies of scale, being pushed to sell and being consolidated into the larger farms; which in turn adds momentum to the cycle by further fostering greater economies of scale. This snowball effect is a fate that agriculturalists have been predestined to endure since the agricultural revolution. Cochrane (1958) famously termed this trend of increasing farm sizes and technology to perpetually compete with output-market prices driven down by others doing the same as the "technology treadmill". It seems that agriculturalists are destined to keep pace with it at the expense of their livelihoods.

At a more profound level this dilemma is founded in the enduring narrative of the old world confronting the ideological imperatives of modernity. The changing nature of markets from a local to a globalised level have reconstructed the economic realities that we live in. Production incentives shift from catering to the local and family level to international demand and price dynamics. This is evident in the shift in incentives away from allocating land to maize and bean towards non-traditional agricultural exports or even selling off land to be consolidated into plantations. The challenges create a clash between two economic paradigms: one with profit and wealth accumulation as its objective function and founded on commodification; the other dependent on the functions of informal institutions and embedded in social and cultural values in the economic system (Polanyi 1957). This transformation into the modern economic system was expressed in the sentiments of Marx et al. (1848, p.3) as; "All fixed, fast frozen relations, with their train of ancient and venerable prejudices and opinions, are swept away, ...All that is solid melts into air, all that is holy is profaned." Though Marx's tone is surely one of lament, this is not to make a claim that this transformation is for better or for worse, it is the reality of our modern globalised economy, and one that our livelihoods function within; the growing pains and frictions of the transition that must be approached in an informed and intelligent way.

6.2 Limitations

The characteristics of the GCM weather models used, as derived from a third order Markov Chain, imply that daily precipitation predictions tend to smooth around a mean over time as opposed to diverge. As well, the autoregressive models used for predicting input and output prices do the same. This result does not indicate the risk associated with yearly weather variance, beyond the El Niño/La Niña weather scenarios incorporated in the model. As such, not only is the non-adaptation scenario dire, there is also a risk of crop failure to compound the issue. At such a low level of profits the marginal cost of a crop failure goes beyond simply forgone income for that season. As has been the case over the last few years, with the levels of income which have been reported, families are unable to save or afford other insurance measures, and thus are often forced to sell off assets and/or be dependent on external aid.

The model does not incorporate an inter-temporal choice variable and thus is not capable of inter-temporal optimization. The model is set up in such a way that it optimizes over multiple projections from a finite set of variable initial conditions. The model assumes that the irrigation system investment is in the first period with a fixed fertilizer and maize/bean genotype combination for the lifetime of the projection. It does not allow for later adaptation of a certain technology, or switching between technologies. For instance, the model cannot determine if it would be optimal for certain technologies to be adopted or abandoned at a later point in time. There is no function included that allows for a choice of when technology adaptation would take place. It is not a matter that incorporating an intercropping choice variable would be difficult, but rather given the lengthy amount of time it takes to run the model, adding a thirty year choice variable would push the model beyond the available processing capacity.

Additionally, the methods used to interpret effects of intercropping used in this study are likewise restrictive. The use of periodic sub-surface common-bean residue applications with associative amounts of nitrogen is a hypothetical substitute. It does not reflect all degrees of symbiosis between the maize and bean genotypes that would naturally take place. Instead the absolute value of nitrogen fixation is considered to be the only benefit of intercropping. Moreover, the use of a convex combination to represent the seeding ratio assumes a linear relation in intercropping effects. Thus, the seeding ratio optimization results do not fully reflect the true optimal point and are off to the degree that the parameter is mis-specified. As yet, DSSAT is not capable of estimating intercropping effects, and it is outside the field of expertise of this author to suggest how such an effect would be parameterised.

Lastly, the model is subject to the limited accuracy of both climatic and price predictions. As for the latter, the last century has demonstrated that the only consistency of markets is in their exceptional inconsistency. The volatility of oil, urea and maize prices makes within-year projections difficult never mind thirty years forward. The nature of the models used in this study are such that they tend to cluster results around the mean as opposed to incorporating the full range of the distribution. Granted, for projections, this result is far better than a divergence over time which would compound as more variables are added. In terms of climatic predictions, this smoothing effect is likewise constraining and present in the GMCs as well as the DSSAT simulations. For this study, interpreting the swings and extremes of weather is crucial, and the inability to do such inhibits the study's capacity to interpret the actual impacts of climate change. The effects of global warming are in the increasing intensity and variability of weather events. Thus, it would be ideal if the model could incorporate the full distribution of potential weather events, with a specific focus on the extremes. Without this result, it is important to understand this limitation in interpreting the results.

6.3 Further Research

For the purposes of this study maize and bean intercropping systems were considered because they reflect current production patterns. As well, since the two crops form not only the majority of production and current planting practices, but also the foundation of the local diet, they are the primary crops in need of analysis. There are other adaptation options available that go beyond maize and bean systems worthy of being analyzed. Over the past two decades there has been a steady shift away from traditional agriculture towards novel horticultural crops, which has offered an alternative source of income to farmers in the region. There is a need for an analysis of the impact of climate change on potential crops beyond maize and bean which can offer farmers in the region greater choice of adaptation strategies than irrigation and novel genotype selection. As long as profit maximization is the objective function, analyzing investment in irrigation infrastructure for maize and bean cropping systems is most probably not optimal. In a way this study is optimizing adaptation strategies subject to the constraint of maintaining a traditional production mix.

The results of this study indicate that, although investments in irrigation were positive for all systems, the highest NPV returned was from the furrow system. This suggests that the relative payoff from increases in water use efficiency in the more expensive systems does not cover the extra cost of the system. However this result is limited to the maize and bean systems used in this study. It might very well be the case that more efficient irrigation systems such as the Dripworks system might return a higher NPV for alternative crops, such as horticultural crops or non-traditional agricultural export crops (NTAE). Therefore there is a potential for gains by expanding the analysis to include alternative crops.

A few non-traditional agricultural export crops (NTAE) have been increasing in importance for smallholders in the region over the past decade. The Guatemalan highlands have become a key producer of cardamom and is now one of the world's largest exporters (Thomas et al. 2006). In the case of cardamom on the international market a kilogram of Guatemalan cardamom sells for between US$12-$14 (CentralAmericaData.com 2015), whereas maize can fetch a price of US$0.50/kg. Snow peas have also increased in importance in the region with farmers reporting $0.74 to $0.84 per kg of snow peas depending on their percentage of export quality (Julian et al. 2001). Although there has been a clear, but slow move towards NTAE there are still barriers to shifting production such as increased costs of production (labour, pesticides, and seeds) and access to export markets (Goldín et al. 2001). There is potential in NTAE to improve the lives of farmers, albeit the potential also comes with greater risk than traditional crops which have established markets and production practices. Lastly, as was the purpose of this study on maize and bean, the impacts of changing weather patterns on these NTAE crops would have to be accessed. Unfortunately, since NTAE crops tend to not benefit from the same plethora of research that the international commodity crops such as maize, wheat, soya, and rice do, there is less information on potential impacts, and thus uncertainty.

Moreover, the price of water is not included within this study because each irrigation system is at the farm level and is fed with a reservoir filled through rain catchment. This is due to two reasons; firstly as described in Section 2.2, GCMs forecast that the region might not necessarily suffer from absolute water scarcity, but rather from a contraction of the rainy season followed by longer dry periods. Secondly, it is difficult to assume a typical farm would not have access to a stream or well as a source of irrigation water. There is potential in expanding the study to analyse a case where irrigation is not limited to reservoir capacity but fed via pumping from a stream or well. However since streams and groundwater are both depletable resources which the community as a whole has access to to, pricing and distribution mechanisms would also have to be analyzed.

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Figures, Graphs, and Tables

Production, Trade and Demographic Trends

Table 8.5: Production and Demographic Trends 1975-2011 (FAO 2015a)

	Percent Change	1975-78 Mean	2009-11 Mean
Total Consumption	247%	921,232	2,274,330
Total Population	237%	6,194	14,707
Total Production	186%	933,542	1,672,241
Rural Population	188%	3,920	7,387
Urban Population	322%	2,274	7,320

Annual Maize Production, Import and Export

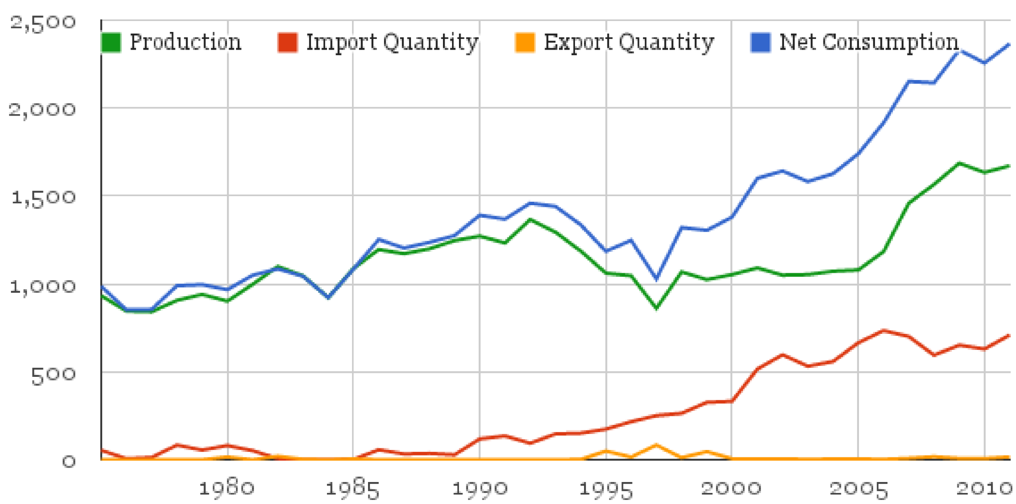

Figure 8.5: Annual Maize Production, Import and Export (1,000 Ton)(FAO 2015a)

Observed and Forecasted Population

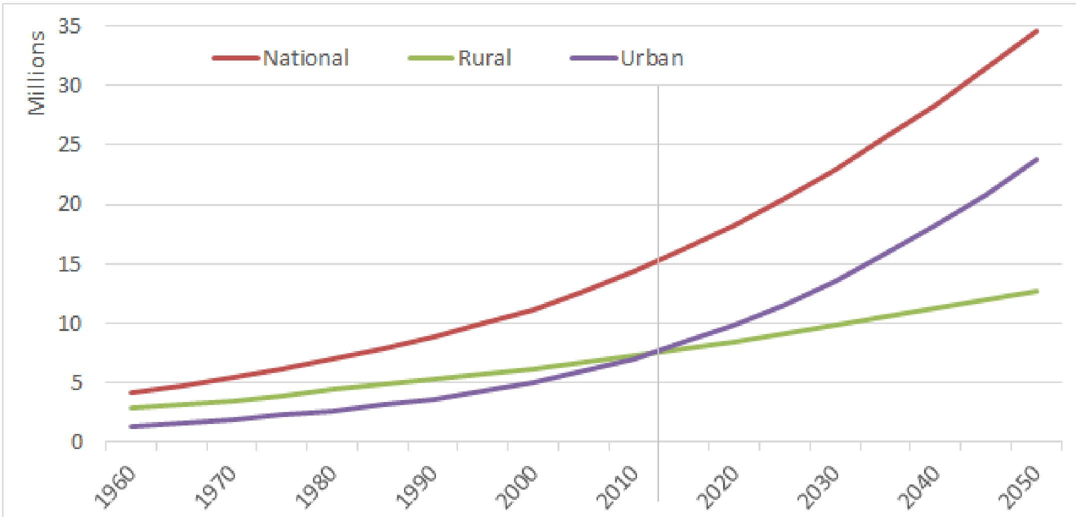

Figure 8.6: National, Urban and Rural population in millions. Observed data between the years 1960-2015 from FAO (2015a). Points beyond 2015 forecasted in Stata using an ARIMA(2,3,2) model.

Observed and Forecasted Price Data

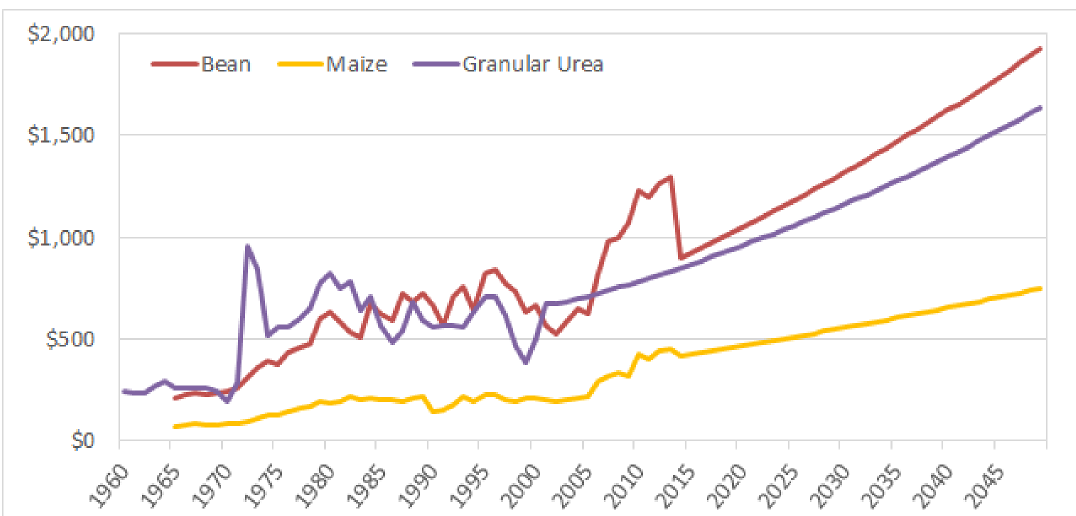

Figure 8.7: Observed farm gate price data in USD/Ton for black bean (1961-2004), White maize (1961-2014), and Urea (1961-2014) from FAO (2015a). Points beyond these years were forecasted with an OLS as specified in Section 4.5.3

Observed and Forecasted Maize and Bean Yields

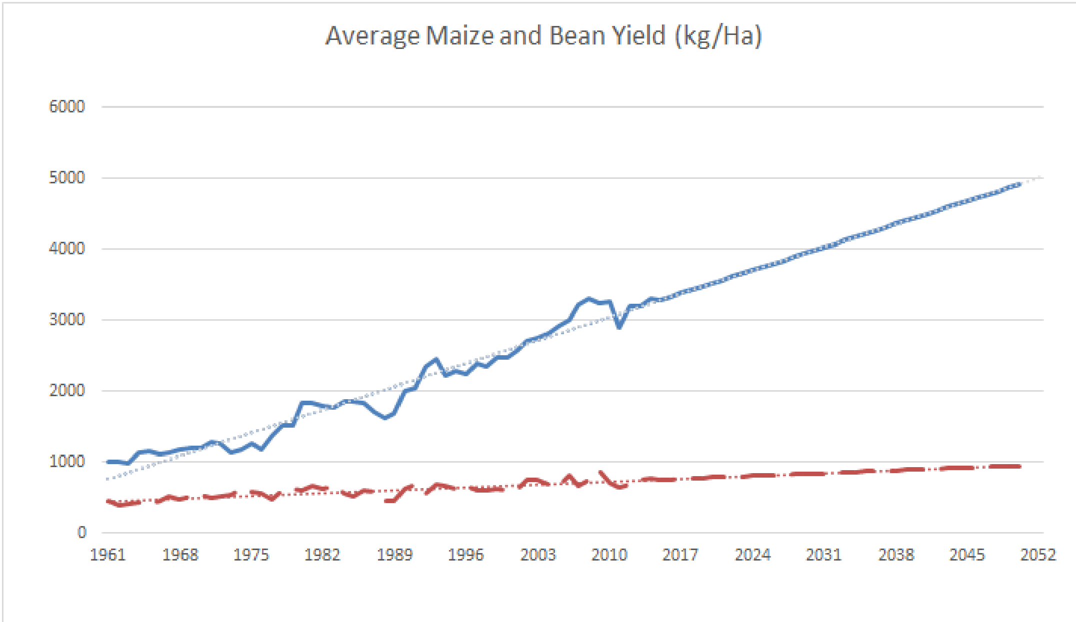

Figure 8.8: The upper solid line represents maize with the lower dashed line bean. Observed data represents average maize and bean yields for Mexico between the years 1960-2015 from FAO (2015a). Points beyond 2015 forecasted in Stata with a linear time series. The biotechnology coefficients are their respective slope coefficients

Average Temperature and Relative Humidity

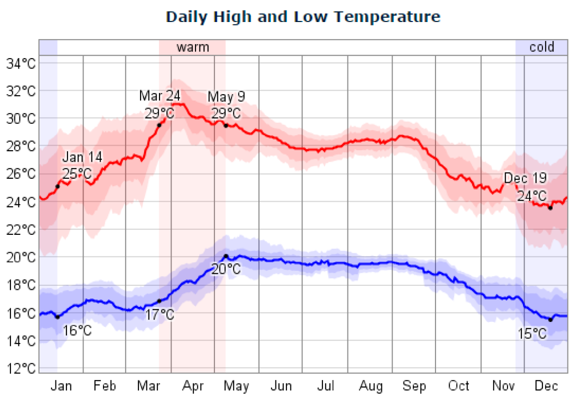

Figure 8.9: Daily average low (blue) and high (red) temperature with 25th to 75th percentile bands (Cedar Lake Inc. 2014)

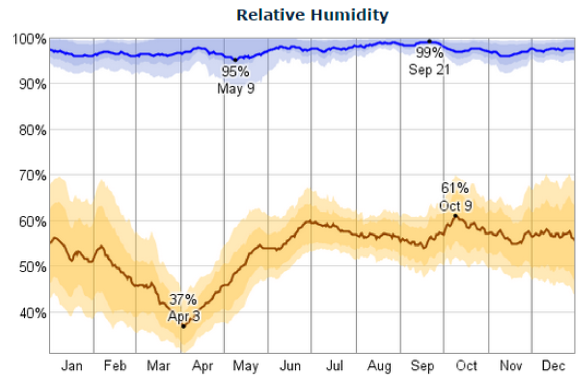

Figure 8.10: The average high (blue) and low (brown) relative humidity with 25th to 75th percentile bands (Cedar Lake Inc. 2014)

Seasonal Vapor Pressure Deficit for Chiquimula

Vapor Pressure Deficit

	Mar-May %RH		Jun-Jan %RH	
Temp.	**37%**	**95%**	**61%**	**99%**
20°C	0.117	1.473	0.023	0.912
25°C	0.158	1.995	0.032	1.235
30°C	0.212	2.673	0.042	1.654
35°C	0.281	3.541	0.056	2.192
40°C	0.369	4.645	0.074	2.876
45°C	0.479	6.035	0.096	3.736

Table 8.6: Calculated VPD given the high and low (day/night) Temperatures and respective Retaliative Humidity (RH) for Chiquimula Guatemala (kPa) (Murray 1967) [15]

15. Formula from Murray (1967), calculations in Excel, table produced in LaTeX

Observed and Projected El Niño Oscillations

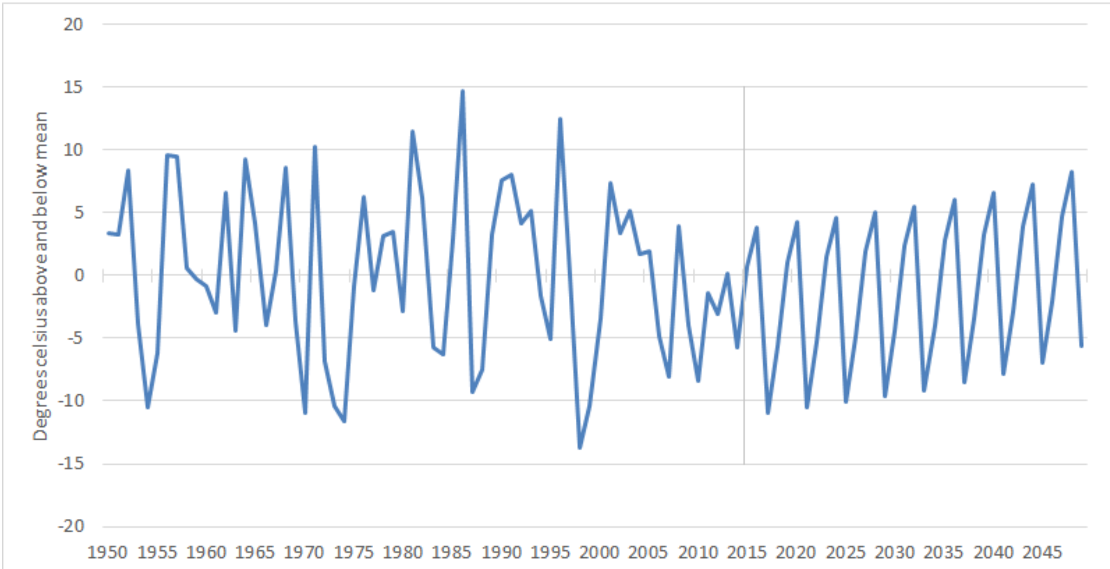

Figure 8.11: Observed El Niño and La Niña Oscillations around the mean temperature for years 1950 until 2015. Oscillations beyond 2015 foretasted using the Holt (2004) and Winters (1960) seasonal multiplicative model in STATA (StataCorp 2013, p.590).

IPCC Scenarios

(Solomon et al. 2007)

A1 Assumes global integration and ease of market access and thus is characterized by:

- Rapid economic growth and technological advancement.
- Global population peaking in 2050 at 9 billion followed by an optimistic gradual decline.
- Open markets leading to a convergent world; quick spread of efficient technologies and converging socio-economic disparities.
- There are subsets to the A1 family based on degree of fossil fuel use:
  A1FI – Fossil-fuel intensive;
  A1B - balanced use of all energy sources;
  A1T - Emphasis on non-fossil energy sources.

A2 Assumes a more heterogeneous world and is characterized by:

- Self-reliant nations operating independently restricted trade.
- Continuously increasing population.
- Economic development is regionally oriented and slower.

B1 Assumes global integration and more ecologically friendly is the most optimistic scenario.

- Rapid economic growth and a shift away from manufacturing towards a service and information based economy.
- Global population peaking in 2050 at 9 billion followed by an optimistic gradual decline.
- Clean and efficient technologies with reduced material intensity.
- An emphasis on global solutions to economic, social and environmental stability.

B2 Assumes an ecologically friendly world, although more divided as in A2:

- Continuously increasing population, but at a slower rate than in A2.
- Emphasis on local rather than global solutions to economic, social and environmental stability.
- Intermediate economic development emphasizing equity and environmental protection.

General Circulation Model Overview

(Randall et al. 2007, p.589)

BCCR_BCM2.0 (Furevik et al. 2003)

Bjerknes Centre for Climate Research, Bergen, Norway

Resolution: 2.8 x 2.8

Time slices: 9 x 10

CNRM-CM3 (Déqué et al. 1994)

Metdo-France, Centre National de Recherches Meteorologiques, Toulouse, France

Resolution: 1.9 x 1.9

Time slices: 9 x 10

CSIRO-Mk3.5 (Gordon et al. 2002)

CSIRO Atmospheric Research Center Victoria, Australia

Resolution: 1.9 x 1.9

Time slices: 9 x 10

ECHam5 (Roeckner et al. 2003)

Max Planck Institute for Meteorolgy, Hamburg, Germany

Resolution: 1.9 x 1.9

Time slices: 5 x 20

INMCM3.0 (Volodin et al. 2010)

Institute of Numerical Mathematics, Russian Academy of Sciences, Moscow

Resolution: 5.4 x 4.0

Time slices: 9 x 10

MIROC3.2 (medres) (Hasumi et al. 2004)

Center for Climate System Research, University of Tokyo, Tokyo

Resolution: 2.8 x 2.8

Time slices: 5 x 20

Abbreviations and Acronyms

ARIMA	= Autoregressive Integrated Moving Average Model
CBA	= Cost Benefit Analysis
CGIAR	= Consultative Group for International Agricultural Research
CIMMYT	= Centro Internacional de Mejoramiento de Maíz y Trigo
DAG	= Days After Germination
DAS	= Days After Sowing
DPP	= Daily Per Person
DSSAT	= Decision Support System for Agrotechnology Transfer
EBM	= Energy Balance Model
EMIC	= Earth Modeling with Intermediate Complexity
ENSO	= El Niño Southern Oscillation
GCM	= General Circulation Model
GHG	= Greenhouse Gas
GFDL	= Geophysical Fluid Dynamics Laboratory
IPCC	= Intergovernmental Panel on Climate Change
LP	= Linear Programming
Mz	= Manzana (0.7 Hectare)
NPV	= Net Present Value
NTAE	= Non-traditional Agricultural Export
OLS	= Ordinary Least Squares
Q	= Quintal = 0.04895 Ton
RC	= Radiative-Convective Model
RH	= Relative Humidity
SVP	= Standard Vapor Pressure
TR	= Transpiration Rate
VPD	= Vapor Pressure Deficit

Formulas and Conversions

VPD (kPa)	= $(((100-RH)/100)*SVP)/1000$
SVP (Pa)	= $610.7*10^(7.5T/(237.3+T))$
Manzana (Mz)	= 0.7 Hectare
Hectare (ha)	= 10,000m^2 = 2.47 acre = 1.43 Mz
Quintal (Q)	= 0.04895 ton
Bushel (corn)	= 0.0254 metric ton
Metric ton	= 39.368 bushels maize
Ton/ha	= 15.94 bu/ac = 29.2 Q/Mz