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Mexican Rural Households' Vulnerability and Adaptation to Climate Change

Authors
López-Feldman, Alejandro
Yúnez-Naude, Antonio
Hernández-Solano, Alan
et al.

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Alejandro López-Feldman[1], Antonio Yúnez-Naude[2], Alan Hernández-Solano[2], J. Edward Taylor[3] and Danae Hernández[4]

1. Centro de Investigación y Docencia Económicas (CIDE)
2. El Colegio de México (COLMEX) and Desarrollo y Alimentacion Sustentable (DAS A.C.)
3. University of California, Davis (UCD)
4. University of California, Santa Barbara (UCSB)

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Abstract

Weather shocks resulting from climate change will have negative impacts on agricultural production in most of Mexico. There is also concern that climate change will negatively affect agricultural production in California, America's richest agricultural state. Agriculture in California as well as northern Mexico relies heavily on surface water from snowpack, which is vulnerable to climate change, and it employs a workforce that is almost entirely from rural Mexico. Agricultural households feel the direct impacts of climate change, but these impacts ripple through local economies, affecting non-farm activities and non-agricultural households, as well.

Recent studies find evidence that climate change will increase migration out of rural Mexico, to Mexican cities as well as to the United States. It will accelerate the movement of people out of farm work and out of rural communities.

Past studies of regional cultures, especially in Mexico, show migration and famine being associated with deteriorating environments. This results in both local regional cultural upheavals as people migrate in response to limiting resources.

The governments of California and Mexico appear committed to reducing carbon emissions. Both also need to understand the vulnerability of humans and their environments to climate change and to increase the resilience of shared social and ecological systems. We are just beginning to understand the extent of households' vulnerability, their interactions with their surrounding environment, and their potential to adapt to climate change, how these vary across regions and households, and how policies can be designed to mitigate the negative impacts and facilitate adaptation.

Introduction

The concentration of greenhouse gases has reached levels that had not been seen on Earth in at least 800,000 years; evidence shows that the high rate at which these gasses have been growing since 1750 is mainly due to human activity (Stocker et al., 2013). As a result, between 1880 and 2012 the average temperature of our planet has increased in 0.85°C. In the Northern Hemisphere the period of 1983-2013 has probably been the warmest of the last 1,400 years (Stocker et al., 2013).

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) establishes that changes in climate have caused impacts on natural and human systems on all continents and across the oceans; heat waves, droughts, floods, cyclones, and wildfires alter ecosystems, disrupt food production and water supply, damage infrastructure and settlements, and increase morbidity and mortality (Field et al., 2014). It is very likely that during the 21st century climate change will reduce human welfare, specifically it might lower economic growth, complicate the efforts to reduce poverty and compromise food security (Field et al., 2014). Climate sensitive sectors, like agriculture, are the ones that will suffer the biggest economic shocks (Fischer et al., 2005; Mendelsohn, 2009). The magnitude of these effects will depend, among other things, on how humans respond and adapt to a changing climate. Households in rural areas in developing countries may be the most vulnerable because they often lack the necessary means to adapt.

Mexico has geographic and social characteristics that make it highly vulnerable to those effects (Ahmed et al., 2009; Mendelsohn et al., 2010; Skoufias and Vinha, 2013: see figures 1a to 1c). That is why the Mexican government is particularly interested in reducing vulnerability as well as in increasing the resilience of both social and ecological systems (ENCC, 2013). The design of policies that aim to decrease rural households' vulnerability to climate change should take into account that there are significant differences, geographic and of other kind, across rural Mexican households (Lopez-Feldman, 2013).

In this paper we provide a review of the existing literature that explores rural households' vulnerability and adaptation to climate change. Our focus is on assessing the current scientific knowledge of the Mexican case. After providing a comprehensive review of the state of the art we highlight existing research needs and opportunities for bilateral cooperation.

III.1 Potential effects of climate change: human dimensions

There is a large amount of scientific evidence that shows that several changes on earth's climate are taking place; among other things, there has been an average increase of 0.85°C in Earth's temperature since 1880 (Stocker et al., 2013). Some of the expected manifestations of climate change are changes in precipitation patterns in mid latitudes, thinning of the ice cover, an increase in the frequency of warm days, a decrease in the number of cold days, and changes in the distribution of extreme weather events (Kirtman et al., 2013). Although part of the changes can be attributed to natural trends it is clear that anthropogenic sources have played an important role behind phenomena like the warming of the earth surface, changes in the global water cycle, changes in extreme weather events, and increases in sea level (Stocker et al., 2013).

Climate change directly affects natural and human ecosystems, which become more exposed to risks derived from weather variability. It is expected that by the end of this century changes in rainfall patterns will cause more frequent droughts and floods, and coastal areas will see more frequent and intense inundation due to sea level rise (GFDRR, 2016). Meanwhile, the extinction risk of a large fraction of terrestrial and freshwater species will increase during the 21st century due to projected climate change (Settele et al., 2014). The geographic ranges of many species will change as well as their seasonal activities, migration patterns and their interaction with other species (Settele, et al., 2014; Field et al., 2014). Given the expected magnitude of climate change the value of the services that ecosystems provide to humans will decrease (Settele, et al., 2014).

It is expected that climate change will have important negative effects on climate-sensitive market sectors like agriculture, forestry, fisheries, energy, construction, insurance and tourism, among others (Schneider et al., 2007). It will also have negative effects on health and on water resources. Some of the effects on health will be direct, like the increase of mortality and morbidity associated with exposure to weather extremes compared to average temperatures; and others will be indirect and related to the prevalence of vector-borne diseases, food-borne infectious diseases, and waterborne diseases (Patz et al., 2005). The effects of increasing temperatures on health could vary across the globe: while there are some regions (e.g., mid-altitudes) more prone to the negative consequences of climate change, others (eg., Europe) could be benefited by the decrease of cold weather-related diseases (Ciscar et al., 2010). In Latin America extreme climate change events in the period between 2000 and 2013 were responsible for the death of 13,833 people (Magrin et al., 2014).

Climate change will not be uniform across the globe and will have heterogeneous impacts in different regions (Stocker, 2014; Hsiang and Meng, 2015). Some countries and regions within countries are more exposed than others because of their geographic characteristics and economic conditions. Low-income countries are the most likely to suffer the negative consequences (Dell et al., 2012; Magrin et al., 2014) and some economic sectors that depend directly on climate, like agriculture, could be more affected than others (Adams et al., 1988; Kane, Reilly and Tobey, 1992). Furthermore, the capacity to cope with the consequences of climate change varies not only between countries but also within them and even between households located in the same locality. In Central and South America, the key risks of climate change identified by the IPCC are water availability, flooding in rural and urban areas, decreased food production and food quality, and spread of vector-borne diseases (Field et al., 2014). In Latin America extreme climate change events in the period between 2000 and 2013 affected 53.8 million with estimated economic losses ascending to 52 thousand million dollars (Magrin et al., 2014).

Recently, the Conference of the Parties in its twenty first session (COP21) agreed that the parties should develop national plans to reduce the greenhouse gases emissions in order to preclude an imminent increase of 1.5°C on average temperatures. Nonetheless, although the COP21 was without a question a very significant step in the right direction, the global emission levels implied by the intended nationally determined contributions (INDCs) communicated by the participating countries are not consistent with achieving the goal of keeping global average temperature rise below 1.5°C with at least a probability of 50% (UNFCC, 2016). Understanding the effects climate change can have on different economic sectors is a crucial step to design adaptation strategies given a reality in which climate will continue to be affected by the current stocks of greenhouse gases and the uncertainty about how effective will international efforts to reduce emissions will actually be.

III.2 Agriculture: a climate sensitive economic sector

Climate is one of the main determinants of agricultural productivity (Adams, et al., 1998; Mendelsohn, 2009). Nonetheless, the relationship between climate change and crop productivity is complex and has not been fully studied. Most of the research has focused on the potential effects of temperature and precipitation but carbon dioxide and ozone can also affect crop productivity. Carbon dioxide in particular can potentially have a beneficial effect on productivity (the so called fertilization effect). However, the net effect that elevated CO_2 levels interacting with high temperatures can have on crop productivity is still not well known; the same is true about the possibility that CO_2 fertilization may come at the cost of crops with lower nutritional quality (Lobell and Gourdji, 2012).

Given current concentrations of greenhouse gases, it is very likely that there will be changes to the climate to which agriculture will have to adjust. This will not only require changes in the type and concentration or mixture of crops produced but also an increase in investment (McCarl, 2010). Beyond adaptation possibilities, it is expected that the agricultural sector will be the one to suffer the most economic impacts (Fischer et al., 2005; Mendelsohn, 2009). The rural sector will be greatly impacted and it is expected that these impacts will affect in a disproportionate way the welfare of poor rural households, making the fight against poverty more challenging (Field et al., 2014). Additionally, climate change will impact food security by affecting the availability and access to food, the stability of food reserves and price volatility.

The information and knowledge currently available suggest that it is likely that a moderate warming of the planet will benefit crop productivity in the more tempered regions and harm semi-arid and tropical ones. Nonetheless, if warming extends to more than mid-century, production in every region of the planet will be negatively impacted (Tubiello and Rosenzweig, 2008); countries' vulnerability will depend, among other things, on their geographical conditions and the type of crops being produced or that could be produced. Agriculture in developing countries faces a greater threat than in developed ones. This is mostly due to higher agricultural dependency, less capital available to implement adaptation measures, and the fact that in many cases developing countries are more exposed to extreme weather events and to temperature levels that are already too high (Fischer, et al., 2005; Mendelsohn, 2009). Within developing countries, small farmers will be the most affected given their low access to technology, inputs, information and monetary resources to implement adaptation measures (Field et al., 2014).

In many settings this small farmers are poor and live in areas that experience higher weather variability (Angelsen & Dokken, 2015; Brouwer et al., 2007). Furthermore, these low-income households often lack access to the necessary mechanisms to cope with weather variability (Brouwer et al., 2007; Davies et al., 2009). The latter is mainly a result of lack of access to credit or insurance mechanisms (Kazianga & Udry, 2006; Hallegate et al., 2016).

Lobell et al., (2008) argue that for South Asia and Africa the most vulnerable crops are some corn varieties, wheat and rice. In Latin America, agro-ecologic and demographic diversity lead to varied expectations within its regions; it is expected that by mid-century the productivity of the southeast of South America will either keep steady or increase slightly, while for Central America it could be reduced in the next 15 years, risking food security for the most impoverished population (Field et al., 2014). In the longer run even moderate warming could cause crop damage in many of the countries in the region (Mendelsohn, 2009; Seo and Mendelsohn, 2008a). The studies available for Mexico show that some of the likely consequences of climate change are: a decline in the area susceptible for cultivation, a decrease in crop yields, and shorter growing seasons due to less days with the necessary humidity (Monterroso, et al., 2015).

IV.1 Vulnerability and adaptation: Conceptual basis

The livelihood of many inhabitants of rural areas is vulnerable to climate change to which they will have to adapt. Adaptation is not new; throughout history, humans have adapted their agricultural practices to respond to changing economic, social and environmental conditions (Kurukulasuriya and Rosenthal, 2013). The main difference is that today climate conditions are changing at a relatively high rate and it is not clear how fast farmers are going to be able to adapt to such changes (Jones et al., 2012). As a matter of fact, the way in which human populations in general and farmers in particular will respond to climate change has not been fully studied (Adams, et al., 1998; Lobell and Gourdji, 2012). Being able to properly measure and assess vulnerability and adaptation is a precondition for the design and implementation of policies aimed at improving adaptation capabilities and reducing vulnerability.

IV.2 Vulnerability

The elements behind vulnerability are context-specific; as such, vulnerability is a dynamic concept that varies with the social and biophysical processes that individuals and groups face over time (Eriksen and O'Brien, 2007). As Birkman (2006) points out it is hard to find a precise definition of vulnerability and different people interpret it in different ways, in fact, even scholars from the same disciplines or knowledge domains might conceptualize vulnerability in very different ways (Füssel, 2007; O'Brien et al., 2007). According to Birkman (2006) there are more than 25 definitions, concepts and methods to systematize vulnerability. Vulnerability assessments based on different views not only reflect disciplinary focus they also have different implications in terms of the type of policy recommendations that will emerge (Kelly and Adger, 2000; O'Brien et al, 2007).

Although it is not the objective of this work to provide a detailed account of the origins and differences across the various concepts of vulnerability, it is important to illustrate some of the issues behind the different definitions.[1] In doing so, we focus on approaches that define vulnerability in relation to an external stressor (e.g., climate change) but there are also definitions based on an undesirable outcome (e.g., famine).

Kelly and Adger (2000) argue that the term vulnerability comes from the Latin *vulnerabilis,* which was used by the Romans to refer to a wounded soldier lying on the battlefield. This definition is the basis for the starting-point (or contextual) approach, which characterizes vulnerability by the current state of an individual or social group in terms of its inability to cope with a given external pressure rather than by what may or may not happen in the future (Kelly and Adger, 2000; O'Brien et al., 2007). In this approach vulnerability is an *a priori* condition determined by socioeconomic factors as well as by political, institutional and technological structures and processes (Füssel and Klein, 2006; O'Brien et al., 2007). The starting-point approach is useful to identify policy recommendations that while helping to reduce vulnerability to long-term climate change are also relevant to the solution of immediate needs of individuals and communities (Kelly and Adger, 2000).

On the other hand, we have the end-point (or outcome) approach, which characterizes vulnerability as an outcome. The vulnerability of a group to climate change is thus a function of exposure, sensitivity and its ability and opportunity to adapt to change (Adger et al., 2003; O'Brien et al., 2007). This is a useful approach when trying to summarize the net effects of climate change once adaptation has taken place (Kelly and Adger, 2000). Originally this was the approach followed by the IPCC, which in its third assessment report defined vulnerability as:

> *"The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity."* (McCarthy et al., 2001, p. 995)

[1] For more details behind the different concepts of vulnerability to climate change see Füssel and Klein (2006), O'Brien et al. (2007) and Smit and Wandel (2006).

Behind the definition of vulnerability, but more importantly behind the effects that climate change could have on human populations there are two clearly defined spheres: external exposure and internal coping (Birkman, 2006). Definitions of vulnerability usually emphasize one over the other, by doing so they make it seem as if both factors are disconnected when in fact they are interlinked. As Füssel and Klein (2006) point out, the original definition of vulnerability used by the IPCC incurs in this mistake by using 'or' instead of 'and' in the first part of the definition. Arguably as a result of this critique the IPCC substituted 'or' by 'and' in the definition of vulnerability included in its fourth assessment: *"The degree to which a system is susceptible to, and unable to cope with ..."* (IPCC, 2007, p. 883).

An even more fundamental change in the definition of vulnerability took place in the fifth assessment of the IPCC. The new definition of vulnerability, although less precise, makes an explicit reference to the concepts of contextual and outcome vulnerability mentioned before:

> *"The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. See also Contextual vulnerability and Outcome vulnerability."* (IPCC, 2014, p. 1775)

Considering that the focus of the present work is on the effects that climate change can have on Mexican rural households as well as on potential adaptation measures that can help to ameliorate such effects we focus on the internal coping aspects and focus on contextual (or starting-point) vulnerability. Defined by the IPCC as:

> *"A present inability to cope with external pressures or changes, such as changing climate conditions. Contextual vulnerability is a characteristic of social and ecological systems generated by multiple factors and processes."*(IPCC, 2014, p. 1762)

Of particular relevance are the questions: who is most vulnerable and why? The answers to these questions will provide a starting point for the design and implementation of policies than can promote and facilitate adaptation measures. Reducing vulnerability, as seen from a starting-point approach, should involve a multidimensional process that in the end leads to a situation where individuals and groups are better equipped to respond to changing climatic conditions (O'Brien et al., 2007).

IV.3 Measuring Vulnerablility

In general, the studies that attempt to measure vulnerability at national and regional levels propose a conceptual framework with a series of indicators that try to capture sensitivity, exposure and adaptation capacity. For example, Brooks, et al. (2005) present several indicators divided in categories that are used to estimate the vulnerability to climate change at the national level. These categories are economic variables, health and nutrition status, education, infrastructure, governance, reliance on agriculture, ecosystem variables, and technology availability. The authors estimate an index to classify several countries according to their level of vulnerability. Lobell et al. (2008) perform a global analysis of adaptation needs in the agriculture sector in order to secure food production. They classify several regions in the world according to nutritional patterns, then estimate the most vulnerable crops and finally identify that South Asia and Southern Africa are the regions that would be more affected if the production of such crops decreases. The vulnerability ranking of Brooks et al. (2005) is consistent with the results of Lobell et al. (2008), since many of the most vulnerable countries found by Brooks et al. (2005) are in the food-insecure regions. In an effort to homogenize vulnerability measurements in communities that are subject to very different circumstances, the German Agency for International Development (GIZ) developed a guide to perform vulnerability assessments based on pilot applications in Bolivia, Pakistan, Burundi and Mozambique (Fritzsche et al., 2014). GIZs guide can be a very useful tool for the monitoring and evaluation of adaptation.

In Mexico the negative impacts of climate change are likely to be heterogeneously distributed across regions (Lopez-Feldman, 2013). This can be explained by differences in adaptation capacity as well as in the level of exposure of each region. In order to better understand how vulnerability varies over space, Monterroso, et al. (2014a) assess vulnerability at municipality level using two vulnerability indices, one uses Principal Component Analysis (PCA) to aggregate all the information while the other uses equal weights for all the variables. The authors identify the dimensions of vulnerability (exposure, sensitivity and adaptive capacity) and associate many variables as proxies to perform their analysis. For adaptive capacity they considered several indicators divided in four categories: human capital (population, education and school attendance), social capital (land tenure and organization within the municipality level), financial capital (access to credit, insurance coverage and income level) and natural capital (land use). To calculate the vulnerability index, the authors add the risk and exposure indicators to consider that these elements are related positively to the vulnerability, and then they subtract the adaptive capacity. According to their results the most vulnerable municipalities are in the States of Oaxaca, Chiapas, Puebla, Guerrero and Veracruz.

Borja-Vega and de la Fuente (2013) provide another analysis of the vulnerability to climate change in the Mexican agricultural sector, the authors look at possible changes in vulnerability up to 2045. The municipality index that they propose also makes use of PCA using variables that can measure vulnerability in the agricultural sector. They divide the vulnerability components as exposure (average temperatures, average precipitation, past and future climate scenarios), sensitivity (food poverty, percentage of maize production under irrigation areas and percent of population in agricultural activities) and adaptive capacity (farmers that belong to organizations, remittances received, distance from roads, and federal disaster assistance per capita). Their analysis shows that municipalities with higher poverty levels also present higher agricultural vulnerability risk. The authors also find that there is high variance in risk exposure between regions in Mexico, the south of the country is more exposed to flood risk whereas the north has higher risk of drought. Furthermore, they find that large-scale producers are representative of municipalities with low levels of vulnerability while self-sufficiency farmers are more prevalent in municipalities with higher levels of vulnerability. They find similar results to Monterroso et al. (2014a) and explain that although the north of Mexico is not currently very vulnerable to climate change, it might experience some changes in the coming decades.

Contrary to the previously discussed studies, the Mexican National Strategy on Climate Change presents a vulnerability assessment that goes beyond the agricultural sector by considering dimensions such as social vulnerability (considering mainly economic indicators), health and livestock production (ENCC, 2013). The Mexican Institute for Competitiveness (IMCO) also has a vulnerability index that is not exclusively focused on agriculture or rural areas. It assesses urban vulnerability to climate events in three dimensions: social, infrastructure and climatic vulnerability (IMCO, 2012). More recently, the National Institute of Ecology and Climate Change considered the studies of Monterroso, et al. (2014a), Gay (2013) and ENCC

(2013b) to develop an official assessment of the most vulnerable municipalities in the country (SEMARNAT, 2014). The official map of vulnerability integrates the three studies to develop its own vulnerability index. According to this index, 480 Mexican municipalities were classified as highly or very highly vulnerable; most of them are in the south-southeast region (SEMARNAT, 2014).

Although the results provided by this analysis are very useful as a first approach to geographically identify the most vulnerable populations, results at a much more disaggregated level are necessary in order to identify the adaptation decision and challenges faced by communities, households and individuals. In the end it is people not municipalities or regions the ones that are vulnerable.

IV.4 Adaptation

Adaptation to climate change can be defined as the process of adjustment to actual or expected climate and its effects (IPCC, 2014). There are different types of adaptation and different ways in which it can be classified (Figure 2). When the measures are reactive we have ex-post adaptation, while adaptation that takes place before the impacts of climate change are observed is known as ex-ante or anticipatory adaptation. Adaptation measures might be beneficial only for the individual undertaking them (private adaptation) but they might also benefit a group of individuals beyond those directly involved in the decision making process (public adaptation). According to their origin, adaptation can be autonomous or planned. Autonomous adaptation refers to voluntary actions or measures that individuals or agents (e.g. agricultural cooperatives) undertake as a response to a climatic stimuli. Meanwhile, planned adaptation is the result of a deliberate policy decision with the objective to complement, facilitate or improve agents' responses to climate change (Tubiello & Rosenzweig, 2008). Finally, when the depth or degree of the measures is taken into account adaptation can be classified as incremental or transformational. The first one refers to actions whose main objective is to maintain the essence and integrity of a system or process at any given scale (IPCC, 2014; Park et al., 2012). Meanwhile, transformational adaptation aims to change the fundamental characteristics of a system (IPCC, 2014; Kates et al., 2012).

A considerable number of adaptation measures for the agricultural sector have been suggested recently. These go from modifying planting and harvest time periods to the construction of large infrastructure, passing through migration and the implementation of new production practices.[2] Some of the low cost adaptation measures (e.g., modifying planting dates or changing to a different crop type or variety) have been or are being adopted by farmers in many regions of the world. Nonetheless, it is very likely that these measures will only be effective when facing small temperature increases (Asafu-Adjaye, 2014).

V.1 Methodological approaches to analyze adaptation to climate change

Climate change has potentially large negative impacts on the welfare of rural households, whose livelihoods are connected, directly or indirectly, with agriculture. Although rural households

[2] Kurukulasuriya and Rosenthal (2013) present a detailed matrix with adaptation options for the agricultural sector.

must adapt in order to reduce the negative effects of climate change, the portfolio of adaptation options available to them will vary. The heterogeneity of adaptation alternatives available across households, as well as the differences in the actual adaptation decision undertaken by them, can be explained by a myriad of factors at the household (e.g., education, capital), community (e.g. access to markets) and even national (e.g., existence of planned adaptation policies) level.

In this section we present a brief review of the empirical literature in economics that has looked at adaptation decisions, and the effect of climate change, in agriculture. We focus on the methodological issues more than on the specific results except for the case of Mexico; results for Mexico are presented in the last part of this section.[3] In the first part of this section we discuss the Ricardian model as well as some of its refinements, in the second part we move onto computable general equilibrium models, the third part discusses approaches that try to understand more directly the determinants of adaptation decisions, while the fourth part reviews approaches that do not fit neatly into any of the above classifications.

V.2 Ricardian and Structural Ricardian Models

A widespread approach followed in the economics literature to estimate the effects of climate change on agriculture is based on the Ricardian Model (RM). This model has been used to estimate the impacts of climate change on land rent, value of agricultural land, and agricultural income, among others. The RM has been applied to different countries and regions such as the US (Mendelsohn, et al., 1994*)*, Canada (Reinsborough, 2003), Africa (Seo and Mendelsohn, 2008c), South Africa (Gbetibouo and Hassan, 2005), South America (Seo and Mendelsohn, 2008a) and Mexico (Mendelsohn et al. 2010; Lopez-Feldman, 2013), to name a few. The basic assumption behind the model original proposed by Mendelsohn et al. (1994) is that in order to maximize profits farmers will adapt to the climatic conditions that they face, adaptation is thus assumed but not explained.

Mendelsohn et al. (1994) proposed the following econometric model to estimate the value of land and buildings per acre (y_i) in a sample of US counties, as a function of precipitation and temperature (c_i) as well as socioeconomic and soil-type variables (x_i):

$$y_i = \beta_0 + \beta_c c_i + \beta_x x_i + \varepsilon_i$$

Where *i* refers to the county and ε_i is the idiosyncratic error.

Under well-functioning markets, land rent should be equal to the net income of the most profitable activity that could be carried out in the farm. The model thus permits to estimate the highest net income that a farmer could earn given the combination of temperature and precipitation. The effects of climate change are calculated by comparing the value of the farm in the baseline against its predicted value once changes in temperature and precipitation, as determined by a climate change scenario, are taken into consideration. The predicted value of each farm corresponds to the most appropriate land use given the new climatic conditions. In principle land use can be different from the original one but it is possible that farmers' reaction

[3] For a synthesis of the evidence of the effects that climate change has on the agricultural sector in other Latin American countries see López-Feldman and Hernández (2016).

to the new conditions was a change in the input mix. The key assumption is that in the process of changing land use or input mix the farmer has adapted to climate change.

Soon after the RM was proposed it was criticized for having several limitations. Reilly (1999) was one of the first to point out that the RM could not say anything about how adaptation actually took place and it provided, at best, a long-run equilibrium analysis. One of the main criticisms to the model came from Deschenes and Greenstone (2007), who argued that the model was too sensible to minor specification changes and pointed to an omitted variables problem as the main reason behind what they saw as an overestimation of the negative effect of climate change in the US agriculture. Although Deschenes and Greenstone's claim that the effect of climate change was in fact positive has been shown to be wrong,[4] the concern about an omitted variables problem remains. Other limitations of the RM are that it does not incorporate price fluctuations and the use of climatic variables aggregated over time and space (Hanemann and Dale, 2006; Mendelsohn and Dinar, 1999).

The most important limitation of the RM for the purposes of the present work is its inability to explicitly model adaptation decisions. As a partial solution to this problem Schlenker, et al. (2005) proposed that instead of implicitly assuming that farmers will adopt irrigation in response to climate change, farms located in counties where irrigation was already available should be analyzed separately from those without irrigation. Schlenker et al. (2006) argue that in addition to a separate estimation for irrigated and non-irrigated farms, climate should be included in way that reflects more accurately what we know from agronomic evidence; they suggest that *degree days* should be used instead of temperature.

The Structural Ricardian Model (SRM), proposed by Seo and Mendelsohn (2008d), is a more appropriate response to deal with this limitation. The SRM explicitly models some of the adaptation decisions taken by farmers. In order to analyze the livestock sector of ten African countries Seo and Mendelsohn (2008d) proposed a two-stage model. For the first stage they assume that the profit obtained by producer *i* who selects livestock type *j* can be represented as:

$$\pi_{ji} = V\left(Z_{ji}\right) + \varepsilon_{ji}$$

Where *Z* is a vector that includes socioeconomic variables as well as soil and climate related factors. Hence the condition to choose the *jth* livestock type is:

$$\pi_{ji}^{*} > \pi_{ki}^{*} \; \forall \; k \neq j \; \leftrightarrow \; \varepsilon_{ki} - \varepsilon_{ji} < \; V\left(Z_{ji}\right) - V(Z_{ki}) \; \forall \; k \neq j$$

The authors assume that ε is independently and identically Gumbel distributed and that *V* is written linearly in its parameters, then the probability that the *jth* livestock type to be chosen by the farmer *i* is:

$$P_{ji} = \frac{\exp(Z_{ji}\gamma_j)}{\sum_{k=1}^{J} \exp(Z_{ki}\gamma_k)}$$

The first stage of the model consists of calculating the selection probability through a multinomial logit regression. The second stage consists in estimating econometrically the net income per animal and the number of animals raised, both conditional on the selected species. The model corrects the possible selection bias. Profit is estimated as:

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[4] For more details on this see Fisher et al. (2012) and Deschenes and Greenstone (2012).

$$\pi_j = X_j\varphi_j + \sigma \sum_{i\neq j}^{J} r_i \left(\frac{P_i \ln P_i}{1-P_i} + \ln P_j\right) + w_j$$

Where X_j consists of socioeconomic and climate and soil-type related variables, the second term is the selection bias correction term and w_j corresponds to the error term. In a similar manner, the authors estimate the optimal number of animals raised *(N_j)* through the equation:

$$N_j = X_j\eta_j + \sigma \sum_{i\neq j}^{J} r_i \left(\frac{P_i \ln P_i}{1-P_i} + \ln P_j\right) + v_j$$

The expected net income of the producer *i* is defined as:

$$W_i(Z_i) = \sum_{j=1}^{J} P_j(Z_{ji})\pi_j(Z_{ji})\, N_j(Z_{ji})$$

Finally, the effect of climate change is measured as the change on the expected net income in the presence of climate change. Therefore, if C_{before} and C_{after} are the levels of temperature and precipitation before and after climate change, the impact associated to it will be:

$$\Delta W = W_i(C_{after}) - W_i(C_{before})$$

It is important to emphasize that the first step of the model allows us to observe explicitly farmers´ adaptation in the face of climate change since it shows how the probability to select each of the different livestock species changes in response to alterations in precipitation and temperature.

Seo and Mendelsohn (2008c) use the results of the first stage to evaluate how climate change will change the odds of raising beef cattle, dairy cattle, goats, sheep and chickens in 2020, 2060, and 2100 in the ten African countries selected. Similarly, Seo and Mendelsohn (2008b) use the approach of the first stage to show how producers adjust their choices to plant fruits and vegetables, maize, wheat, squash, rice, potato, and soybeans in seven South American countries. Galindo et al. (2015a) estimate a SRM to identify the adaptation crop options in Peru under different climate change scenarios. After estimating the probability to choose a given crop the net income conditional on crop selection is estimated. Fleischer and Kurukulasuriya (2011) use a variation of the SRM to estimate the effects of climate change on irrigation selection by African and Israeli farmers. Their results indicate that notwithstanding that irrigation may be a way to adapt to climate change by African farmers, access to water for irrigation may be limited. In Israel the situation is different due to the fact that all households have access to irrigation and the focus is in estimating the adaptation process of farmers by selecting alternative irrigation technologies. Finally, Da Cunha et al. (2015) use a switching regression model to obtain one of the few empirical estimations of the adoption of irrigation in a Latin American country.

The SRM approach allows us to explicitly model some of the adaptation decisions that, given new climatic conditions, the farmers make. The assumption behind the model is that farmers will optimally choose the new technology and set of inputs to grow the new crop or to raise new cattle types. However, the SRM ignores the costs of adaption, i.e. does not consider that to adapt farmers would need to incur in transition costs such as investments and/or disinvestments.[5] In addition, as the RM, the SRM assumes that prices are constant through time (Seo and Mendelsohn, 2008d).

V.3 Computable General Equilibrium Models

Computable General Equilibrium Models (CGEM) can overcome several of the drawbacks of the Ricardian model: they consider prices and inter-sectoral linkages that can capture both direct and indirect effects of climate change. Furthermore, when explicitly modeled, CGEM can capture adaptation. Darwin et al. (1995) present one of the first applications of a CGEM to look at the effects of climate change. They analyze the effects on world food production and find very low negative effects in general and even positive effects for cereals.

The scope of the CGEMs available in the literature varies, among other things, according to the level of disaggregation: multinational, county specific, regional or local. For example, the Global Trade Analysis Project (GTAP) has multi-country, regional and multi-sector CGEMs. This model has been used to estimate the effects of climate change for regions as well as for several countries. With respect to agriculture, the common procedure followed is to simulate climate change through its estimated effects on crop yields (Ahmed, et al. 2009, and Hertel et al., 2010) or on farmers' income (Mideksa, 2010).

Hertel, et al. (2010) use the GTAP to estimate the effects of climate change through changes in crop yields for 15 developing countries. The yield shocks due to climate change used in their simulations vary by country and crop and are based on estimations presented in the literature for rice, wheat, coarse grains, oilseeds, sugar, cotton, and other crops. The authors consider three scenarios: 1) low-productivity caused by rapid heating, high crop sensitivity due to climate change, and a small fertilization effect due to CO_2; 2) high-productivity caused by a slow change in temperature, low crop sensitivity caused by global warming and a high CO_2 fertilization effect; and 3) the most probable, in which the impact of climate change on yields lies between the first two scenarios. The simulation results indicate that in the low yield scenario, poverty would increase by 1.8%, which is equivalent to 2.7 million people. Meanwhile, in the high yield scenario, the increase will be slightly higher. For the medium yield scenario, there will be no change on poverty incidence. The differences in impacts are a result, among other things, of the worldwide heterogeneity of climate change effects on yields as well as of the variation in households' main income source across countries.[6]

The models that we have discussed so far allow input substitution within productive activities in the face of climate change, as well as rearrangements of the factors of production and inputs towards the most productive activities, but none of them consider adaption to climate change explicitly. Döll (2009) presents a review of the main CGEMs that have been used in the literature to estimate the impacts of climate change. Four of the six models that he reviews are particularly relevant for this work since they consider adaptation. These four CGEMs are: AD-DICE (Adaptation-Dynamic Integrated Model of Climate and the Economy), AD-RICE

[5] Timmins (2006) proposes a structural model with endogenous land use that allows him to estimate the effects of climate change in Brazil under both the assumption of cero adjustment costs and the assumption of prohibitively high adjustment costs.

[6] Hertel, et al. (2010) stratify households of each country according to their primary source of earnings: farm agricultural self-employed; non-agricultural self-employment; urban wage; rural wage; dependency on transfers; and the remaining households are distinguished according to the region where they are located: urban or rural.

(Adaptation–Regional Integrated model of Climate and the Economy), PAGE (Policy Analysis for the Greenhouse Effect), MERGE (Model for Evaluating Regional and Global Effects of greenhouse gases reduction policies), and FUND (Climate Framework for Uncertainty, Negotiation and Distribution).

AD-DICE and AD-RICE consider adaptation as an endogenous decision, since its purpose is to estimate the balance between the levels of adaptation made and the costs generated by climate change that maximize intertemporal welfare. In these models costs of climate change are equivalent to a fraction of GDP that include (1) expenses used to achieve the chosen level of adaptation and (2) the damage caused by climate change considering the adaptation applied. Both AD-DICE and AD-RICE consider mitigation of greenhouse gases. The main difference between them is that the first assumes the impacts of climate change in the economy as a whole, while the second assumes that those impacts can be different in each of the thirteen regions of the world.

MERGE focuses on five world regions and its purpose is to calculate the optimal balance between the abatement of greenhouse gas emissions and the costs of climate change. It estimates two types of damage that result from climate change: market and non-market. Market damages are expressed in function of the expected change in temperature and in GDP, and are calculated by region. Non-market damages are estimated using a willingness to pay approach. The adaptation process is implicitly considered when the damage market function is calibrated.

PAGE analyzes the effects of adaptation and mitigation to climate change in eight regions of the world. The economic impacts of climate change are expressed as percentage loss of GDP by year and region, covering economic and non-economic damages. The model assumes that climate change only affects the economy when the temperature reaches a threshold. With adaptation, the threshold increases and reduces the damage caused by the phenomenon.

Finally, FUND examines the effects of climate change in sixteen regions of the world by assuming that changes in temperature caused by this phenomenon directly affect nine key-areas that include mortality, agriculture, and water resources. The impacts of climate change are expressed as percentage loss of GDP or monetary damages. FUND puts greater emphasis on simulating mitigation actions although it also considers adaptation. In the latter case, the model assumes that it can only be applied in agriculture.

It is important to emphasize that the level of aggregation of all this CGEMs hide local adaptation as well as adaptation by individual agents. Döll (2009) argues that CGEMs that explicitly incorporate adaptation at these two levels are necessary. In section III.5 we summarize a disaggregated microeconomic CGEM, applied to the rural economy of Mexico that partially responds to Döll's recommendations. To our knowledge this is the first effort to begin modeling a local/individual adaptation perspective in CGEMs.

V.4 Determinants of adaptation decisions and perception of climate change

While there exist a relatively abundant literature that looks at the potential impacts of climate change as well as assessments of potential adaptation practices or techniques, there is a relative lack of studies that look at the capacity and willingness of individuals to actually implement the adaptation options that in theory are available (Füssel and Klein, 2006). The emphasis of most of the studies that we have mentioned so far has been to estimate the potential effects of climate change on agricultural outcomes either assuming that adaptation will take place or assuming that the choice of crops, animals or inputs that we observe is in fact the result of an adaptation decision to respond to climatic variables.

In this section we review studies that analyze adaptation decision in a direct way using disaggregated data. Understanding the determinants behind the adoption of different adaptation strategies, the barriers that households face when making adaptations decisions and the way in which households' perceptions of climate change affects their decisions, is a key aspect towards the design of public policies that can successfully increase household's adaptation capacity.

One of the first studies to pay special attention to the determinants of adaptation was Di Falco et al. (2011). They estimate a simultaneous equation model to explicitly account for the decision to adapt. To do so, they use household level data on farmers' perceptions and understanding of climate change, as well as on the responses that the households might have taken to adapt their farming practices. In a related study Di Falco et al. (2012) use a farm productivity as well as a Ricardian model to estimate the determinants of adaptation for farmers in Ethiopia. They show that extension services, access to credit and information on climate change are significant drivers of adaptation. They also show that adaptation has a significant effect on productivity and revenues. Di Falco and Veronesi (2013) estimate a multinomial endogenous switching regression model of climate change adaptation and crop revenues and find that changing crop varieties has a positive impact on net revenues only when it is coupled with water or soil conservation strategies.

One of the advantages of these types of studies is that they identify differences in behavior among farmers with similar levels of exposure to climate change, like Alpizar, et al. (2011) who use experimental economics to unravel coffee farmers' preferences and risk aversion in Costa Rica. One of their findings is that farmers seem to adapt more when they have poor or non-reliable risk information than when the risk is known. Disaggregated studies can also find specific adaptation strategies that farmers are undertaking to cope with the consequences of climate change, like water storage implementation and changes in crop varieties (Di Falco and Veronesi, 2013) or reliance on family networks to diminish the possible shocks of climate change (Di Falco and Butle, 2013).

V.5 Other methodologies and approaches

The shifting of growing seasons is arguably one of the least expensive and easier to implement autonomous adaptations that a rural household can undertake. Nonetheless, there are not many studies that have looked specifically at this adaptation option. Ortiz-Bobea and Just (2012) propose a structural econometric model that allows for the simulation of changes in the planting date of the crop. For the empirical application they use a panel dataset with count-level information for 8 states in the US. They estimate c corn yields and show that changing the planting date could significantly reduce projected corn yield damages due to climate change.

Fernandes et al. (2012) developed the *Agro-ecological zone simulator*, a platform that allows the estimation of the effects of agro-climatic factors and of crop-field management on the productivity of four crops (wheat, soy beans, maize and rice) in Latin America and the Caribbean using biophysical models. [7] Using the projections of expected changes in temperature and precipitation for 2020 and 2050, this platform can calculate the impact of climate change on productivity with or without the use of adaptation measures. The measures considered include the use of improved seed varieties, change of sowing dates, use of irrigation, or a combination of any of these changes. The results indicate that climate change will have significant harmful effects on crop productivity, particularly on maize, soybean, and wheat in the majority of the countries producing theses staples. However, adaptation measures can reduce its negative effects. In addition, the estimated productivity shocks obtained with the Agro-ecological zone simulator provide an input for a dynamic, multiregional and multisector CGEM called ENVISAGE to estimate the economic impacts of climate change. The results indicate that with no adaptation the GDP of Latin America and the Caribbean region could be reduced by 1.7% in 2050.

Nelson et al (2009) link a biophysical crop model (DSSAT) with a global agricultural supply-and-demand projection model (IMPACT 2009) to evaluate the effects of climate change on food security and human welfare. The study is for all world regions except Antarctica. The biophysical model is used to assess the effects of changes in temperature and precipitation with or without CO_2 fertilization in five crops (rice, wheat, maize, soybeans, and groundnuts). The IMPACT 2009 is a partial equilibrium model that simulates the supply and demand of 32 crops. By comparing scenarios with or without climate change in 2050, the results show that the number of undernourished children will increase and the daily calorie per capita consumption will decrease. The authors estimated the levels of investment that would be necessary in agricultural research, rural roads, and irrigation in order to avoid the two aforementioned negative effects. The results show that developing countries have to invest between $7.1-$7.3 billons USD annually to avoid the effects of climate change on nutrition. In the case of Latin America and Caribbean, the amount needed is around $1.2-$1.3 billons.

Medellin-Azuara, et al. (2011) use a hydro-economic approach to estimate the effects of climate change on the California agricultural sector. For this purpose they use the SWAP and CALVIN models. SWAP is an agricultural production model and CALVIN is a hydro-economic model used to manage the Californian water system and aimed to minimize water scarcity and operational costs. The model includes exogenous and endogenous processes; the latter are driven by population and income changes. Other feature of the authors' methodology is the inclusion of water scarcity as well as the typical climate change variables (precipitation and temperature variations). In Medellin-Azuara et al (2011), adaptation takes place by changes in the cropping patterns.

The World Bank designed a two-step method to estimate the cost of adaptation to climate change required to protect infrastructure and development investments from the effects of climate change. In the first step the World Bank calculates the percentage of current infrastructure and development investment –formed by official development assistance, foreign direct investment and gross domestic investment- that could be affected by climate change. In the second step the costs required to enhance resilience of the percentage calculated above is estimated. With this basis the World Bank concludes that adaptation cost for developing countries are between US$9 - US$41 billion per year (World Bank, 2006 and Parry, 2009).

In its calculations, the United Nations Development Program or UNDP (2007) updates the data used by the World Bank and concludes that the amount needed to protect the

[7] The simulator is available in www.azsimulator.org

investments of developing countries in the presence of climate change for is at least US$ 44 billion per year. In addition, UNDP calculates that for the programs aimed to reduce poverty, the adaptation cost would be at least US$40 billion annually.

The United Nations Framework Convention on Climate Change (UNFCC, 2007) provides estimations for 2030 of the investment and financial flows required for adaptation (and also for mitigation), dividing the world into 8 regions and for the following sectors: agriculture, forestry, and fisheries; water supply; human health; coastal zone; and infrastructure.[8] The estimations are done independently for each sector by using the most appropriate available methodology for each sector. The results of UNFCC indicate that USD 49-171 billion would be needed for the aforesaid sectors to adapt to climate change in 2030; and approximately USD 14 billion for the agriculture, forestry and fisheries sector. For the later, the study calculates the investment and financial flows needed to cope with the expected economic and population growth with and without the presence of climate change. Adaptation costs are defined as the difference under these two later scenarios and include expenditures in research, extension services and investment in physical assets. Most of that estimates are made by using the current expenditure in the sectors, and by a rule of thumb based on available studies. The exception is the investment in physical assets needed for economic and population growth without climate change that is calculated with the OECD ENV-linkage model.[9]

More recently the World Bank (2010) carried out other study on climate change adaptation costs for developing countries, covering: infrastructure, coastal zones, water supply and flood management, agriculture, fisheries, human health, forestry, and ecosystem services, as well as extreme climatic events. For its estimations, the World Bank assumes that the well-being of humans located in the studied regions would be the same with respect to the scenario without climate change. The results reveal that the adaptation costs for developing countries would be $75-100 billion per year for the period 2010-2050, and that the greatest portion of these costs would be needed in East Asia and in the Pacific region.

Oxfam (2007) estimates that the required expenses to adapt to climate change in the developing countries would be at least USD 50 billion annually, without specifying the year or period under consideration. In addition, Oxfam uses its Adaptation Financing Index (AFI) that indicates the percentage of total funding worldwide that each developed country should contribute for the implementation of adaptation policies in developing countries. The AFI is calculated from two identically weighted criteria: the responsibility for the harm done to the environment by all countries and their financial capacity. Oxfam considers that only the countries with the highest level of human development and C02 emissions have the obligation to finance adaptation of climate change required by developing countries. In particular, the USA must contribute with 43.7% of the required financing, the European Union 31.6%, and Japan, 12.9%.[10]

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[8] The regions considered are: Organization for Economic Co-operation and Development (OECD) North America; OECD Pacific; OECD Europe; transition economies; developing Asia; Latin America; Africa; and Middle East.

[9] Details of the OECD ENV-linkage model at: http://www.oecd-ilibrary.org/docserver/download/5jz2qck2b2vd.pdf?expires=1461795638&id=id&accname=guest&checksum=A41049F32FA706FE6083096BA0C4C39D

[10] Another study on adaptation is that of Garrido et (2011), focused on the role of insurance to cope with the effects of climate change for the cases of maize and wheat production in the Iberian Peninsula.

One limitation of the studies that measure the costs of adaptation in the face of climate change is that the assumptions about costs are too simplistic. For example, according to McCarthy (2011), the costs generated for the implementation of three sustainable land management practices—agroforestry, soil and water conservation and grazing land management- strongly vary due to factors such as the adopted strategy, the region, the agro-ecological zone, the farmers-households characteristics, property rights on land, etc. This suggests that modeling of agricultural adaptation to climate change should have a micro focus.

V.6 Results for Mexico

The potential effects of climate change in the Mexican agricultural sector have not been widely studied in the literature but there are already some important results available; studies looking specifically at adaptation to climate change are even scarcer. Here we provide an overview of the main findings for the Mexican case.

Boyd and Ibarraran (2011) use a CGEM applied specifically for Mexico to estimate the costs of climate change on the Mexican economy. The authors estimate that in 2030 the drought as result of climate change would reduce Mexico's Gross Domestic Product or GDP by 1.1% and would affect negatively the welfare of its habitants, in particular those with low income. Although this model is not specific to the agricultural sector the results show that it will be adversely affected with an 11% reduction in field crop production; forestry and livestock will suffer a 15% and 10% reduction of their production respectively.

Hertel et al. (2010) present results for Mexico based on simulations using the following yield shocks caused by climate change: -15%, -3%, and 9% for rice, wheat, oilseeds, cotton and other crops; -12%, -5%, and 2% for coarse grains; and no impact for sugar cane. The estimates indicate that the incidence of poverty of self-employed agricultural households in Mexico would have changes of -11%, 0%, and 18%, under low, medium and high yield scenarios, respectively.

Meza-Pale and Yunez-Naude (2015) estimate econometrically the effects of rainfall variability on maize production of rural households, as well as on these households income. They use a representative survey of the Mexican rural economy (ENHRUM for its acronym in Spanish) as well as historical meteorological data.[11] Their results show that rainfall variability would reduce significantly maize production by small farmers in rain-fed plots. However, no evidence is found of significant effects of rainfall variability on farmers' net income. Similarly, Gay et al (2006) use an econometric approach based on a production function model. They find that for 2020 climate change could affect coffee production in Veracruz, potentially leading to farmers' abandonment of this activity.

Mendelsohn et al. (2010) follow the Ricardian approach to analyze the effects that climate change could have on the value of agricultural land in rural Mexico. They estimate that by 2100 climate change could reduce the value of land between 42% and 54%, and that between 30% and 45% of farms could be affected, especially those with no irrigation. Galindo, Reyes and Alatorre (2015b), also use the Ricardian approach and employ annual panel data for the period

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[11] ENHRUM (Encuesta Nacional de Hogares Rurales de México) is representative of the rural population at the national level as well as at the regional level. The five regions of Mexico are: south-southeast, center, west-center, northwest and northeast. For more details about visit http://das-ac.mx/comunidad-enhrum/ .

2003-2009, to calculate the effect that a 2.5 °C increase in temperature along with a 10% reduction in precipitation would have on Mexican agriculture. The results show that a change of this magnitude could have, depending on the year, an impact of -18.6 to -36.4% on net income of the farms. Moreover, classifying municipalities as irrigated, rain fed and mixed, the expected losses are 26-55%, 14-25%, and 27-37% respectively.

Lopez-Feldman (2013) presents the results of what is, to the best of our knowledge, the only household-level analysis of the potential effects that climate change could have on poverty. He uses the ENHRUM data to estimate a Ricardian model of the relationship between precipitation, temperature and agricultural income. The econometric results along with the climate change simulations used by Mendelsohn et al. (2010) provide the basis to simulate impacts on income at the household level. The ENHURM data set allows the estimation of the potential poverty impacts of climate change at the regional level. By doing this the geographic heterogeneity in terms of both climate change predictions and relevance of agricultural income can be captured. The results show that by 2100 climate change could reduce rural net income between 11% and 15%, leading to an increase of almost a quarter million of rural households below the poverty line; of those households almost 50% will be located in the south-southeast region and more than 25% in the center.

Skoufias and Vinha (2013) analyze the impact of weather fluctuations on households' consumption patterns. They analyze the impacts through the agricultural cycle, this is, they analyze if the shocks and households ability to cope with them is the same depending on the timing of the shock and on what part of the agricultural cycle they occurred. The authors find that higher temperatures shocks are the most damaging and households in arid climates are especially sensible when these shocks happen from April to June.

Juarez-Torres and Sánchez-Aragón (2012) provide a first insight of the likely development of hedging strategies to protect against weather variations in Mexico. They analyze the possibility of implementing weather derivatives that would function as an insurance against climatic threats. The area of study is Valle de Santiago that is located in the region of Guanajuato, Mexico. This setting, as many parts of Mexico, has two primary agricultural periods: Spring-Summer (wet season) and Fall-Winter (dry season), but this region is characterized by the irrigation dependence during the dry period. The authors argue that it is possible to spread risks through derivatives based on a rainfall index. In order to perform their analysis, they first consider a baseline scenario that estimates the optimal water allocation between the two seasons and calculate the profits for farmers. They include rainfall climate change scenarios to calculate the new optimal water allocation strategies. Finally, they calculate the compensations for a given shortfall in any weather variable.

Yunez-Naude and Rojas-Castro (2008) use a CGE approach to focus on the effects of water scarcity for irrigated crop production in the five rural regions of Mexico, plus the Rio Bravo basin. Amongst other simulations and impacts, they estimate that a 50% reduction on water availability for irrigation would adversely affect the real income of all Mexican households, both rural and urban, independently if they are poor, middle-income, or rich. However, the results are asymmetric, since the simulated shock affects more the rich households in the rural sector, especially those in the Northern and the Rio Bravo Basin regions. With regards to agricultural production, it is estimated that a 50% reduction in water supply would reduce irrigated crop production by 17.9%, while rain-fed crop production would increase by 2.9%. The authors include a simulation to inquire about the possible impacts of adaptation under the scenario of water scarcity for irrigation. They conclude that, if done by farmers' water associations, investments on water use improvements on irrigated agriculture could reduce the negative impacts of water scarcity.

Hernandez-Solano (2015) proposes a CGEM that has a microeconomic character since it disaggregates rural households according to the size and ownership of plots dedicated to agricultural production and takes into account transaction costs in maize and labor markets. The ENHRUM data is used to build Social Accounting Matrixes (or SAM) for each of the five rural regions of Mexico. The results indicate that the poorest region of Mexico, the south-southeast, would be the most affected by climate change, reducing its households net real income by 8%; followed by the central west and northwest regions (5.5% and 3.9% income reduction respectively), whereas net income of households located in the center and northeast agricultural regions would experience a rise of 5.8% and 1.3% respectively. The results are based on a simulation of climate change shocks for 2050, based on estimated effects of climate change on maize yields that differ between regions.

According to Hernandez-Solano (2015) the effects of climate change on rural households' real income are heterogeneous. On the one hand, in the regions negatively affected by climate change such as the Northwest, it is expected that landowners with plots of more than 5 hectares will be the most affected, with a reduction of 15% of their real income; landowners with less than 2 ha in the South-southeast and those with landholdings between 2 and 5 ha in the Center-west will experience a decrease of 14% of their income. On the other hand, in the Center and Northeast regions, the estimation shows that the households that benefit the least are the non-agricultural producers, with less than 1% increase in their real income. With respect to rural food production, results indicate that climate change could reduce maize production by 6.6%, increase production of the rest of the crops by 1.3%, and reduce livestock production by 1.2%. Finally, climate change would increase rural outmigration to the rest of Mexico and to the US in the regions where maize yields drop and to a decrease in the regions where maize yields rise.

Saldaña-Zorrila and Sandberg (2009) present results of a spatial econometric model that estimates the effects that weather related disasters have on migration. Their results show that a 10% increase in the frequency of disasters increases migration rates by 13% in non-marginalized regions and 5% in marginalized ones. Feng et al. (2013) use state level data to analyze the impact of weather fluctuations on migration from rural Mexico to the United States. They predict that the decrease of agricultural production caused by climate change will considerably increase the number of Mexican migrants to United States; it is estimated that by 2080 climate change will induce an additional 1.4 to 6.7 million adult Mexicans to migrate. Jessoe et al et al. (2014) on the other hand, use a panel data model obtained from ENHRUM to evaluate the effects of temperature and precipitation on households' migration decisions as a consequence of climate change. In their econometric analysis they find that temperature has a statistically significant effect while precipitation does not. Using a medium emissions scenario, the authors find that in 2075 climate change could increase domestic migration by 0.7-1.4%, while the increase in Harmful Degree Days will reduce rural employment by 0.5-1.4% and increase migration to the US by 0.1-0.25%. It is important to emphasize that in these two studies migration is the only adaptation measure that is being explicitly considered and therefore the estimated effects might very well represent upper bounds.

To the best of our knowledge there is no study that has used econometric methods to analyze the determinants behind rural Mexican households' decision to adapt to climate change. Nonetheless, there are some cases studies that use qualitative methods to analyze the adoption of specific adaptation strategies. Conde et al. (2006) analyze the strategies that rain-fed maize producers in three municipalities of the Mexican state of Tlaxcala, in the central region of Mexico, can use in order to cope with weather variability. They gathered information with experts about existing or possible strategies, concluding that some of the most useful strategies could be greenhouse construction, use of organic fertilizers and drip irrigation. Tucker et al (2010) perform a qualitative study in the region of Veracruz, Mexico to analyze coffee farmers' risk perceptions to weather stressors and their way to cope with them. Even though some of these farmers faced several weather shocks in the years previous to the study they did not make land use changes and few of them adopted new crops. The authors argue that even if there are weather shocks, the farmers might incorporate these anomalies as part of a "normal" scenario. As we argue in section V, much more analysis is needed to understand the determinants of adaptation decisions at a household level.

VI.1 Reducing vulnerability and promoting adaptation: Public policies and economic instruments

Although vulnerability to climate change is an elusive concept and we have only begun to understand and measure it, all the evidence suggest that Mexico's population could be negatively affected by climate change in significant ways (Ahmed et al., 2009; Borja-Vega and De la Fuente, 2013; Lopez-Feldman, 2013; Monterroso, et al., 2014a; Skoufias and Vinha, 2013). Furthermore, in spite of the most recent efforts to reduce global emissions it is expected that global average temperature will rise in the coming decades (UNFCC, 2016). It is therefore very likely that rural Mexican households will have to adapt to climate change.

In some instances autonomous adaptation will be enough, nonetheless, adaptation faces behavioral obstacles (e.g., time inconsistent decisions, deferral of choosing between ambiguous choices) as well as many barriers (e.g., transaction costs, externalities, information asymmetries, lack of property rights) that can lead to suboptimal adaptation or even situations where no adaptation is done (Chambwera, et al., 2014). Under these circumstances, government intervention through the design and implementation of policies that can improve adaptation capacity, including by encouraging autonomous adaptation, is paramount to attenuate the effects of climate change. Given the uncertainty, non-linearity and long term horizon of the potential effects of climate change this is no small task. To further complicate things adaptive capacity needs to be promoted in a context of competing development objectives, the reduction of poverty being one of them.

VI.2 Poverty, vulnerability and adapation

The incidence of poverty in Mexican rural households is high. For example, based on the head count measure of Foster, Greer and Thorbecke, in 2013 it was as high as 40% when using household expenditure and the official minimum income line for food access. Poverty incidence rises to 70% when applying the official measure of welfare that includes food and non-food access. These figures rise to 58% and 84% respectively for the indigenous rural population (Yunez et. al (2014).

As in other developing countries Mexican rural households diversify their economic activities. As shown in Table 1, these households' economy depend heavily on agriculture, directly, from their food production (23.5% comes of their net income comes from crop and livestock production), and indirectly through their members’ participation in the agricultural labor market (17.3%). Another important source of households’ income comes from their use of natural resources.

In rural Mexico, poor households tend to be dependent for part of their income on activities that are highly sensible to climatic conditions, like agriculture and natural resources. In fact, natural resources not only provide a very important source of income they also can be a form of insurance for many poor households (Lopez-Feldman, 2014). On the other hand, these households are also very exposed to extreme climate events. According to (Yunez et. al, 2014) in 2013, around 60% of the surveyed households faced severe climate events (i.e., draughts, extreme rainfall and landslides), and 55% suffered from plagues. It is clear that in rural settings poverty is strongly correlated to vulnerability to climate change.

Nonetheless, not every poverty reduction measure will reduce vulnerability to climate change. Shrimp farming, for example, can improve incomes and reduce poverty in the short-run, but if mangroves are lost in the process households might end-up being more vulnerable to extreme weather events associated with climate change. On the other hand, adaptation measures are not guaranteed to contribute to poverty reduction and they might even increase inequality (O’Brien et al., 2007). Thornton & Herrero (2014) provide a list of adaptation policies and their impact on food security, resilience, diversification promotion and risk management; their analysis suggest that the options that have more potential to increase resilience have not the same impact on food security and vice versa. Paavola (2008), reports that some of the measures that rural households in Tanzania have taken to adapt to climate change have reduced environmental quality, which is an important input in other households’ livelihood.

It is clear then that policies aiming to promote and facilitate adaptation to climate change should not be disassociated from those whose objective is poverty reduction, rural development or the conservation of natural resources (Howden et al., 2007). Adaptation to climate change should not be seen as an isolated issue but as part of a development strategy that aspires to be climate resilient (OECD, 2014). The integration of adaptation actions with economic development policies can maximize the synergies between the two to attain the complementarity between development and adaptation (Chambwera, et al., 2014).

VI.3 Autonomous versus planned adaptations

Over time rural households have taken voluntary measures to adapt to changing climatic conditions and continue to do so. Nonetheless, it is very likely that most of the low cost autonomous adaptation measures (e.g., modifying planting dates or changing to a different crop type or variety) that households can undertake will only be effective when facing small temperature increases (Asafu-Adjaye, 2014). Because these voluntary adaptations are not expected to be enough to deal with climate change, the application of planed adaptation measures that include local, regional, national and even international components is necessary (Howden et al., 2007). The measures that could have the largest effects (e.g., expanding irrigation or developing new crop varieties) generally imply elevated costs (Lobell et al., 2008). Efficient adaptation measures will require an interdisciplinary effort in which agronomists, economists, engineers, geographers, ecologists, development specialists and climatologists, among others, need to be involved (McCarl, 2010).

Even though at this time there is not much empirical evidence in relation to the efficiency and success of the different planed adaptation measures, there are some strategies generally considered as worth undertaking. Some of these include: increasing the level of knowledge that farmers have about climate change; improve the education levels and abilities of the rural populations; create and introduce temperature resistant varieties; promote irrigation;[12] generate early alert systems in relation to rain temporality and severity; strengthen formal and informal seed exchange systems; improve physical infrastructure; and, solve issues concerning the lack of access to credit and agricultural insurance (Asafu-Adjaye, 2014; Di Falco et al., 2012; Kabubo-Mariara and Karanja, 2007).

All the previous measures could be seen as traditional adaptation measures but recently a new category of practices based on ecosystems has been promoted (they are known as EbA, Environmental based Adaptation). Two of such measures are the establishment of protected areas and the systems of payment for environmental services (Magrin et al., 2014). The basic idea behind this type of measures is to promote or improve the ability of ecosystems to isolate human communities from the adverse effects of climate change through the provision of environmental services (a typical example of this is the protection that mangrove swamps provide local populations against storms and hurricanes). EbA measures could complement or even substitute the traditional ones. An additional advantage of EbA measures is that they can provide a series of co-benefits (e.g. biodiversity preservation) that are hardly obtained with other measures (Jones et al., 2012).

Irrespective of the nature of the adaptation measures, it is of the upmost importance for the design of effective public policies to understand the factors that can facilitate or impede the timely adoption of adaptation measures by rural households. Although there is not enough research on the determinants of adoption, the evidence shows that incomplete financial markets, limited access to information and limited capacity to process and understand the information available, as well as lack of extension services and technical assistance are some of the main barriers that rural households face when trying to adapt (Asafu-Adjaye, 2014; Di Falco et al., 2012).

According to Monterroso et al. (2015) there is evidence that Mexican farmers have already started to implement autonomous adaptation strategies like modifying planting dates, increasing the number of plants per area and changing varieties, among others. The Special Program on Climate Change (PECC) enumerates the main planned adaptation strategies for the agricultural, fishing, forestry and water sector, as well as for ecosystems, which include generic measures like promoting changes in farming techniques and processes and improvements in irrigation, among others.[13, 14] What is not well known is how effective those measures, both

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[12] In relation to irrigation, it is important not to lose sight of the fact that one of the expected climate change effects is the modification of precipitation patterns. In this sense, it is vital that before promoting large irrigation infrastructure works in a particular region, water availability projections are taken into account. On the other hand, it is possible that the projects that involve more efficient irrigation technologies instead of saving water end up provoking a bouncing effect, with the resulting increase in water use (Ward and Pulido-Velázquez, 2008).

[13] In Appendix I we briefly summarize Mexican laws and policies related to climate change with special reference to adaptation.

[14] See Yunez and Aguilar (2012), Annex 11. Monterroso et. al., (2014b) present a summary of the adaptation programs that have been proposed or implemented in Mexico at the state level. Meanwhile, Lopez-Feldman (2015)

autonomous and planned, are and what kind of barriers farmers face when trying to adopt them. Furthermore, the effective and efficient implementation of the PECC strategies requires coordination between the federal government ministries involved (e.g. between the ministry of agriculture and the ministry of natural resources for irrigation projects), and between the three levels of government. These conditions have not been properly addressed yet and they require, among other things, the elimination of the traditional separation between environmental, productive and social policies (Yunez and Aguilar, 2012).

VI.4 Economic instruments

Economic instruments provide incentives than can influence actions that are consistent with a policy objective (e.g., emission taxes to reduce emissions). Nevertheless, although economic instruments have the potential to be valuable tools in the promotion of adaptation, its use in this context has been very limited and has basically focused on insurance mechanism (Chambwera, et al., 2014, Garrido et.al. 2011). Index based insurance has been mentioned as an attractive alternative that, although suffering from basis risk (variability between the value of losses as measured by the index and the value of losses experienced on the farm), can provide a safety net in developing countries, Collier et al, 2009). The implementation of this mechanism is not without problems among other things due to lack of market infrastructure and scarcity of weather stations that can measure precisely the weather conditions that farmers are subject to (Mushoff et al. (2011).

To the best of our knowledge few economic instruments whose main objective is to promote the adaptation to climate change are currently in practice in Mexico. Even insurance, one of the common instruments to protect farmers' income from unexpected climate events is extreme low; for example, in 2012 just 3.1% and in 2014 only 3.6% of Mexican units of agricultural production had insurance.[15] The source of these figures does not specify the portion of insurance aimed to promote adaptation of Mexican farmers, but we suspect that if any, its coverage is minimal.

VII. Final considerations and research needs

The evidence available shows that Mexican rural households are vulnerable to climate change. Although results described in this paper suggest that vulnerability can vary across regions as well as across households inside the same community more research is still needed in order to better understand the determinants of vulnerability. An aspect that has not been sufficiently studied is the link between adaptation capacity and vulnerability. Micro-CGEMs that explicitly include adaptation are one path to fill that void. Equally important is the need to better understand the determinants of adaptation to climate change at the household and individual level. This requires the use of household (individual) level datasets that provide detailed information not only on the livelihood strategies that households (individuals) follow but also on how they respond or could respond to weather related events. Data on how individuals perceive weather related information as well as climate change information is also key to better understand household adaptation

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presents a brief description of some of the main policies that have been implemented in Latin America to promote adaptation in the agricultural sector.

[15] INEGI, http://www.inegi.org.mx/est/contenidos/Proyectos/encuestas/agropecuarias/ena/Ena2014/.

decisions. Creating such datasets is neither easy nor cheap but they are a crucial input to perform the vulnerability and adaptation research that is needed in order to design and implement effective public policies.

Most climate models predict that the worst negative effects of climate change will start to unfold decades from today. Nevertheless, considering the uncertainty about climate change predictions the implementation of public policies that can promote Mexican rural households’ adaptation needs to start as soon as possible in order to avoid potentially catastrophic outcomes.

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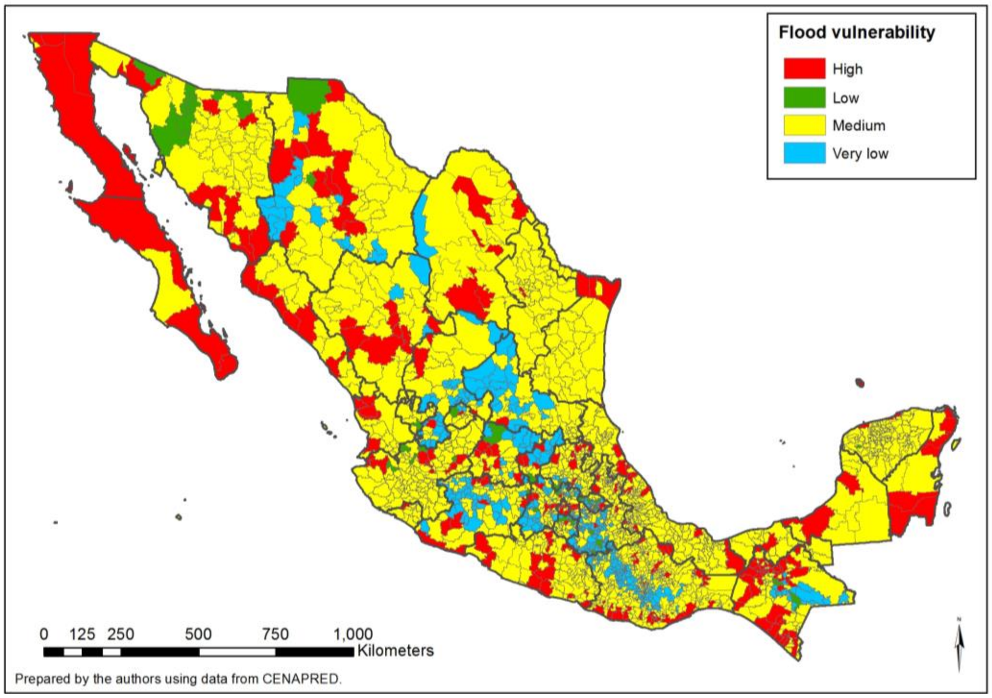
Figure 1a



Vulnerability to floods

Figure 1b
Vulnerability to droughts

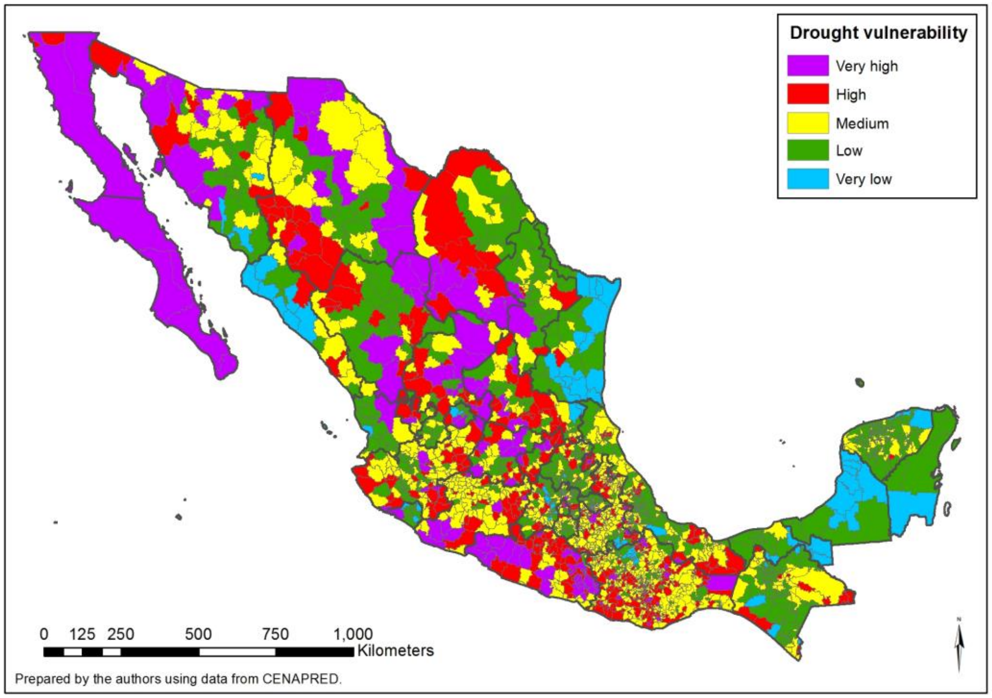


Figure 1c
Social vulnerability

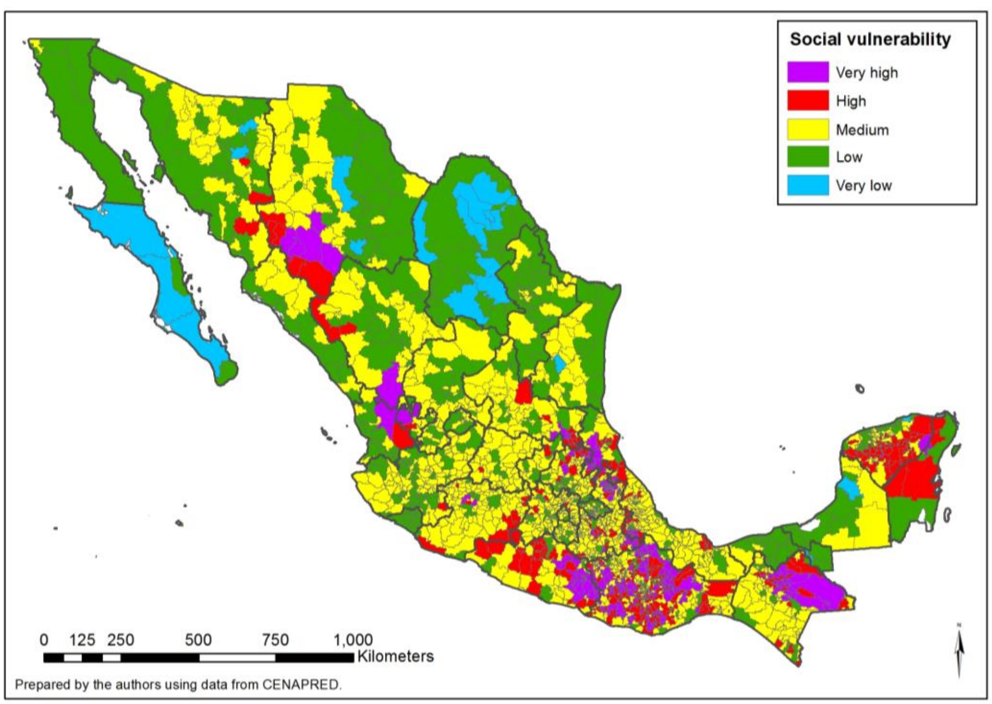


Figure 2
Adaptation

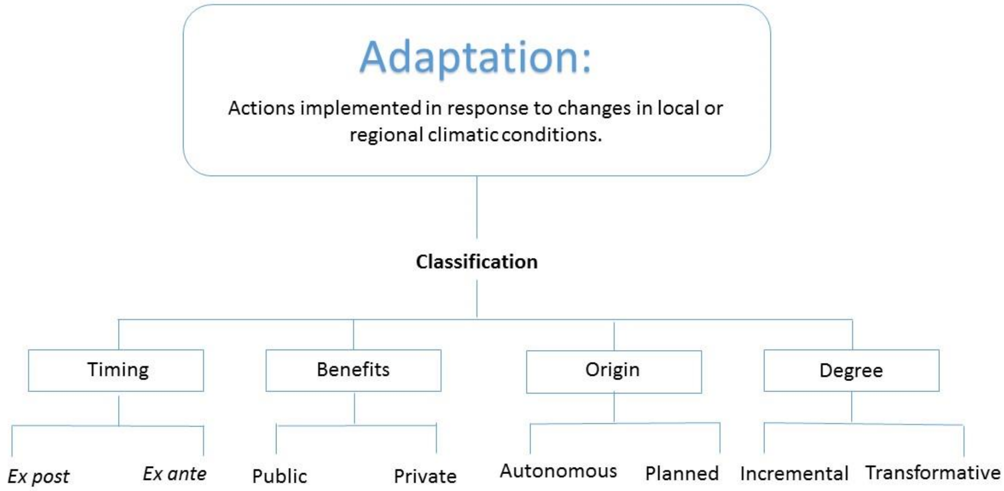


Table 1. Rural Households' Net Income by Source (2013)

Source	Average (pesos)	Weight (%)
Agricultural Plots (1)	458.17	0.9
Field Crops	8,484.69	17.0
Livestock and Processing	3,220.66	6.5
Other Goods and Services	4,453.57	8.9
Natural Resources	2,102.48	4.2
Govenment Transfers	5,300.07	10.6
Other Transfers	755.10	1.5
Remittances from USA	1,511.53	3.0
Remittances from the Rest of Mexico	1,192.36	2.4
Salaries within the Rural Sector	8,629.54	17.3
Urban Salaries	13,663.07	27.5
Total Net Income	49,771.23	100.0

* Includes land sales, rented land and lands under sharecropping

Source: Own estimations based on the National Rural Household Survey (ENCHOR, Spanish acronym), http://www.coneval.org.mx

Appendix I

Mexico: Laws and actions related to climate change and adaptation policies

In 2012 Mexico enacted the General Law on Climate Change (*Ley General de Cambio Climático)*; it was one of the first countries to enact a climate change law. In accordance to this law, the Mexican State created the National Institute of Ecology and Climate Change (INECC), whose mandate includes coordinating and implementing research projects on "climate change, environmental protection and preservation and restoration of ecological equilibrium" in collaboration with academic, public, and private research institutions, domestic as well as foreign. It also includes a commitment to human resource development in the areas of environment and climate change, and to recommending policies and actions for mitigation and adaptation to climate change.[16]

In Mexico, policies related to climate change are based on the above mentioned General Law, on the National Strategy on Climate Change (ENCC) and on the Special Program on Climate Change (PECC). With respect to adaptation, the objectives of the General Law are to reduce the vulnerability of ecosystems caused by climate change and to enhance resilience and resistance of natural and human systems (D.O.F., 2012)

The ENCC has three components: 1) to reduce vulnerability and promote resilience of the social sector with respect to the impacts of climate change; 2) to reduce vulnerability and promote resilience of the strategic infrastructure and productive systems; and 3) to preserve and use in a sustainable manner the ecosystems and maintain the environmental services it provides (INECC, 2013).

The ENCC has twelve objectives and/or criteria for selecting the most convenient adaptation policies. They include: the attention to the most vulnerable populations; the design of policies, programs and projects with a transversal character; to promote prevention and to enhance the sustainable use of natural resources; to foment ecosystem and biodiversity conservation; to promote the active participation and training of the potential beneficiaries; to use effectively and efficiently public budget; to coordinate actions of actors and the public sector; and to monitor and evaluate of the effectiveness of adaptation policies.

Finally and in accordance with the ENCC, the PECC has two general objectives: one is related to vulnerability, resilience and adaptation measures, and the other to the preservation and sustainable use of ecosystems. With respect to adaptation and to the first objective, the Program concentrates the actions of the federal government for an integrated territorial risk management scheme; for attending health risks of the population; for the maintenance and construction of strategic infrastructure; and for reducing the vulnerability of industry and services sectors. As for the second objective, the PECC aim is to preserve, restore and manage in a sustainable manner the ecosystems in other to guarantee its environment services to mitigate and adapt to climate change. In addition the PECC seeks to enhance the local management of the ecosystems and to reduce local current pressures to them; as well as to take advantage of forestry, agriculture and other soil uses to reduce CO_2 emissions) and to increase carbon sequestration).

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[16] INECC http://www.inecc.gob.mx. Most of the text in this appendix is taken from this INECC's website.

In addition, the federal government of Mexico has adhered to the Nairobi Working Plan, to the Kioto Adaptation Fund, to the Cancun Adaptation Framework or CAF and more recently to the Paris Agreement.[17]

[17] A discussion of climate change policies related to the rural and agricultural sector of Mexico is in Yunez Naude, and. P. Aguilar (2012).