Inter-American Development Bank

Office of Strategic Planning and Development Effectiveness

TECHNICAL NOTE

No. IDB-TN-652

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May, 2014

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2014

Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library

McCarthy, Nancy.
Climate-smart agriculture in Latin America: drawing on research to incorporate technologies to adapt to climate change / Nancy McCarthy.
p. cm. — (IDB Technical Note ; 652)
Includes bibliographic references.
1. Climate change mitigation—Latin America. 2. Agricultural conservation—Latin America. I. Inter-American Development Bank. Strategy Development Division. II. Title. III. Series.
IDB-TN-652

http://www.iadb.org

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Climate-Smart Agriculture in Latin America: Drawing on Research to Incorporate Technologies to Adapt to Climate Change

Nancy McCarthy[1]

Abstract: Climate change could have serious effects on agricultural production worldwide, and particularly in Latin America. It threatens to increase the incidence of drought in some regions and flooding in others, while increasing climate volatility and thus exacerbating variance in yields in all regions. A number of technologies and agronomic techniques have been developed to reduce the effects of climate change by keeping yields high and stable. This paper outlines four of these key climate-smart agriculture techniques: conservation agriculture (tillage, cover crops, and rotation), irrigation, agroforestry, and soil conservation structures. The paper examines the results of current research on the effects of these techniques, their gaps and limitations, and the extent to which they have been adopted in Latin America. The analysis then serves as the basis for recommendations on how to better design projects promoting climate-smart agriculture and assess their future impact on Latin American farmers.

Key words: climate smart agriculture, climate change, agriculture, development effectiveness, impact evaluation

JEL Classification: H43, Q15, Q54, Q55

Resumen: El cambio climático podría tener efectos graves en la producción agrícola en todo el mundo, y particularmente en América Latina. Este amenaza con aumentar la incidencia de la sequía en algunas regiones e inundaciones en otras, al mismo tiempo que aumenta la volatilidad del clima, exacerbando así la variación en rendimientos en todas las regiones. Una serie de tecnologías y técnicas agronómicas se han desarrollado para reducir los efectos del cambio climático para mantener rendimientos altos y estables. El presente documento esboza cuatro de estas técnicas claves: la agricultura de conservación (siembra directa, cultivos cubierta y rotación), el riego, la agroforestería y las estructuras de conservación de suelos. El documento cubre los últimos estudios en estas cuatro técnicas y se enfoca en analizar sus efectos, sus vacíos, limitaciones, y el grado en que se han adoptado en América Latina. El análisis a continuación, sirve de base para recomendar cómo mejorar los diseños de los proyectos que promueven la agricultura resistente al estrés climático y evaluar su futuro impacto en los agricultores de América Latina.

Palabras clave: agricultura resistente al estrés climático, cambio climático, agricultura, efectividad en el desarrollo, evaluación de impacto

Clasificación JEL: H43, Q15, Q54, Q55

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1. Climate Change and Agricultural Households in Latin America and the Caribbean

Global average surface temperatures have increased by 0.74°C over the past 100 years, with the biggest increase of 0.55°C occurring over only the past 30 years (Mertz 2009). Temperatures worldwide are projected to increase by an additional 1.5–5.8°C by the end of the 21st century (Rosenzweig et al. 2001). Climate change is expected to have a range of consequences on agriculture, chief among them yield declines and higher yield variability. This is a huge challenge considering that the global population is expected to increase to 9.1 billion by 2050, meaning that global agriculture will need to feed some 2 billion additional people (UNFPA 2011; Bruinsma 2009). It is estimated that the number of people at risk of hunger will increase by 40 million by 2020 and then by another 24 million by 2050 and a further 55 million by 2080 (Parry et al. 1999). Currently, 75 percent of the 925 million food-insecure individuals in the world live in rural areas and earn incomes either directly or indirectly from agriculture (FAO 2010). Within Latin American and the Caribbean (LAC), the Central American countries, Brazil, and the Andean region alone account for 7 percent of the world's malnourished population (Lobell et al. 2008). Thus, efforts to ensure food security in the face of climate change must focus on the livelihoods of these developing-country farmers by improving the resiliency of their farming systems and their capacity to adopt technologies that are adapted to the effects of climate change and can help mitigate it where possible (Parry et al. 1999).

1.1. Expected Climate Changes in Latin America and the Caribbean

The Intergovernmental Panel on Climate Change forecast an increase in temperatures in LAC of 0.4–1.8°C by 2020 (IPCC 2007), while four different models cited by Schimmelpfennig et al. (1996) predicted temperature increases by 2100 in LAC of 2.6–4.7°C. Perhaps of even greater concern than the projected average temperature increases is the fact that climate change is also expected to increase inter-annual and seasonal climate variability, making it difficult to make agricultural management decisions (IPCC 2007; Rosenzweig and Tubiello 2007).

Within LAC, climate change is expected to have different effects in different geographic areas. For example, higher temperatures have already caused a significant retreat of Andean glaciers over the past three decades, which is expected to cause critical water shortages in the near future in downstream areas of Bolivia, Ecuador, Colombia, Peru, and Chile, where many rural communities obtain up to 80 percent of their water from snow melt. The Andean region is also exposed to greater flooding as a result of this same phenomenon (Coudrain et al. 2005). By changing the oscillation of weather circulation patterns in the tropical Pacific, like the El Niño Southern Oscillation (ENSO), climate change is expected to increase weather variability, with dry areas becoming even drier and rainfall levels increasing where rainfall is already high (Salinger et al. 2000; Baez and Mason 2008; Candel 2007). Steady precipitation increases have already been observed in parts of southeastern Brazil, Argentina, Uruguay, Paraguay and Brazil

(Schimmelpfennig et al. 1996) and are likely to increase in much of the Amazon forest region (IPCC 2007). On the other hand, steady declines in precipitation have been observed in areas of southern Chile, Peru, northeast Brazil, and most of Central America (IPCC 2007).

The incidence and severity of extreme weather events are also projected to increase. Central America and the Caribbean are particularly vulnerable to increased weather extremes because of their already-high exposure level to hurricanes (Mirza 2003; Baez and Mason 2008). This can have a huge effect the economy. In 1998 in Honduras, for example, a single storm, Hurricane Mitch, caused losses of $5 billion, or 38 percent of that country's capital stock (Mirza 2003).

1.2. Expected Effects of Climate Change on Agriculture in Latin America and the Caribbean

Temperature increases stimulate respiration, which can increase growth, but this positive effect on yields is often offset by an increased prevalence of diseases, as pathogens are able to survive warmer winters, and because of lower water availability due to higher temperatures (Rosenzweig et al. 2001; Baez and Mazon 2008). This presents a huge problem for crops that are already being grown close to the high temperature tolerance threshold. Yield declines have already been observed in several areas where this is the case, including Sonora, Mexico (maize yields) and coastal areas of Peru (mango and cotton yields) (IPCC 2007).

Much of the research on crop yield effects is based on programming models that incorporate information on different climate change scenarios into the model in order to predict likely changes in yields stemming from climate change. Climate variables generally include data on rainfall and solar radiation, in addition to temperature. Adams et al. (1998) reviewed a number of studies that attempted to project yield decreases in major field crops in South and North America as a result of climate change through 2020. They reported projected maize yield declines of from 4 to 36 percent in Argentina, 2 to 25 percent in Brazil, and 6 to 61 percent in Mexico. The estimates for wheat had more interesting geographic variation, with an estimated decline of 30 percent in Uruguay and 15 to 50 percent in Brazil, but a projected yield increase in Argentina of 3 to 48 percent due to warmer temperatures. Jones and Thornton (2003) also used modeling to project an average yield decline of 10 percent for maize by 2055, but with dramatic variation across geographic areas. That study projected the largest yield declines in Venezuela, Uruguay, Belize, Guyana, and Brazil, but found that the yield of maize should actually increase in Chile and Panama by 2055.

Wheat is one the crops that has been the subject of most of the long-term research in Latin America. A long-term study of wheat in Yaqui Valley, Mexico (Ortiz et al. 2008) has shown that in some years, particularly 1991, wheat yields were very low because of high minimum temperatures, high rainfall, and low solar radiation levels caused by a severe ENSO event. This study provides good data for projections of the effect of climate change on wheat yields in Mexico, and gives an idea of the strategies that would help to minimize the effects of climate variation. These strategies include growing varieties that can tolerate warmer temperatures, incorporating agroforestry to reduce temperatures, and shifting cultivation to other regions. Unfortunately, this type of detailed long-term data is currently lacking for many other crops and regions in Latin America.

The effects of climate change are expected to vary by crop. Models estimated by Lobell et al. (2008) showed that yields of potato, maize, barley, rice, and wheat in the Andean region, and of rice and wheat production in Central America and the Caribbean, will decline significantly, but that yields of cassava, sugarcane, soybeans, and palm in the Andes and of maize, cassava, and sugarcane in Central America will increase. Detailed data are lacking on many crop-region combinations. These gaps will need to be filled in the near future in order to enhance adaptation efforts, in particular.

Mean estimates aggregated by country also hide important variation across different groups of people. Smallholder farmers in developing countries are most at risk to the negative effects of climate change (Eakin 2005; Morton 2007; Smit and Pilifosova 2003; Hertel et al. 2010). Vulnerability to the effects of climate change, and thus food insecurity, is highest for groups that cultivate the most marginalized land, those with the lowest level of assets (and thus resources for adaptation), those with low access to technology and training, and those with low market power who are already vulnerable to input and output price volatility (Smit and Pilifosova 2003; Mertz et al. 2009).

1.3. Climate Change Adaptation and Mitigation Strategies for Agriculture

Throughout history farmers have had to deal with climate variability using various coping strategies. As noted by Rosenzweig and Tubiello (2007), adaptation can be considered the "norm rather than the exception in agriculture." However, the adaptation process is not instantaneous and even now often entails huge losses in the interim (Smit and Pilifosova 2003). This section examines existing autonomous adaptation strategies as well as those that can be promoted and encouraged by outside initiatives in the future. The same strategies that allow individuals to adapt to the effects of climate change in many cases also help to mitigate the causes of climate change by promoting carbon sequestration and decreasing emissions, so it is doubly in the interest of public institutions to support farmers in implementing these strategies (Delgado et al. 2011).

Cooper et al. (2008) classify strategies for adapting to climate variability into three categories: ex-ante risk management options, in-season adjustment of management options in response to specific climate shocks, and ex-post risk management options that minimize the effects of adverse climate shocks to one's livelihood. Ex-ante strategies include the choice of risk-tolerant varieties, crop diversification, investment in irrigation and other water management techniques, the use of terraces, cover-crops and other techniques to reduce erosion, and off-farm employment. This category of strategies could also include data gathering to develop new calendars for planting and harvesting in response to a shifting hydraulic cycle (Valdivia et al. 2010; Delgado et al. 2011). In-season options include adjusting labor for weeding and other inputs to yield expectations and replanting failed plants with early-maturing varieties. One extreme version of in-season adaptation, known as "response farming," entails altering crop patterns in response to seasonal fluctuations in weather predicted by climate models. Though this type of adaptation is under study in some areas, its potential is limited because it requires a great deal of data and knowledge about the relevant farming system (Blench and Marriage 1998; Van Viet 2001; Lemos et al. 2002). Ex-post options include grazing animals on failed fields, distress sales of assets, borrowing, increasing off-farm employment, and cutting expenditures.

Crop diversification—which can include rotating crops, growing different varieties of the same crop, intercropping different species together in the same plots, and employing agroforestry methods—can help suppress pests and diseases and mitigate the risks from agronomic or market failure of any single crop (Zhu et al. 2000; Krupinsky et al. 2002; Tengö and Belfrage 2004; Lin 2011). Shade for agroforestry systems acts as a buffering mechanism to temperature variation and storm events (Lin 2007; Philpott et al. 2008; Lin 2011). In LAC, a great deal of staple crop production—more than 40 percent of cassava, 60 percent of maize, and 80 percent of beans—is already grown in polycultures as a risk-reduction measure (Altieri 1999). Other adaptive measures include early planting, switching to cultivars that mature more rapidly, and adopting cultivars with reduced vernalization requirements (Rosenzweig and Tubiello 2007).

Less intensively managed and more diverse farms were found to suffer lower losses from natural disasters like Hurricane Mitch in Nicaragua and mud slides in Mexico (Holt-Gimenez 2002; Philpott et al. 2008). In a survey of 2,000 farmers in seven South American countries, Seo (2010) found that 42 percent of farmers operated mixed systems of both livestock and crops to mitigate risks, and that farmers in hotter climates with less rainfall were also more likely to have mixed systems. Economic analysis showed that in response to climate change predictions, land values should fall for all three systems, but only by 10 percent for the mixed system compared to 20 percent for a system with crops only (Seo 2010).

However, it is far easier for farmers to adapt to a smooth change in temperature and precipitation levels than to adapt to an increase in variability, which is predicted under a number of climate change models (IPCC 2001). At present there is a dearth of research on strategies to address climate and yield variation, particularly in LAC. The research that does exist, primarily in North America and Europe, suggests that practices that can decrease the yield variability coefficient in the face of climatic variability include fallowing, crop rotation, integrated pest management, introduction of irrigation, and various soil and water conservation investments and practices (Rounsevell et al. 1999; Salinger et al. 2000 and 2005; Rosenzweig and Tubiello 2007).

Climate change adaptation and mitigation are intimately related not only to one another, but also to soil and water conservation practices. Climate change is expected to increase potential erosion rates by 10–20 percent in extreme cases, as flooding increases run-off and as farmers move onto marginal land with steep slopes because temperature fluctuations make lower-altitude land unusable (Mendelsohn and Dinar 1999; Delgado et al. 2011). Changing rainfall patterns and increased drought mean that water conservation is ever more important, while increasing soil fertility via conservation methods is critical to maintaining yields in the face of climatic variation. Conservation methods are also crucial for mitigation of climate change, since they help to decrease the level of chemical inputs like fertilizer, which generate high greenhouse gas emissions during manufacture and transport (Delgado et al. 2011).

In terms of climate change mitigation, agriculture can contribute to reducing greenhouse gas emissions through three main pathways:

(1) Engaging in on-farm practices that sequester carbon, such as the use of cover crops, and investing in soil and water conservation structures;
(2) Engaging in practices that reduce on-farm greenhouse gas emissions, such as reducing fuel use associated with zero tillage and reducing inorganic fertilizer use through precision application; and
(3) Reducing incentives to expand agriculture into currently existing forests.

The remainder of this paper focuses mainly on the first pathway. There is more extensive evidence on the second pathway, which is largely associated with large-scale commercial farming and far less relevant for most smallholders. The third pathway is important in LAC. Forest degradation and deforestation is most severe in the Andean region of South America, Mexico, and Central America, where one-quarter of the vegetated land is degraded (Redclift 1989; Pichón and Uquillas 1997). The rate of deforestation in South America remained high at about .43 percent per year over 2000–2010, and Central America currently has the highest deforestation rates in the world, at 1.2 percent annually over the same time period (FAO 2010). Nonetheless, this pathway has also been extensively covered, primarily in literature looking at deforestation rates more broadly (Gloor et al. 2012; Angelsen 2010; Angelsen and Kaimowitz 1999).

1.4. Extent to which Climate-Smart Adaptation and Mitigation Strategies Have Been Adopted

This paper focuses on four specific climate-smart agriculture practices that have dual benefits, and that contribute both to adaptation and mitigation of climate change: conservation agriculture, small-scale irrigation, agroforestry, and soil conservation structures.

Conservation agriculture has been defined by the United Nations Food and Agriculture Organization (FAO) as being comprised of three components: minimum soil disturbance, permanent soil cover, and crop rotation. Unfortunately, not all studies on conservation agriculture use the same definition, and many studies provide evidence on the adoption of only one of the three components. Bearing that in mind, the evidence still suggests that there has been a rapid expansion of conservation agriculture worldwide in the past decade, with area under reduced or no tilling expanding from 45 million hectares in 1999 to 105 million hectares in 2008 (Derpsch and Friedrich 2009). LAC is actually the region in the world with the highest level of adoption of conservation agriculture, with 49,586,900 hectares or 47 percent of the world's total area under no-tillage. In 2007–2008, there were 25.5 million hectares under zero tillage in Brazil alone (38 percent of cropped area), 19.7 million hectares in Argentina (59 percent), and 2.4 million hectares in Paraguay (54 percent). A number of other LAC countries also used conservation agriculture that accounted for 0.1–47 percent of cropped area (Garcia-Prechac et al. 2004; Kassam et al. 2009).

The vast majority of conservation agriculture in LAC, and in the world as a whole, takes place on relatively large commercial farms using heavy equipment. This is primarily because conservation agriculture reduces fuel requirements in these systems, and such farmers have the capacity to finance the use of herbicides (McCarthy et al. 2011; Wall 2007). Many smallholders do not use fuel-based mechanization and so do not save fuel costs, and also cannot afford the higher costs of weeding. However, there are a few exceptions, including 200,000 hectares of land farmed by smallholders in Brazil and 480,000 hectares in Paraguay. The smallholders in Paraguay are encouraged by government grants for no-till equipment provided to small farmers (Sorrenson et al. 1998; Wall 2007; Kassam et al. 2009). Conservation agriculture is currently mostly limited to a few field crops, primarily soybeans, maize, wheat, sunflower, canola, cassava, potatoes, and leguminous cover crops (Kassam et al. 2009).

Irrigation is another technology that can have a huge impact on insulating farmers from climate shocks, but which also tends to be used more by larger farmers and on an industrial scale. The adoption of irrigation also varies dramatically by geographic area, depending on the availability of water and the farming system. There were 263 million hectares of land irrigated worldwide in 1996, of which 17 million hectares were located in LAC (Howell 2001). Irrigated land accounted for 11 percent of cropped area in the region, though the level of irrigation differed by crop: 11 percent of wheat area, 44 percent of rice, 10 percent of maize, 19 percent of barley, 16 percent of sorghum, 35 percent of sorghum, and 24 percent of cotton (Ringler et al. 2000). Agricultural land under irrigation increased by 72 percent worldwide between 1961 and 1997, with Central America and the Caribbean experiencing an 80 percent increase (Lin et al. 2008).

The portion of agriculture under irrigation also varies dramatically by country in LAC. For example, in 2010 Argentina had 1.55 million hectares under irrigation (4.7 percent of arable and permanent crop area), Brazil had 4.45 million hectares (6.8 percent), Chile had 1.1 million hectares (140 percent, because Chilean farmers irrigate during multiple seasons), Mexico had 6.3 million hectares (23 percent), and Peru had 1.2 million hectares (27 percent).[2] National

[2] See the International Commission on Irrigation and Drainage database at http://www.icid.org/imp_data.pdf (accessed 6 August 2013).

differences are shaped largely by water availability and irrigation infrastructure. For example, as of 2000 there were 532 dams in LAC built specifically for the purpose of irrigation, but 387 were located in Mexico, 48 in Brazil, and 46 in Chile (Ringler et al. 2000).

LAC as a whole has fairly abundant water resources, accounting for 30.8 percent of global available fresh water in a region with only 8.6 percent of the world's population. But this resource is very unequally distributed across the region, with over 50 percent of the total found in the Amazon watershed alone (Ringler et al. 2000). In fact, 60 percent of the population of LAC is concentrated on only 20 percent of the land, with only 5 percent of the region's available water. The countries with the most limited water resources are Barbados, the Dominican Republic, Haiti, and Peru. On the other hand, Belize, Guyana, Nicaragua, Panama, and Suriname have abundant water resources, and water available per capita is also fairly high in Brazil (Ringler et al. 2000).

With respect to agroforestry, three separate studies have estimated that approximately 1 billion hectares of land are under agroforestry worldwide is (Dixon 1995; Ramachandran Nair et al. 2009; Zomer et al. 2009). Specifically in the LAC region, agroforestry covers between 200 million and 357 million hectares, depending on the definition (a minimum of 10 percent or 30 percent tree cover) (Somarriba et al. 2012). That breaks down to between 14 million and 26 million hectares in Central America and the Caribbean and between 88 million and 315 million hectares in South America. The most common type of agroforestry throughout LAC is intercropping with shade trees and commercial crops, particularly coffee and cocoa, though silvopastoral systems and biodiversity-based sustainable forestry projects have also been more widely promoted in LAC than in any other region in the world (Vandermeer and Perfecto 2005).

Less information is available on soil and water conservation structures at more aggregate levels. This is partly because this is a rather broad category that includes a number of different practices, including crop rotation and cover crops, which are also considered part of the conservation agriculture package. Several studies based on satellite imagery estimate that there are approximately 1 million hectares of terraced land in Peru, but much of it (61 percent in one area) has been abandoned (Denevan and Hartwig 1986; Masson 1984). Similarly, Wright et al. (2000) found that 80 percent of terraced land in northern Chile was abandoned. In both the Peruvian and Chilean cases this was linked to lower availability of water, since terraces traditionally were combined with irrigation (Guillet et al. 1987). Nonetheless, such structures are particularly important in hilly areas, which are abundant in LAC.

1.5. Organization of the Paper

The sections that follow discuss the four specific climate-smart agriculture practices, followed by a section on payment for environmental services contracts and weather insurance contracts. Each section first briefly describes each practice or contract, reviews the current evidence on benefits to adoption, then examines factors that affect adoption levels. Each section ends with a discussion on the implications of the current evidence for impact evaluations of future projects. The evidence base is very large for some practices and quite limited for others. The final section provides concluding comments.

2. Conservation Agriculture

As described above, conservation agriculture is a system of farming that employs a minimum of techniques that disturb the soil for planting; maintains permanent soil cover via crop residues, mulches, or cover crops; and employs crop rotation (FAO, 2010; Giller et al. 2009; Stagnari et al. 2010). This system has several goals, including preventing soil erosion, maintaining soil structure, increasing organic matter content, and improving water infiltration and retention, all of which have the potential to increase long-term yields and reduce yield variability even in the face of climate change (Bot and Benites 2001). Some studies have shown that conservation agriculture increases the amount of carbon stored in soils, thus it may have some mitigation potential (La Scala et al. 2006; Stagnari et al. 2010). However, more recent studies have shown this potential to be fairly low under most agro-ecological circumstances (Govaerts et al. 2009).

While the potential agronomic benefits from the adoption of conservation agriculture are well established, its overall profitability will also be a function of the costs of adoption. On the one hand, on large-scale, fuel-dependent mechanized farms, it enables farmers to no longer pay the fuel and labor costs for multiple tractor passes to prepare and sow the land. On the other hand, conservation agriculture often involves higher upfront expenses in the form of specialized equipment for sowing, as well as increased expenditures on herbicides or labor for hand-weeding, particularly in the short to medium term (Wall 2007; Giller et al. 2009). Although the adoption levels of conservation agriculture in LAC are fairly high, they tend to be concentrated among wealthier farmers and industrial operations, though in some regions efforts have been made to better target smallholder farmers as well (Sorrenson 1998; Wall 2007; Kassam et al. 2009). The remainder of this section covers empirical evidence on the estimated benefits of conservation agriculture in different regions of LAC, the main factors affecting its adoption, and recommendations for how to better assess the impact of future conservation agriculture projects in LAC, particularly among smallholders.

2.1. Effects of Conservation Agriculture on Crop Yields, Yield Variability, and Greenhouse Gas Emissions

There are many empirical studies on the effects of conservation agriculture, both on soil properties and yields, in different LAC countries, though the vast majority of peer-reviewed literature focuses on tillage rather than the other two components of conservation agriculture. Another point that should be made early on is that the effects of conservation agriculture have generally been found to differ based on the type of soil, with a positive effect only expected on fine-texture soils because of increased risk of compaction and nutrient-leaching on coarse-textured soils (Giller et al. 2009). A study of conservation agriculture on several soil types throughout Brazil (Zinn et al. 2005) did find that in coarse-textured soils, no-till led to a reduction in soil organic carbon over time compared with conventional tillage. But in fine-textured soils, like oxisols, this was not the case. For the literature reviewed below, the soil texture is not reported in each case (though the researchers invariably do report this), but note that when there is a positive effect of conservation agriculture the soil is mostly of a finer texture.

Alegre et al. (1991) reviewed the studies on conservation agriculture in LAC that had been conducted through 1990 and found that most rigorous studies took place in Brazil. The estimated effects of conservation agriculture varied by region and type of soil, but fairly consistent yield increases were found for no-till systems compared with conventional tillage. For example, Derpsch et al. (1986) found 19 percent higher wheat yields and 34 percent higher soybean yields under no-till in a seven-year experiment in Parana, Brazil, largely because water retention was consistently higher under no-till. A number of other studies in Brazil found that no-till was the most effective system for promoting infiltration and reducing soil erosion (Mondardo et al. 1979; Sidiras et al. 1982; Roth et al. 1986). Eltz et al. (1989) found that no-till increased aggregate stability and nutrient availability in the upper layer of the soil, leading to a 22 percent increase in grain yields.

Alegre (1991) also reviewed three different studies that examined the effects of tillage on a sandy loam soil in Gualba Rio Grande do Sul, Brazil. Two of these studies found that soil loss was significantly lower for no-till compared to conventional systems (Machado 1976; Levien et al. 1990). However, Bertol et al. (1989) found no significant difference in soil erosion between tillage methods, but instead found that the key component was maintaining ground cover. Machado (1976) also found that bulk density of soil under no-till was 11.5 percent lower and that soil organic matter was 127 percent higher. In a 12-year study in southern Brazil, DeMaria et al. (1999) found that no-till led to higher levels of phosphorus, potassium, and soil organic matter, but to lower levels of magnesium, than conventional tillage. The study also found that crop rotation helped soils retain soil organic matter, but that none of these changes in soil properties led to different yields.

Garcia-Prechac et al. (2004) looked at the effects of no-till and crop-pasture rotation systems versus conventional tillage in Uruguay. The results showed that soil erosion was six times lower under no-till and three times lower under crop-pasture rotation when compared to conventional tillage. Soil organic matter accumulation was also higher under no-till when crop residues were left on the soil, and even higher under the crop-pasture rotation systems. By contrast, a study in eastern Paraguay and the adjacent areas of Brazil found that in the first years after a transition from conventional tillage to no-till, soil organic matter levels declined (from 1.59 to 1.45 percent), though they increased again after 10 years under no-till (to 1.9 percent) (Riezebos and Loerts, 1998). Franchini et al. (2012) presented the results of a 23-year study of tillage and crop rotation in a wheat-soybean system in southern Brazil. They found that, with few exceptions, no-till showed higher soybean yields than conventional tillage from the seventh year of the experiment onward (with the yield advantage of no-till increasing steadily over time), especially under crop rotation and in growing seasons with lower water availability. The yields of wheat and maize were not influenced by the tillage systems, but wheat yields were increased by crop rotation.

A few studies have focused on the effects of crop rotation or cover without also looking at tillage. For example, Calonego and Roselom (2010) specifically examined the effect of crop rotation on soybean cropping in Brazil compared to traditional crop succession with chiseling. Results showed that in the first year yields were higher with chiseling, but that rotation with pearl millet and triticale, because of their aggressive root systems, increased root penetration and yields in subsequent years even without chiseling. Scopel et al. (2004) provide a review of the potential and observed advantages of direct-seed mulched systems throughout LAC, including a chart of the different benefits provided by the most useful cover crop species. However, that study does not statistically estimate the effect of direct-seed mulched systems on soil properties and crop yield.

After Brazil, perhaps the second largest body of research on conservation agriculture in LAC has been conducted in Mexico. Long-term research by the International Maize and Wheat Improvement Center (CIMMYT) in El Batan, Mexico showed that over a 10-year period (1996–2006) grain yields for both wheat and maize were consistently higher and more stable when grown under the full conservation agriculture recommended practices when compared to conventional tillage systems (Govaerts et al. 2005; Erenstein et al. 2012). According to Govaerts et al. (2005), average maize yield over 1991–2004 was 48 percent higher and that of wheat was 27 percent higher in the no-till crop rotation system with (full or partial) residue retention compared to the plots with conventional till, continuous cropping, and no residue retention. However, these yield benefits did not manifest themselves until five years after establishment of the plots.

Results in Mexico when considering only partial adoption of the conservation agriculture package are more ambiguous. For example, Astier et al. (2006) conducted a two-year study in central Mexico on maize with green manures either left on the surface (not tilled) or incorporated (tilled) into the soil, and found that soil nitrogen and carbon as well as yields were higher under the system with incorporated green manures, though conventional tillage with no green manure had by far the lowest yields and soil nutrient levels. Roldán et al. (2003) compared no-till and conventional tillage systems with varying levels of retained residues in the Patzcuaro watershed in central Mexico and found that no-till had higher soil nutrient levels than conventional till, and that these levels increased further under higher levels of retained residue. That study did not look at yield effects.

There are also a number of studies of the effects of conservation agriculture in Argentina, particularly the Argentine pampas (Diaz-Zorita et al. 2002; Fabrizzi et al. 2005; Alvarez and Steinbach 2009), where the practices have been widely adopted (over 70 percent of the annual cropping area was under no-till in 2009). Alvarez and Steinbach (2009) reviewed 35 different field experiments conducted in the region and found that water infiltration and aggregate stability were significantly higher in soils under limited tillage, but they found few other positive effects. In most cases no-till also increased soil compaction, so that soybean yields were not affected by the type of tillage, and wheat and corn yields were 10–14 percent lower under limited tillage without fertilizer (though not significantly different when fertilizer was added) (Alvarez and Steinbach 2009).

Another review of tillage in the Argentine pampas (Diaz-Zorita et al. 2002) utilized data from records of growers collected by the Regional Consortium for Agricultural Experimentation (CREA) and found that soil organic carbon was lower under moldboard plow and chisel-tillage systems than conservation tillage, and that soil organic carbon levels had a significant positive correlation with crop yields. Fabrizzi et al. (2005) looked at the effect of tillage on a corn-wheat rotation in a different area of Argentina, near Buenos Aires, and found that no-till (compared with minimum till) led to higher water storage during the critical growth stage of corn and most of the wheat life cycle. Wheat yields were the same in both systems, but corn yields were actually lower for no-till compared to minimum till with no nitrogen fertilizer, but the same when nitrogen fertilizer was applied.

Though many of the studies reviewed here found positive yield effects of conservation agriculture, particularly in the long term, there are other studies in LAC that have found negative yield effects. Barber et al. (1996) studied the effects of four different tillage treatments (no-till, flexible till, chisel plowing, and conventional disc tillage) on soil properties and crop yields in Santa Cruz, Bolivia. Results showed that after four years (eight seasons) the chisel plowing system had the lowest level of soil compaction, followed by conventional tillage, flexible tillage, and no-till. Yields significantly differed between treatments in only three of eight seasons, and they were highly correlated with soil compaction, so no-till had the lowest yields. However, no-till resulted in the least chemical degradation, with higher soil organic matter and nitrogen content than other treatments (Barber et al. 1996). Basamba et al. (2006) compared no-till to minimum tillage under different crop rotation systems in Colombia and found moderately higher yields under minimum tillage and much more significant increases in yield due to crop rotation, particularly a maize-soybean-green manure rotation.

A great deal of evidence worldwide and in LAC suggests that conservation agriculture offers the greatest benefits in drier areas than in areas with higher rainfall. For example, trials in Jalisco, Mexico found that conservation agriculture led to 2.5 percent higher maize yields in zones with favorable rainfall (600–800 mm/year) compared to 74.4 percent higher yields in zones with marginal rainfall (400–600 mm/year) (Scopel 1996). Similarly, in another comparison of types of tillage in a semiarid zone of Mexico, Scopel et al. (2013) found that disk plowing resulted in the highest maize yields at the wetter sites but that conservation tillage produced the highest yields at the drier sites, under two different soil types. Analysis of soil properties under the different systems suggested that this difference is related to the fact that water uptake is the most limiting factor for production in the driest areas, and no-till significantly increased soil water retention.

A study in central Mexico over three years (Monneveux et al. 2006) found that no-till caused lower biomass and grain yields and increased ear rot during the wet season, but that it led to superior root development and water uptake during the dry season. Given both positive and negative effects of no-till, the study did not find a significant difference in yields. A long-term study of a rainfed maize system in the highlands of Mexico (Verhulst et al. 2011) found that yields under no-till exceeded those under conventional tillage by 31 percent on average from 1997–2009, but that the benefit of no-till was especially pronounced in very dry years, particularly in 2009 when there was a prolonged drought and the no-till system had a yield benefit over other practices of 126 percent. The study by Franchini et al. (2012) in southern Brazil also found that over the long term, no-till and crop rotation promoted more stable yields, particularly in years with little rainfall.

A few studies have attempted to estimate the economic returns to farmers of adopting conservation agriculture practices, based on estimated yield benefits and changes in costs. In Nicaragua, Aleman (2001) reported a net return to no-till of $762.5/ha and to conventional till of $648/ha, while in the Dominican Republic, Thomas (1985) found a net return to no-till of $109/ha compared to $261/ha for conventional till. Knowler and Bradshaw (2007) analyzed 29 different studies in developing countries worldwide and found a positive net present value (NPV) to conservation agriculture adoption in 89.7 percent of those studies. That analysis included 18 studies in LAC, 88.9 percent of which had a positive NPV.

Conservation agriculture is also of interest because of its potential for climate change mitigation in the form of increased carbon sequestration. Evidence on the effect of conservation agriculture on carbon storage is mixed, however. Sisti et al. (2004) analyzed the differences in carbon levels in soils under no-till versus conventional tillage under several different crop rotation systems after a 13-year experiment in southern Brazil. Results showed that soil organic carbon was not significantly different between the two tillage treatments, though systems grown with vetch as a winter cover crop had significantly higher soil organic carbon levels. Manley et al. (2005) conducted a meta-regression analysis looking at the carbon accumulation under no-till and conventional till systems (using data from 51 different studies, or 374 total observations) and compared it to results of regression analysis on the cost of switching to no-till (using data from 52 studies, for 536 total observations). Results showed that no-till was a low-cost way to sequester carbon in some regions ($10/tC), especially the southern United States, but very costly in other regions ($100-400/tC), particularly the U.S. Great Plains, because carbon storage was very low for no-till in the prairie soils.

Manley et al. (2005) included only eight studies from LAC, however, so no rigorous conclusions can be made about the cost of carbon sequestration in that region. With regard to carbon storage, Manley et al. (2005) included six different studies from LAC, including four from Brazil. In all six cases carbon sequestration was higher under no-till than under conventional tillage, with the proportional increase ranging from 3.8 to 22 percent. In another study, La Scala et al. (2006) compared sugarcane in Brazil under no-till and conventional tillage and found that no-till resulted in significantly lower greenhouse gas emissions.

As noted above, the more recent research estimating the ability of conservation agriculture systems to increase the store of carbon indicates that large gains are unlikely, except under very specific circumstances. And as will be discussed in Section 3.3, uncertainty in the likely sequestration gains has big effects on the sample size needed to ensure some confidence in measured effects (where the project hopes to establish these gains).

2.2. Adoption of Conservation Agriculture

There is a fairly extensive literature that seeks to determine the factors affecting adoption of conservation agriculture practices, though relatively few of these studies have been carried out in LAC. Knowler and Bradshaw (2007) conducted the largest review of conservation agriculture adoption studies to date, covering 31 different analyses, of which five were based on studies in LAC. The factors that appeared most often in the studies analyzed included awareness of soil erosion problems, education, age, larger farm size, lower rainfall, presence of steep slopes on the farm, secure land tenure, off-farm income, extent of social networking with other farmers, extension services, and subsidies for the adoption of conservation agriculture. However, while many of these variables more often than not had a positive correlation with adoption, the results were mixed and inconclusive for age, farm size, rainfall, land tenure, off-farm income, and labor arrangement.

McCarthy et al. (2011) and Wall (2007) review the empirical evidence on major constraints to the adoption of conservation by smallholders, although again, much of the evidence is outside of LAC. Nonetheless, the authors found the following costs and barriers to be most important empirically:

(1) The need in many areas to use crop residues for animal feed;
(2) Increased expenditures on herbicides and/or labor for weeding, at least during the initial years;
(3) Weak links to extension services to acquire information on conservation agriculture (which is a relatively knowledge-intensive technology, at least initially);
(4) Limited access to direct seeding equipment;
(5) Limited availability of appropriate cover crop seeds in the market; and
(6) Tight networks among farmers, which may work to reinforce traditional tillage practices.

Thus, smallholder farmers in areas with more integrated markets, with higher labor availability, greater access to machinery and herbicides and other inputs, and who are in contact with extension services, would be more likely to adopt conservation agriculture practices.

A few studies look specifically at the factors affecting the adoption of conservation agriculture in LAC. De Herrera and Sain (1999) examined the adoption of no-till for maize in Azuero, Panama and found that it was largely motivated by potential cost savings (fuel) in the short term rather than by longer-term considerations such as reduced soil erosion. Results of the empirical analysis showed that factors affecting adoption included land tenure (renters were less likely to adopt than landowners), lack of access to direct seeding equipment, and lack of information on conservation agriculture technologies. A case study of the adoption of conservation tillage in Guaymango, El Salvador by Sain and Barreto (1996) found widespread use of the practice (with 94 percent of cropped area under conservation agriculture by 1983) because of two major factors: first, the combination of components to increase productivity with elements to improve environmental sustainability into a clear "package" of recommended practices; and second, the use of incentives to encourage adoption of conservation agriculture (improved credit and input access). The authors also found that areas with more cattle, a longer grazing period, and a high market value for crop residue had lower rates of conservation agriculture adoption.

In a study of the adoption of mulching with crop residues and cover crops, Erenstein (2003) found that adoption was much higher among large-scale farmers, particularly in no-till systems in the southern cone of South America, and that successful adaptation of mulch drills was crucial in promoting adoption. Erenstein et al. (2012) also found that the adoption of conservation agriculture in Mexico is low among smallholders because of lack of access to seed drills and other necessary inputs, the need for techniques less reliant on herbicides, and competition for crop residues to feed livestock. Though outside of LAC, Ersenstein et al. (2012) found that in recent adoption studies in India, 60 to 74 percent of no-till adopters did not own a drill and instead gained access to one via a producer cooperative or a service provider who rented out a machine to them. Apparently, there is little empirical evidence of this type of drill provision in LAC.

Neill and Lee (2001) did not study conservation agriculture adoption directly, but rather examined the dis-adoption of maize-velvet bean crop rotation systems in Honduras, which is highly related to conservation agriculture. This crop rotation system was used widely in the 1970s and 1980s, but by 1997 only 38 percent of surveyed farmers still used it, 45 percent had previously used it but since abandoned it, and 16 percent had never adopted it. The key motivations for abandoning the system were rising weed pressure, which was more difficult to deal with under the rotation system; decreased tenure security, including reclamation of parcels by the landowner; preference for switching to pasture or another crop as market values for products changed; lack of sufficient land (with land sizes shrinking and minimum parcel sizes necessary to practice the rotation profitably); and the high cost/difficulty of herbicides or other maintenance.

Most studies analyzed by Knowler and Bradshaw (2007) indicated a positive correlation between overall income and adoption (Gould et al. 1989; Saltiel et al. 1994). Experience has also been found to be positively correlated with adoption (Rahm and Huffman 1984; Clay et al. 1998) or insignificant (Traoré et al. 1998), but was never found to be negatively correlated with adoption. Likewise, education was found to be positively correlated with adoption in most cases (Rahm and Huffman 1984; Shortle and Miranowski 1986; Traoré et al. 1998). In several studies of soil conservation adoption, farmers' opinions on the severity of soil erosion in their area were a significant factor (Allmaras and Dowdy 1985; Shiferaw and Holden 1998; Traoré et al. 1998). Related to this, farms with medium (10–40 percent) or very steep (>40 percent) slopes were found in many studies to have a significantly higher likelihood of adopting conservation agriculture (Shiferaw and Holden 1998; Soule et al. 2000; Neill and Lee 2001).

Access to information on the relevant technology via extension services, connections to other farmers, and other sources is expected to have a significant positive correlation with adoption. Empirical evidence tends to support this hypothesis. Several studies directly included availability of information as a variable and found a positive correlation with adoption (Traoré et al. 1998; Prokopy et al. 2008). Other studies found a correlation between adoption and a specific source of information, such as visits from extension agents (Feder and Umali 1993; Fujisaka 1994), experience working with an NGO (Bandiera and Rasul 2006), or participation in field trials and workshops (Traoré et al. 1998).

Several studies have shown that social network effects play a major role in the adoption of new technologies more generally (Conley and Udry 2003; Bandiera and Rasul 2006; Knowler and Bradshaw 2007; Prokopy et al. 2008). Few of these studies were undertaken in LAC, however. Similarly, several studies on the adoption of conservation agriculture found a positive correlation with membership in a producer organization (Smit and Smithers 1992; Traoré et al. 1998; Swinton 2000), though not necessarily in LAC.

Ding et al. (2009) specifically considered the possibility that an increase in climate change, and the ensuing increase in droughts, might increase farmer interest in and adoption of conservation agriculture techniques. They use Zellner's "Seemingly Unrelated Regression" technique and panel data from states in the Midwestern United States to estimate the rate of adoption of no-till and conservation tillage compared to conventional tillage. Results showed that, controlling for other factors, extremely dry conditions in recent years increase the adoption of conservation tillage, while spring floods in the year of production reduce the use of no-till.

To summarize, the most important constraints to the adoption of conservation agriculture in LAC and elsewhere have been identified as limited availability of and access to equipment and other inputs (herbicides), and high opportunity costs of crop residues as soil cover. On the other hand, larger farmers, especially those reliant on fuel-based mechanization, are more likely to adopt conservation agriculture, as are farmers with secure tenure and/or who own the land farmed, who have greater access to information on conservation agriculture (e.g., through extension), and who are located in areas prone to soil erosion and lower rainfall.

2.3. Lessons for Future Conservation Agriculture Projects and Impact Analyses

This review of the conservation agriculture literature suggests a number of recommendations for how to structure impact analyses of future conservation agriculture projects in LAC. First, it is apparent from the literature that the vast majority of current empirical studies of the effects of conservation agriculture are restricted to just a few countries, primarily Brazil, Mexico, and Argentina. These effects cannot necessarily be generalized to other countries and regions because conservation agriculture has different effects depending on the climate and soil type in a given area (Zinn et al. 2005; Giller et al. 2009). Perhaps more importantly, experiences in these three countries are dominated by farmers who rely on fuel-based farming systems, which have a completely different cost-benefit structure than smallholder systems that use no fuel or limited amounts of it. Thus, it is critical to generate information from impact assessments for smallholder systems, and such assessments need to control for a number of differences expected to affect the size of potential gains, including climate and agro-ecological characteristics. An impact assessment that includes farmers using both fuel-based and nonfuel-based systems will need to stratify by these characteristics, particularly if the goal is to understand not just impacts, but factors affecting successful adoption in the first place. Similarly, if control groups are to be selected, they must reside in areas of similar agro-ecological and climate conditions, and obviously must also have producers operating under similar farming systems.

Because conservation agriculture is composed of three separate components—reduced or no tillage, crop rotation, and retention of ground cover through crop residues or cover crops—it has proven difficult to tease out the effects of each of these components individually or in combination. Where studies have tried to do this, they have found that benefits are much higher with the entire conservation agriculture "package," and that adopting no-till alone, for example, may result in negligible or even negative yield effects (Sisti et al. 2004; Basamba et al. 2006; Rusinamhodzi et al. 2011; Erenstein et al. 2012; Franchini et al. 2012). Each component also includes a number of practices that may satisfy it. For instance, some project implementers may consider that both no-till and another reduced-till method satisfy minimum soil disturbance; that permanent ground cover may be achieved through crop residues or through cover crops or other green mulches; and that many different crops can be used in a rotation but with potentially different effects. It is crucial that the range of practices adoptable under a conservation agriculture project be identified before any baseline data are collected. More importantly, because this is a package, the impact assessment sampling framework must account for the likelihood of partial adoption of different combinations of the package, as well as nonadoption. In the literature, this is often referred to as "failure to follow treatment protocol" (Winters et al. 2010). Differential adoption levels by the "treated" group can have big effects on the sample size needed to recover effects of adoption. An impact assessment team would need to sit down with project implementers and discuss which combinations could reasonably be assessed, and which cannot be assessed given budget and logistical reasons. In addition, recall that many of the empirical results above compared "conventional" practices not only to different conservation agriculture systems, but also to altering additional inputs such as fertilizer. The point is that complex "package" projects need to be assessed in detail between the impact assessment and project implementation teams to isolate exactly what the impact assessment can hope to recover, especially given budget constraints on the sample size.

Another lesson from existing studies is that it is crucial to conduct long-term studies of the effects of conservation agriculture on crop yields. Many of the studies that found no significant effects of conservation agriculture on soil or yields were carried out over five years or less (Astier et al. 2006; Roldán et al. 2003), but the longer-term studies all found positive results from the adoption of conservation agriculture (Erenstein et al. 2012; Franchini et al. 2012). The long-term impact on yields has a number of implications for the design and implementation of an impact assessment. The long time scale needed to quantify ultimate effects on yields has fairly severe implications for attempting to implement any type of randomized treatment, and even for determining appropriate control groups ex ante, particularly given the likelihood of attrition. Alternatively, intermediate outcomes that are likely to accrue more quickly and are linked with higher yields in the long term can be identified from the agronomic literature. These intermediate outcomes would relax the rather severe constraints imposed by long time-lag effects on yields. Such outcomes include reduced soil erosion, soil moisture content, and soil nutrient levels, among others.

Related to the above discussion, a good deal of empirical evidence suggests that projects implemented in relatively dry areas but with fine soils less prone to compaction may lead to observable short to medium-term effects on yield variability, or more specifically, to higher yields in low rainfall years vis-à-vis those practicing conventional methods (Scopel 1996; Scopel et al. 2013; De Vita et al. 2007; Monneveux et al. 2006; Verhulst et al. 2011). This is particularly important for conservation agriculture projects that are trying to establish a link to climate change through increased adaptive capacity and resilience, since it is expected that in the short to medium term, climate variability will be a greater challenge than changes in mean precipitation (IPCC 2001; Zegarra 2005; Rozensweig and Tubiello 2007). Thus, an impact assessment may pick up important information on the effects of conservation agriculture on yields in dry years in the shorter term, before the impact on mean yields shows up. Such an impact would more likely be seen in relatively dry areas subject to erratic rainfall patterns; relatively high rainfall areas with a lower likelihood of significant rainfall deficits would not be good candidates. Additionally, given that recall information on yields diminishes over time, it would be imperative that the impact assessment team be flexible enough to implement a post-baseline survey in the event of a poor rainfall event. In other words, if the impact assessment aims to pick up a baseline and then a final survey at the end of five years, but poor rainfall occurs in the third year, it would be best to collect information after harvest during that third year.

As described in detail in Winters et al. (2010) and Duflo et al. (2008), it is always a good idea to pick up additional information in the baseline and final surveys that can subsequently be used to:

(1) Provide evidence that the evaluation strategy chosen is appropriate for the circumstances;
(2) Reduce standard errors and thus the sample size required to reach significance and the power levels desired;
(3) Provide additional information on which to recover estimates of impact if implementation of the evaluation strategy does not proceed as planned; and
(4) Provide information on factors affecting the extent of adoption in order to inform future project design.

Finally, the review also suggests that the information on climate change mitigation—specifically carbon sequestration under conservation agriculture—is still very limited (Sisti et al. 2004; Manley et al. 2005). There is limited research across a wide variety of conditions (soil types, climates, countries) and of combinations of the three different conservation agriculture components to guide impact assessment of carbon sequestration. Also, there is limited research using the large sample sizes required to detect a statistically significant change. Because establishing such an impact would be important to enable smallholder farmers to connect to global carbon markets (formal and informal, public and private), it may be worth the costs of undertaking this assessment for specific projects. However, costs must be realistically assessed at the outset, and these costs will largely be a function of a conservative sampling strategy in the absence of good data on which to calculate the sample size. Also note that the unit of analysis relevant for assessing carbon sequestration is going to be some unit of land area, and not the household.

3. Irrigation

Irrigation reduces farmers' reliance on natural rainfall patterns, which in general reduces vulnerability to climatic variation. There are a number of different irrigation systems, including surface (flood or canal/furrow), sprinkler, and drip irrigation (surface or sub-surface). The source of irrigation water also comes from many different sources, including hand-drawn or pumped well water, water diverted from natural rivers, or water delivered via diversion canals from man-made reservoirs or run-off catchment structures.

Larger irrigation projects require significant infrastructure investment and often involve the local or national government. Government institutions then often remain involved in managing water distribution and allocation and infrastructure maintenance. There are also micro-irrigation technologies, however, that require lower levels of investment and can be accomplished by individuals or local communities. Finally, there are technologies and methods that aim to increase water-use efficiency of cropping systems, including "deficit irrigation" in which water is only delivered during the crucial growth stages of a crop. Given the emphasis here on climate change and agriculture, it is particularly important to consider the water-use efficiency of irrigation systems, since that efficiency has major implications for how effectively irrigation systems can maintain production in the face of drought, for instance. This section explores the literature on the estimated effects of these different forms of irrigation and methods to increase water-use efficiency, as well as the determinants of adoption of these technologies, with a focus on smallholder production systems.

3.1. Effects of Different Types of Irrigation on Crop Yields, Water-Use Efficiency, Yield Variability, and Greenhouse Gas Emissions

Worldwide, irrigated land comprises 15 percent of total cropped area but supplies 36 percent of production (Howell 2001). The disproportionate share of production on irrigated land is even greater for some middle-income countries: 70 percent of grain in China and 50 percent of grain in India is produced on irrigated land, while in Brazil only 5 percent of cropped land is irrigated but this accounts for 35 percent of production (Howell 2001; Laclau and Laclau 2009). Across LAC, those countries with the highest cereal production are also those with the highest proportion of irrigated land (Ringler et al. 2000; San Martin 2002). This indicates that irrigation significantly increases yields, though the amount of this increase varies widely by crop, irrigation system, and geographic location. Irrigation not only helps increase yields on existing land, it also enables cultivation of land that would not be arable without irrigation technology. Across LAC there is a great deal of potential for increased irrigation development, particularly in countries that currently exploit less than 2.5 percent of available water resources, including Brazil, Bolivia, Colombia, Ecuador, and Venezuela (San Martin 2002).

While there is considerable evidence that irrigation increases yields, there is less evidence regarding which crops use water most effectively. For instance, a field experiment of two varieties of wheat in Londrina in the state of Paraná, Brazil found that irrigation increased the yields of both varieties by an average of 51.5 percent (Destro et al. 2001), even though one variety was less sensitive to water stress than the other. More recently, Cesano et al. (2013) collected data on irrigation in seven different districts in Brazil and found that in all of them the average benefits of irrigation (in terms of production and revenue increases) outweighed the costs, with annual net profits from irrigation ranging from 17 to 126 percent across the different districts. Nonetheless, across LAC, irrigation efficiency currently ranges from 30–40 percent (San Martin 2002), so there is a lot of room for improvement. According to Ringler et al. (2000) increased efficiency of irrigation systems, and agricultural water use in general, should be a key priority for LAC in its attempt to deal with climate change. A number of studies have investigated various measures to increase water-use efficiency, including use of drip irrigation with sensor technology, which automatically irrigates when soil moisture drops below a certain level (Dukes et al. 2003; Erdem et al. 2006). Unfortunately there are few studies on the effect of such technologies in LAC, even though they are likely to be cost-prohibitive for many farmers.

There is also a fairly extensive literature in Brazil that seeks to determine the optimal type and level of irrigation for certain commercially important crops like processing tomatoes (Silva and Marouelli 1999; Marouelli et al. 2003; Marouelli and Silva 2007). Marouelli and Silva (2007) explained that drip irrigation is superior to surface or deficit irrigation systems for processing tomatoes because it reduces water use by 30 percent while not adversely affecting yields. They then tested a number of different levels of drip irrigation at various life stages of processing tomato growth in order to develop the optimal irrigation strategy for the crop under local conditions

Another way to increase water-use efficiency is a system called deficit irrigation, which has received more attention in LAC. It involves irrigating only at critical growth stages of a plant. According to Geerts and Raes (2009), this type of irrigation will not necessarily maximize yields, but can help stabilize yields and optimize water productivity. The difficulty arises in that deficit irrigation requires extensive knowledge of the physiology of a crop (Kirda et al. 2005), and thus successful scale-up in LAC would require more information on the effects of deficit irrigation on a wider range of crop varieties, and across a wide range of regions and environments. The review of deficit irrigation worldwide by Geerts and Raes (2009) included only two studies Latin America, specifically in Brazil and Bolivia (Marouelli and Silva 2007; Geerts et al. 2008). Geerts et al. (2008) tested the effects of deficit irrigation on quinoa production in the Bolivian altiplano. Results showed that at one site with adequate rainfall during the crucial growth stage, deficit irrigation had no effect on yields, but that yields were 147 percent higher under deficit irrigation at the site with low rainfall. The results also showed that deficit irrigation enabled stabilization of quinoa yields at 1.2–2 Mg/hectares while requiring half the water of full irrigation.

3.2. Adoption of Irrigation and/or Participation in Public Schemes

Despite the potential of irrigation to stabilize and increase yields in areas with limited rainfall, its adoption, particularly by smallholders, remains limited in LAC. There is quite an extensive literature on irrigation adoption in developed countries that looks either at the choice to irrigate at all or the type of irrigation system chosen (Caswell and Zilberman 1985; Dinar and Yaron 1992; Negri and Brooks 1990; Dinar and Zilberman 1991; Mendelsohn and Dinar 1999; Koundouri et al. 2006). Results of these studies generally suggest that the significant factors affecting irrigation adoption include farmer income/wealth level, the price of water, the cost and availability of irrigation inputs, crop prices, farmer organization characteristics, soil type, and climate conditions (ambient temperatures and average precipitation). Koundouri et al. (2006) specifically look at the decision of farmers in Greece to adopt more efficient irrigation technology under a situation of increasing uncertainty due to climate change. They found that farmers did, in fact, choose to adopt the technology in order to hedge against production risk, and that farmers in areas with a higher aridity index were more likely to adopt. They also found that a number of human capital variables such as education, receipt of extension services, and awareness of climate change increased adoption.

Mendelsohn and Seo (2007) developed a theoretical model of farmers' choices of farm type (crops, livestock, or both) and whether or not to irrigate, and they tested the model using data from 2,000 farmers across Latin America. Results showed that the decision to adopt irrigation was significantly affected by average temperatures and precipitation, the type of farming adopted, and soil type. Seo (2011) analyzed public and private irrigation schemes in South American countries. In the sample, 65 percent of farmers used no irrigation, 21 percent relied on public water schemes for irrigation, and the remaining 15 percent used private irrigation schemes. Results showed that public irrigation has not increased in response to increasing temperatures, though private irrigation has increased. Furthermore, private irrigation investment is done gradually, while public irrigation investments are distributed in lump sums with large time gaps, which often results in local overprovision or underprovision of services. Dinar and Keck (1997) also looked at private irrigation investment in LAC, specifically in Colombia, and found that it was significantly influenced by violence, climate, and governmental price and credit policies.

Cunha et al. (2013) conducted an empirical study of the determinants of irrigation adoption among smallholder farmers in Brazil. They expressly wanted to investigate the role of irrigation in climate change adaptation, so they included a number of climate variables. Results showed that increased winter temperatures, increased temperature variability, decreased mean and winter precipitation, higher water resources in a region, increased soil erosion, Internet access, and higher education levels all increased the likelihood of a farmer adopting irrigation.

Cesano et al. (2013) discussed efforts by a local organization, Adapta Sertão, to help smallholder farmers in a semiarid region of Bahia, Brazil adapt to climate change. The organization's principal initiative is facilitating adoption of drip irrigation. This is a pilot project implemented in Bahia since 2006 in four municipalities. The project first identified private vendors of drip irrigation systems who were interested in expanding their markets, and subsequently created partnerships between these vendors and local farmer associations for distribution and promotion. Adapta Sertão also successfully piloted microfinance programs to help farmers pay for the irrigation technologies. Finally, the organization conducted weekly monitoring of the systems, including crop yields, costs, and revenues. This enabled Adapta Sertão to show that drip irrigation was highly profitable, thus attracting more farmer interest and investment by various organizations.

Many smallholders rely on publically funded surface water schemes such as large or small dam gravity-based surface/canal schemes. Expansion of these schemes may be an attractive option, particularly where private irrigation systems are simply not technically possible or cost-attractive. Many such schemes rely on local user groups to manage and maintain these systems, with varying degrees of success. One of the biggest factors explaining success around the world, and in a few cases in Latin America, is heterogeneity among irrigators. Socioeconomic heterogeneity makes it harder to rely on moral suasion to monitor and enforce rules. Economic heterogeneity means that different irrigators face different costs and benefits, with resulting different incentive structures to maintain irrigation infrastructure. Dayton-Johnson (2000) looks at how different governance systems—one that does not take into account heterogeneity and another that attempts to allocate costs in proportion to benefits—affect aggregate maintenance efforts. Proportional cost allocation rules increase aggregate maintenance efforts, and are more likely to be chosen in older schemes and where irrigators are indeed more heterogeneous. However, if equal cost allocation prevails, economic heterogeneity negatively affects maintenance efforts (Bardhan and Dayton-Johnson, 2007; Dayton-Johnson, 2000). McCarthy and Essam (2009) also find a negative impact of economic heterogeneity on collective maintenance, with subsequent negative effects on crop yields. Additionally, they find that other characteristics of the water-user association—such as the number of members, connections with supra-community organizations, and decision-making processes—explain a great deal of the variation in successful infrastructure maintenance. Individual farmer characteristics positively associated with contributions to maintenance include larger landholdings and other agricultural assets, more educated households, and households with a younger household head.

3.3. Lessons for Future Irrigation Projects and Impact Analyses

This review suggests that irrigation can have a dramatic effect on stabilizing and increasing yields of many crops, and that farmers are increasingly interested in irrigation because of increased climate variability (Mendelsohn and Dinar 2003; Koundouri et al. 2006; Cunha et al. 2013). Though a few studies have addressed this topic, more research is clearly needed on the effect of different irrigation systems in terms of both water-use efficiency and on yields of different important crops in LAC in order to determine the technologies to help farmers achieve optimal yields with the lowest amount of water (Ringler et al. 2000; San Martin 2002).

There have been very few rigorous impact assessments of the net returns to irrigation for the different technologies. While there are sufficient data to substantiate that yields increase and become more stable, costs to farmers can also be quite high, and water-use efficiency differs across the systems. It is important to note that much of the irrigation research summarized above has been conducted at research stations under controlled conditions. For private irrigation, only Cesano et al. (2013) gathered data directly from farmers using private irrigation systems and then used the data to assess the economic benefits of adoption. There remains limited evidence on farm households' net revenues, and especially water-use efficiency, via-à-vis public schemes, particularly those that are essentially managed at the local level by water-user associations. What we do know is that the structure and functioning of the local association is likely to be a key factor in explaining both maintenance of the system and subsequent effects on farmers' well-being and efficient water use (McCarthy and Essam 2009; Bardhan and Dayton-Johnson 2007).

There are a number of implications for designing a rigorous impact assessment given the studies reviewed above. Three broad categories of irrigation projects can be analyzed:

(1) Those where the counterfactual is no irrigation (e.g., public investment in large dams or small-dam infrastructure);
(2) Individual investment in irrigation infrastructure with the counterfactual still being no irrigation; and
(3) Interventions designed to improve efficiency and resilience of an already-existing irrigation system.

In the first category, in many cases, the counterfactual of no irrigation in the absence of the intervention will likely be easy to motivate (e.g., where private investments are not cost-effective), but even here, picking up information on control farmers outside the scheme can be important to verify ex-ante assumptions on net revenue trends in the absence of irrigation, and to confirm continued lack of incentives for private investment in irrigation infrastructure. This is particularly important when there will only be one "treatment" (one large dam irrigation scheme) and where farmers subsequently participating in the scheme are quite similar in terms of wealth, ability, productive assets, etc.[3] Also, the evaluation team must make sure it understands—and can obtain information on—criteria for participation in the scheme. There may be options to introduce some randomness—for instance, if more farmers are eligible than plots available, a lottery system may be employed.

As noted above, public schemes have not been as responsive as private investment to increasing investments in irrigation in the face of uncertainty introduced by climate change. This suggests that smaller-scale projects operated by local microfinance organizations or producer cooperatives might be more successful in both promoting and distributing irrigation technologies to smallholder farmers (Seo 2011; Cesano et al. 2013). For private investment, probably the most important characteristic for a control group would be that the controls be located in an area that has roughly similar water resources, and thus where farmers face the same costs in financing private investment in irrigation. Alternatively, an "encouragement" design could be employed, possibly implemented through producer cooperatives and microfinance organizations, that could help tease out effects. Since it is unlikely that all farmers exposed to the intervention will be willing and able to finance irrigation, random encouragement can be used as an instrument for actual investment, which can subsequently be used to assess effects on yields, net revenues, etc. Random encouragement can take many forms, but it is critical that the encouragement itself not directly affect the outcome measures, such as yields. So, for instance, both vouchers to reduce input costs or a training course on irrigation infrastructure would affect yields only through the adoption of irrigation. A training course that covered many more topics, however, might affect yields directly, as well as indirectly through irrigation. Additionally, an encouragement incentive needs to be well designed so that take-up is sufficiently higher among those encouraged versus

[3] When the unit of treatment is "clustered" above the unit of observation (generally households), the determination of sample size will be a function of intra-cluster versus inter-cluster variation. For instance, if individuals within a cluster have very similar characteristics, then it is better to sample a larger number of clusters and fewer individuals per cluster. However, this does not work when the number of treatment clusters is very small. This means it is critical to find a compelling control group.

those not encouraged. This requires a good understanding of the efficacy of different encouragements, and likely some pre-testing. Finally, it is critical to remember that the follow-up survey must cover all those who were originally encouraged and not encouraged. This may sound straightforward, but earlier studies simply dropped those that were encouraged (or were at least "intended to be treated"), as documented in Duflo et al. (2008).

There are too many different possible project designs aimed at improving water management to consider each type individually. Instead, we will focus on those projects attempting to increase water-use efficiency within existing irrigation systems. Many interventions will be undertaken on existing public (government-managed) or collective (user-managed) schemes, where the treatment unit will likely be higher than the individual (e.g., a water-user association). This means that cluster treatment design must be accounted for in the sample size determination, being mindful of potential problems cited in footnote 3. Spillovers and externalities arising from individual actions are almost certain to affect others within the irrigation system. First, the sampling design, and particularly the choice of controls, needs to account for these externalities. Basically, this strongly suggests that control irrigators should not be located within the same irrigation scheme. As with conservation agriculture, partial compliance and noncompliance by individual irrigators within these schemes may be a problem. It will be crucial to get information on factors that help explain partial compliance or noncompliance, factors likely to be tied to both individual farmers as well as water-user associations (population densities, socio-cultural and economic heterogeneity, etc.). The importance of group-level factors in explaining successful maintenance of irrigation infrastructure means that sampling should include many clusters.

Finally, in almost all cases, farmers will still be able to self-select which crops to grow, and crop choices can have big effects on water-use efficiency. If the goal is to assess the effects by crop, it will be critical to identify specific "major" crops that are likely to be grown ex ante in order to get a reasonable estimate of the proportion of each crop likely to be grown, and thus to determine the sample size needed.

With regard to covariates of adoption, this review shows that farmers are increasingly interested in adopting irrigation technologies, particularly technologies with greater water-use efficiency, because of the increased risk of climate variability (Koundouri et al. 2006; Cunha et al. 2013). But the wealth level of farmers, crop prices, and input costs are major determinants of irrigation adoption—installing irrigation is an expensive investment that many smallholder farmers do not find affordable (Mendelsohn and Dinar 1999; Koundouri et al. 2006; Cunha et al. 2013; Cesano et al. 2013). Current studies also indicate that smallholder farmers who face a higher risk from climate change (i.e., those who live in areas with higher temperature variability, lower precipitation, and high soil erosion) are most likely to irrigate (Cunha et al. 2013). Future projects aimed at promoting irrigation could consider targeting these most at-risk areas first, since this would likely generate the highest impact per farmer and maximize the rate of adoption. Smallholders who farm only crops, as opposed to those who also raise livestock, are also more likely to irrigate (Mendelsohn and Seo 2007). And for smallholders reliant on local irrigation schemes organized through water-user associations, it will be important to collect information on socio-cultural and economic heterogeneity, as well as other characteristics affecting the structure and function of the association.

4. Agroforestry

Agroforestry is a broad term that encompasses a number of different practices but essentially amounts to incorporating trees into agricultural systems to increase sustainability (Steppler and Nair 1987). It can include direct intercropping of timber or native shade trees with other agricultural crops, either annuals or perennial tree crops. Agroforestry also encompasses silvopastural systems, wherein livestock are grazed on forages grown under tree canopy, and improved fallow systems with fast-growing leguminous trees are used to more rapidly restore fertility to degraded soil. In all these different systems, trees are incorporated into the landscape in several different ways, including block planting, alley cropping, contour planting, border planting for live fences, and as windbreaks (Current et al. 1995). This section reviews studies on the effects of these various types of agroforestry systems on environmental sustainability, yields of agricultural products, and farmer incomes in LAC. It also reviews studies of the factors affecting agroforestry adoption. The section then discusses implications of the literature on future agroforestry projects and impact assessments.

4.1. Effects of Agroforestry Practices on Crop Yields and Greenhouse Gas Emissions

Agroforestry also can play a significant role in adaptation to climate change: deep roots enable trees to access more water, increase soil porosity, reduce run-off and increase soil cover (which increases infiltration and thus water-use efficiency), have higher evapotranspiration rates and thus help to aerate the soil, contribute organic matter to the soil via leaf litter, lower the temperature under the canopy (thus creating a buffer against temperature increases), and produce higher-value products that can strengthen farmers' income levels (Rojas-Blanco 2006; Verchot et al. 2007).

There is actually a long history of agroforestry research and promotion in LAC, much of it conducted by the Center for Tropical Agronomy Research and Education (*Centro Agronomico Tropical de Investigacion y Ensenanza* – CATIE) in Costa Rica. Muschler and Bonneman (1997) reviewed 31 studies of agroforestry conducted in affiliation with CATIE between 1979 and 1994 and summarized the key benefits of agroforestry systems in LAC, including increased soil fertility, reduced soil erosion, increased crop growth, and increased economic viability of the integrated system. However, they pointed out that outcomes are highly site-specific and tree-specific, and other studies have also shown that yields can vary dramatically even in nearby areas with similar climates). Muschler and Bonneman (1997) also point out the main limitations to scaling up agroforestry, including the often-substantial lag time between investing in agroforestry and resulting benefits, and the political/demographic pressures to engage in more intensive farming systems that maximize food production, which may not be compatible with agroforestry.

One very important type of agroforestry in LAC is shade-grown coffee and cocoa (Current et al. 1995; Vandermeer and Perfecto 2005). Both crops are understory trees, and research has shown that shade can increase the sustainability of these crops, and in the case of coffee may actually help increase yields, particularly in a situation of increasing climatic extremes (Muschler 1997; DaMatta 2004; Lin et al. 2008). Coffee phenology is highly vulnerable to the quantity and timing of precipitation (Nunes et al. 1968; Magalhaes and Angelocci 1976; Cannell 1985; Carr 2001), and the optimal temperature for Arabic coffee is between 18°C and 21°C (Alegre 1959). Climate fluctuations can have a devastating effect on coffee yields, as evidenced by the 40–80 percent observed production decreases in southern Mexico in ENSO years (Castro Soto 1998).

Shade helps keep the coffee cooler during the day and warmer at night (Lin 2007), so moderately shaded coffee plants have been found to experience photosynthetic rates three times higher than plants under full sun (Lin 2007). Shade also prevents overbearing of fruit on a branch, thereby preventing biennial fluctuations in yield (Cannell 1983). However, the effect of shade on coffee yields is still inconclusive because of the many confounding factors that also affect production (Beer et al. 1998). Some studies show a decrease in yield with more shade (Lagemann and Heuveldop 1983; Nolasco 1985), while others show an increase (ICAFE 1989; Ramirez 1993; Muschler 1997). In a study conducted in Chiapas, Mexico, Soto-Pinto et al. (2000) found that coffee yields were actually highest under 23–38 percent shade cover, though production decreased with shade cover over 50 percent. But there is generally a consensus in the literature that shade has more positive than negative effects in situations of high climatic variability and temperature extremes (Lin et al. 2008; Schroth et al. 2009).

Some limited research exists on agroforestry systems with other commercial crops in LAC. For example, Ilany et al. (2010) compared soil nutrient characteristics of 30-year old and 50-year old yerba mate plantations in Argentina grown under monoculture or intercropped with a native tree species. Results showed lower soil nutrient levels for intercropping in younger plantations, but the opposite in older plantations, indicating that agroforestry has a long-term positive effect on soil fertility. However, the study did not look at the effects of intercropping on yields.

There is a great deal of research on the positive effects of improved fallows on soil conditions and subsequent crop yields, though much of it has been conducted in African countries (Sanchez 1999; Kandji et al. 2006). In LAC, Kettler (1996) found higher biomass yields on improved fallows in Costa Rica, but no significant difference in subsequent bean yields. Kass and Somarriba (1999) reviewed traditional fallow systems in LAC, some of which used leguminous trees as part of the rotation. One example of this is a traditional cropping system in southern Brazil, where *Bracatinga* trees (a local leguminous species) are grown on fallow land for a period, then thinned for under-planting of a maize and bean intercrop. Studies of the system have shown that it is more profitable than fertilized maize and beans grown with chemical inputs, and that crop and firewood production in the system do not decline over the first three years as they do in the same system without *Bracatinga* intercropping (Baggio et al. 1986; Graça et al. 1986).

Nichols et al. (2001) experimented with the use of agroforestry systems to restore degraded pastureland in Costa Rica, comparing mono-cropped planting of a commercial timber species (fertilized and unfertilized) to intercropping of the timber species with leguminous trees, cover-crops, or beans. Results showed that timber growth was highest in the plots intercropped with leguminous trees, and tree height was comparable to the fertilized plots, meaning that the agroforestry system can be used as a low-cost substitute for chemical inputs (Nichols et al. 2001). A similar experiment was conducted by Plath et al. (2011) in degraded lands in Panama, looking at growth of native timber trees in mono-culture or planted with leguminous companion trees. Results showed no significant difference in tree growth between the treatments but better water uptake and higher total biomass production in the intercropped treatments.

A number of studies have attempted to calculate the economic benefits of agroforestry systems to farmers. Current et al. (1995) reviewed 21 agroforestry projects in eight countries of Central America and found that alley cropping was the most cost-effective system, requiring only 56 labor-days per year, with a payback period of 1.9 years and a cost-benefit ratio of 2.1. Contour planting was another very profitable system, requiring 116 labor-days per year, with a payback period of two years and a cost/benefit ratio of 1.6. Interplanting trees with annual crops required 130 labor-days per year, with a payback period of 3.4 years and a cost/benefit ratio of 1.8. Interplanting perennial crops with other tree species required 139 labor-days per year, with a payback period of four years and a cost/benefit ratio of 1.8. Finally, block planting required only 53 labor-days per year but had a payback period of 4.9 years and the highest cost-benefit ratio, at 2.5.

Grieg-Gran et al. (2005) conducted case studies of four agroforestry payment-for-environmental-services (PES) projects, two in Costa Rica and two in Ecuador. Results showed that the monetary value of payments varied greatly across projects: one project paid $6–$12/ha, another paid $68–$119/ha, another paid $225/ha, and the last paid $515/ha. Nonmonetary benefits of the PES schemes included increased diversification and increased tenure security, strengthened community organization, decreased erosion, increased biodiversity, and increased ecotourism. Reported problems and limitations included a drop in water quality in one case, deterioration of road quality in another (due to increased traffic by forestry equipment), and the fact that in several cases participants lost eligibility for other government benefit programs (Grieg-Gran et al. 2005).

In terms of greenhouse gas emissions, agroforestry is generally recognized as the climate-smart agriculture practice with the greatest potential for contributing to climate change mitigation via high carbon sequestration in tree species and in the soil (IPCC 2000; Wright et al. 2000; Kandji et al. 2006; Verchot et al. 2007). In South America specifically it is estimated that agroforestry systems can sequester 39–102 Mg C/ha in humid tropical areas and 39–195 Mg C/ha in dry lowlands over a 50-year period (Kandji et al. 2006). Of course, the level of carbon storage varies by tree and the duration of time planted, so the level of sequestration, and therefore the potential revenues that can be earned in the carbon market, vary dramatically by region and system. For example, Oelbermann et al. (2004) looked at the carbon storage levels in alley cropping systems with one tree species, *Erythrina poeppigiana*, in Costa Rica. In four-year plantation the carbon storage was 120 Mg C/ha, while in 19-year plantations it was 180 Mg C/ha.

Many countries in LAC have already participated in reforestation and afforestation projects funded by climate-mitigation financing. In 2011, there were nine such projects being implemented in LAC under the Clean Development Mechanism (CDM) program of the United Nations Framework Convention on Climate Change (UNFCCC) and 11 more projects operating under the Climate, Community and Biodiversity standards established in February 2011 (Locatelli et al. 2011). Most of these projects focus on carbon sequestration, though they also include measures to address adaptation. For example, in northern Peru a GTZ project called AdapCC has facilitated carbon contracts between a local coffee producer association and Café Direct, a UK-based trading company. Under the project, 10 percent of the carbon payments are used to fund adaptation measures (Locatelli et al. 2011).

4.2. Adoption of Agroforestry

There are two main types of empirical agroforestry adoption studies: ex-post studies, which look at the adoption outcomes in given regions and use regression analysis to determine the impact of various factors; and ex-ante studies, which rely primarily on social and financial analyses of on-farm trials of agroforestry innovations to assess adoption potential (Mercer 2004). The most important ex-ante studies in the literature are Franzel and Scherr (2002), who review agroforestry studies in Kenya and Zambia, and Current et al. (1995), who review 21 agroforestry projects in Central America.

Current et al. (1995) suggested that a number of key factors affect the adoption of agroforestry in Central America. First, farmers are attracted to adopt agroforestry by financial results, based on the profitability of a given system compared to alternative land uses, the resource requirements of the given system, local costs of labor and materials, and local prices for tree products. Adoption is also affected by risk management issues, including the extent to which a given agroforestry system stabilized yields and provided multiple sources of income. Current et al. (1995) observed that farmers first adopt for family subsistence needs, and then pay attention to marketing opportunities, which are often increased by local producer organizations or NGO projects. The study also found that adoption is greater on large farms, though smallholders were not always excluded. In El Salvador, for example, 40 percent of participants in a community nursery program had less than one hectare of land (Current et al. 1995). Lack of formal land tenure decreased adoption but was not a binding constraint; in fact, lack of tree ownership and disposal rights was much more problematic.

Current et al. (1995) also found that external factors like demonstrations, technical assistance, training, provision of planting materials, programs to increase credit access, and other financial and material incentives increased adoption. With regard to extension, the report suggested that farmers adopt agroforestry gradually over a period of five to 10 years and discussed a successful program in Guatemala that saw 550 farmers adopt agroforestry over a five-year period. The authors argue that the program succeeded because the choice of the supplied seedlings was based on farmer input from community meetings. Farmers tend to prefer specific tree species for agroforestry based on their familiarity with the species, growth performance, ease of propagation and management, market values of products, multiple uses, and interactions with other crops (Current et al. 1995). In addition to formal extension, authors such as Besley and Case (1993), Conley and Udry (2003), and Acemoglu et al. (2008) emphasize the influence of social learning on technology adoption in general. Gamboa et al. (2010) found social networking to have a significant effect on agroforestry adoption in Ecuador.

In addition to the extensive work by Current et al. (1995), there are several ex-ante adoption studies that focus on LAC. For example, Vosti et al. (1998) discussed the adoption potential of cocoa and coffee intercropped with bandarra, rubber, and black pepper in the western Brazilian Amazon. They found that major constraints to agroforestry adoption by smallholders included investment requirements, negative cash flows in early years, and uncertain demand for agroforestry products. A study of silvopastoral systems in Costa Rica found that the primary barriers to adoption were high financial risk, incomplete knowledge, limited access to capital and markets, and the poor genetic quality of livestock (Jansen et al. 1997). In some cases cumbersome regulations and procedures, including restrictions on the harvest and transport of timber in agroforestry systems, have hindered adoption. Panama, Honduras, and Nicaragua still have very cumbersome regulations, but Guatemala and Belize have adopted simplified protocols that have improved farmer attitudes toward agroforestry (Somarriba et al. 2012).

Pattanayak et al. (2003) summarized the findings of 32 different studies, a few of which were conducted in LAC, and found that the most robust significant factors in agroforestry adoption include security of land tenure (included in 72 percent of studies, and positive in 100 percent of those cases), membership in a producer group (included in 44 percent of studies, positive in 100 percent of those cases), and access to extension (included in 32 percent of studies, positive in 100 percent of those cases). However, most studies of adoption look at land tenure as a simple binary variable—formal private tenure or lack thereof. The reality in many cases in LAC is much more complicated because of the prevalence of community tenure over both forests and agricultural land more generally. Examples of community land management include the *ejidos* of Mexico, community forestry concessions in Guatemala, indigenous territories in

Panama and Costa Rica, and the Mayangna territories in Nicaragua, to name just a few (Klooster and Masera 2000; Locatelli et al. 2011).

Other variables like education, market access, land size, and wealth have been included in many agroforestry adoption studies, but overall results have not been conclusive (Pattanayak et al. 2003). For example, some studies have found that wealthier farmers are more likely to adopt agroforestry because they are thought to be less risk-averse, have access to financing, and be more able to bear a short-term negative cash flow. Others have found that poor farmers in isolated areas are more likely to adopt agroforestry in order to diversify products for household subsistence (Adesina et al. 2000; Casey and Caviglia 2000; Mercer 2004; Sood and Mitchell 2006; Gyau et al. 2012). It is hard to compare across studies, however, because agroforestry can include many different tree species. In general, evidence suggests that wealthier, educated farmers with relatively large landholdings are more likely than smallholders to invest in relatively expensive seedlings that have delayed benefits in terms of tree products, effects on soil quality, etc. Alternatively, smallholders should be more likely to invest in relatively cheap seedlings that generate benefits relatively quickly.

Caviglia-Harris (2003) looked at the choice between using slash-and-burn agriculture and adopting more sustainable agricultural practices in Rondonia, Brazil. The practices examined included agroforestry, pisciculture, and apiculture, all of which were promoted by a local producer group called the Association of Alternative Producers (APA). Results showed that the most important determinants of adoption were membership in a cooperative union, the number of years that the family resided on the same lot, and knowledge of sustainable agricultural practices. Other significant factors that increased the probability of adoption were locality (e.g., adoption was highest in Ouro Preto, where APA was based), the number of female members in the household over age nine, and distance to the closest market center.

Jansen et al. (2006) looked at the effects of a number of factors on the adoption of several conservation methods, including tree planting, in hillside communities in Honduras. The report focused on the effect of a "livelihood strategy" among producers (e.g., coffee + grains, or grains + horticulture + livestock). Results showed that tree planting was highest for coffee + grain producers, but was also high for other coffee-based livelihood strategies. Tree adoption was also found to have a U-shaped relationship to local population density. It was also positively correlated with the number of external organizations active in the area that focused on integrated development or on production.

4.3. Lessons for Future Agroforestry Projects and Impact Analyses

This review suggests that some of the most promising agroforestry systems in LAC include shade-grown coffee, improved fallows, and efforts to connect small farmers engaging in agroforestry to carbon markets. On balance the literature finds positive effects of shade on coffee yield stability and sometimes even the level of yield, but work on other commercial crops is limited (Lin et al. 2008; Schroth et al. 2009). Leguminous trees can rehabilitate degraded land in as little as eight months, and a number of traditional systems in LAC already use fallows, so programs could build on and improve these systems in concert with small farmers (Kass and Somarriba 1999; Sanchez 1999; Kandji et al. 2006). Agroforestry has the highest estimated carbon sequestration potential of all climate-smart agriculture practices (Montagnini and Nair 2004; Oelbermann et al. 2004; Kandji et al. 2006), so it offers the greatest potential for smallholders to gain increased income from selling credits in the global carbon market.

As with the earlier climate-smart agriculture technologies examined in this paper, the impact of agroforestry in LAC needs to be expanded in geographic scope, as it is currently limited primarily to Costa Rica, Brazil, and Mexico (Somarriba et al. 2012). The effects of agroforestry vary widely by location (Muschler and Bonneman 1997), perhaps more than any of the other technologies discussed here, because the tree species most appropriate for agroforestry will vary geographically, and because of the variation in cropping systems and the most appropriate types of agroforestry arrangements. Some types of agroforestry may be inappropriate for certain regions and cropping systems because in some cases shade cover does lower crop yields significantly, and this may do more harm than good in places with major food security problems (Muschler and Bonneman 1997). Thus, a great deal of value-added can be gained by even basic research on different agroforestry varieties in different agro-ecological regions.

In terms of impact assessment, the dearth of basic data on expected gains from various species in different agro-ecologies poses difficulties for determining the expected gains from participation in agroforestry projects, and thus for determining the sample size for an impact evaluation. However, given acceptable information on expected gains, agroforestry projects are likely to be less complicated to evaluate than either conservation agriculture projects or public or community-based irrigation project interventions. Agroforestry projects, unlike forestry-based projects, are more likely to be undertaken on privately-controlled farm plots rather than on community land, even in systems operating under the communal tenure systems discussed above.[4] While most projects will have multiple components, they are unlikely to be as complicated and complex as conservation agriculture projects.

Probably the most critical issue to address is the potential for spillovers, both positive and negative. For instance, more trees on one farmer's plot may have a positive impact on soil quality on neighboring plots. Any plots affected by these spillovers would not be good candidates for "controls." Farmers who invest in new trees and bushes on their own plots may increase deforestation on other land (communal, protected areas) if the farmer previously harvested other species, such as fast-growing trees and shrubs, for timber, fodder, etc. Though less problematic for agroforestry projects than for reforestation and deforestation avoidance

[4] However, different community-based tenure regimes may affect adoption rates and this should be accounted for, for example by sampling relatively more "clusters" (communities) and fewer households per cluster, depending on how important this factor may be.

projects, existing land use needs to be well established in order to account for potential spillovers.

Finally, as with all of the climate-smart agriculture interventions, determining the impact on resilience, particularly to climate shocks, would improve if there were more observations on the same farmer/plot over time, rather than estimates of the impact on average yields. This can be accomplished mainly by implementing a very short mid-term survey that only collects information on yields for the past few seasons since the baseline, and then again, by asking recall questions for intervening seasons on the final follow-up survey.

In terms of potential implementation designs, given the potential for spillovers as well as equity concerns, the level of treatment is likely to be at the community level. For those species for which the benefits are expected to materialize relatively rapidly, a randomized roll-out may be the best option. If species to be introduced are relatively well known and inexpensive, an "intention to treat" via an encouragement design might be used (since under those circumstances the difference between those encouraged and those not encouraged is expected to be relatively high). Often, the most difficult problem with adoption of agroforestry is to ensure seedling survival, so some additional interventions specifically designed to ensure survival can be randomly assigned to different communities. Finally, to the extent that adoption of agroforestry generates positive environmental services (e.g., carbon sequestration), a project might actually design specific payment schemes for adoption. These can be somewhat difficult to evaluate due to site selection issues, as will be discussed in Section 6.

5. Soil and Water Conservation Structures

This section reviews structures for soil and water conservation, which include terraces, bunds, live barriers, contour cultivation, grass strips, diversion ditches, check dams, and irrigation pits. The goal of all these structures is to reduce run-off and soil erosion, which can help to increase yields, especially on steeply sloped land. Terraces are earth embankments constructed at a right angle in to order to create a flat surface for cultivation even on a hillside (Obalum at al. 2011). Bunds, also called contour banks, are small banks built along the contour of a slope that help to hold in ponded water (Obalum et al. 2011). Both terraces and bunds are often combined with contour cultivation, which consists of cultivating the land on or close to the contour, and at right angles to surface water flow. Each furrow acts as a small dam, slowing down the movement of run-off over the soil and giving the water time to infiltrate into the soil (Obalum et al. 2011). Diversion ditches are channels dug into a hillside that channel water during a high rainfall event, either directing the water into a natural waterway or a hillside irrigation pit, a small reservoir that can be used to later deliver water to terraced land. Check dams are small dams built across the drainage ditch that help to reduce gullying and allow sediments to settle.

There is significant overlap in the soil and water conservation literature on the other climate-smart agriculture practices covered thus far. For example, contour planting of trees and hedgerows is also covered in the agroforestry literature, while cover crops figure prominently both in conservation agriculture and soil and water conservation studies. Irrigation is also often intricately tied to soil and water conservation structures, because in many highland areas those structures are introduced together to make it possible to farm otherwise nonarable land. This section covers the effects of soil and water conservation structures on soil erosion and crop yields, as well as the factors affecting the adoption of soil and water conservation. Some of the papers reviewed discuss adoption of "conservation practices" in general, including but not limited to specific conservation structures. Thus, in some ways this section is a catch-all group for all remaining studies of sustainable practices that did not fit well into one of the previously discussed climate-smart agriculture categories.

5.1. Effects of Soil and Water Conservation Structures on Crop Yields

Pretty et al. (2006) reviewed 286 projects of various types in 57 developing countries, all aimed at promoting conservation and sustainable agricultural practices. Results showed that these practices increased production on 12.5 million of the 37 million hectares reviewed, that the average yield increase was 79 percent, and that the average increase in water-use efficiency was 257 percent. However, the Pretty et al. (2006) study was not limited to soil and water conservation structures and also included practices like integrated pest management, agroforestry, no-till, and aquaculture. Only a small number of papers on the effects of specific conservation structures could be found, and even fewer were specific to LAC.

Lutz et al. (1994) conducted a fairly comprehensive literature review of studies on soil erosion and the cost-benefit calculations of various soil and water conservation practices in Central America. The authors estimated the amount by which production should drop over time, in the absence of soil conservation methods, for several different crops in different countries. Results showed, for example, that coffee yields in Costa Rica would drop by 33 percent and corn yields in Honduras would drop by 61 percent in 30 years (Lutz et al. 1994). The report also estimated the internal rate of return (IRR), initial investment, and number of years needed to break even for several different soil and water conservation practices. For example, the report estimated that terraces for corn cultivation in Guatemala would generate a 15.6 percent IRR but would still take over 100 years to pay off because of high initial costs. In contrast, diversion ditches for corn cultivation in Honduras had lower initial costs and an estimated IRR of 21.9 percent or 56.5 percent (depending on the region of study) and thus a payoff period of only 18 or 4 years, respectively.

Swinton (2000) performed regression analyses on data from 197 farms in the Peruvian altiplano to estimate the effect of soil and water conservation practices on the level of erosion and crop yield loss. Results showed that soil losses over 20 years were significantly reduced by longer fallow periods and the use of vertical furrows. This latter result contradicted expectations and past studies, which suggested that furrows should be oriented perpendicular to a slope as in contour cultivation (Swinton 2000). With regard to crop yields, vertical furrows had no significant effect, but yields were significantly higher on land with longer fallows, in foot slope areas, and on non-sandy soils, a result confirmed by studies of the effect of fallow period length in Brazil (Silva-Forsberg and Fearnside 1997). Similarly, Hellin and Haigh (2002) looked at the effect of live barriers of vetiver grass on maize yields on steeply sloped land in Honduras. Results showed no significant difference in yields between the treatment and control plots, with one exception being in 1997, an unusually dry year caused by a severe ENSO episode. In that case, maize yields just above the live barriers in the treatment plots were 23 percent higher than those in the control plots, indicating that live barriers could play an important role in areas made drier by climate change, but may not be profitable under other circumstances.

Posthumus (2005) calculated the economic effects of adopting terraces in the Peruvian Andes. She stated that the primary benefit of terracing is increased water availability in the terraced land, which can increase productivity, though terracing also reduces the total surface area of agriculture and thus net profitability is not guaranteed and often requires a shift to a more intensified system or higher-value crop. Empirical results showed that grain yields were 79 percent higher when terraces were used on hills with a 25 percent+ slope in one study region (Pacucha). However, there was no significant difference for the full sample in Pacucha or for any subset in the other study region, Piuray-Ccorimarca.

In the Posthumus (2005) study, the estimated profitability of terracing was high in the dry years, with an IRR between 16 and 37 percent in 2002. The estimated profitability was dramatically lower in 2003, a wetter year (1 percent IRR). Furthermore, the marginal product of land was actually lower for terraced fields than for nonterraced fields in the Pacucha region because isolation and imperfect factor markets made intensification difficult. The opposite was the case in Piuray-Ccorimarca, which had better functioning markets and greater access to capital.

The literature also includes several case studies of soil and water conservation promotion projects in LAC. For example, Nimlos and Savage (1991) discuss the Sustainable Land Use Management Project (SULAMAN) in Ecuador, which promotes soil conservation via a variety of practices, including bunds, contour planting, and bench terraces, in addition to some conservation agriculture and agroforestry practices. Crop yields under the project's various management technologies increased significantly: 92 percent for garlic, 421 percent for peas, 216 percent for barley, 47 percent for beans, and 260 percent for potatoes. Furthermore, with terracing the value of the land increased dramatically, from about $65 to $900 per hectare (Nimlos and Savage 1991). Another case study in Piaui, Brazil by Oliveira et al. (2012), analyzed a community-led initiative to introduce new mulch for watermelon cultivation. Results showed that watermelon yields doubled with use of the mulch. The study did not look at net returns, however.

Ellis-Jones and Mason (1999) estimated the economic costs and benefits of planting live barriers for soil conservation in fields of *Phalaris*, a popular fodder crop in Bolivia. Using local data and simulation models, the report found that the economic viability of live barriers varied dramatically for irrigated versus nonirrigated plots, and based on the farmer's discount rate. For example, live barriers would not be viable even with a discount rate as low as 5 percent if the yield increase was 5 percent or less. If the productivity increase was 10 percent, then returns to live barriers would be positive, but only for irrigated fields and with a discount rate of 10 percent or lower. Assuming a 20 to 30 percent productivity increase and a discount rate up to 20 percent, live barriers would be profitable on irrigated plots in all regions and nonirrigated plots in only one of the study regions.

To summarize, several studies that attempted to estimate the economic profitability of soil and water conservation structures revealed that profitability varies dramatically based on type of structure, level of rainfall, degree of slope, type of soil, type of crop, local market conditions, and many other factors (Nimlos and Savage 1991; Lutz et al. 1994; Witter et al. 1996; Ellis-Jones 1999; Pagiola 1999; Posthumus 2005; Jansen et al. 2006). Not only does the rate of return to farmers define the ability of soil and water conservation to increase incomes, and thus facilitate climate change adaptation, it also is a crucial factor affecting adoption rates (Witter et al. 1996; Shiferaw and Holden 2001; Ellis-Jones and Mason 1999). It is crucial that future projects continue to estimate the rates of return to specific technologies under specific conditions, both prior to introduction of soil and water conservation practices (to the extent possible) and ex post. The literature also provides fairly clear evidence that soil and water conservation structures have the potential to stabilize crop yields in particularly dry years (Hellin and Haigh 2002; Posthumus 2005). This suggests that programs promoting soil and water conservation should target areas more vulnerable to climate change, both to maximize the positive effects of conservation for farmers and to increase adoption rates.

5.2. Adoption of Soil and Water Conservation Structures

Worldwide literature on the adoption of soil and water conservation structures suggests that some of the most important factors affecting adoption include the extent to which a given practice is expected to increase on-site productivity, estimated net economic returns to farmers, transactions costs, property rights issues, and use of participatory extension methods (Pagiola 1999; Cramb 2000; Smith et al. 2007). A few studies have estimated the factors affecting adoption specifically in countries in LAC, and these tend to be small-sample empirical studies. For example, in a case study of a new mulch-based conservation system for watermelon cropping in Brazil, Oliveira et al. (2012) found that adoption was increased by participatory methods involving farmers in the design process, and that it was increasing over time because collective benefits of the technology increased with greater adoption. Ashby et al. (1996) conducted a case study of factors affecting the adoption of live barriers for soil conservation in coffee farms in Colombia. They concluded that adoption was significantly increased by greater farmer participation at all levels of the process, including design, evaluation, and promotion of the selected soil and water conservation practices. For example, during the later years of the project farmers were invited to help select the species to be used in the live barriers, and this coincided with a big jump in adoption.

Case studies of the Plan Sierra conservation program in the Dominican Republic (Witter et al. 1996) and the SULAMAN project in Ecuador (Nimlos and Savage 1991) both found high levels of adoption, even in the absence of government subsidies, because of high private economic returns to participating farmers and strong extension efforts. Witter et al. (1996) directly asked farmers their reasons for adopting soil and water conservation practices, and the key responses were personal benefits from the conservation structures (43 percent), encouragement by family or friends who had previously adopted the practices (28.7 percent), and encouragement by Plan Sierra extension agents (24.6 percent). In their study of live barrier adoption in the inter-Andean valleys of Bolivia, Ellis-Jones and Mason (1999) concluded that profitability and thus adoption was higher for irrigated than for nonirrigated agriculture. The discount rate of a given farmer, local input and output prices, and the expected yield effects of the conservation structure were found to have an impact on adoption.

Hansen et al. (1987) applied a model used to test adoption of (unspecified) soil conservation practices in the United States to a sample of 281 farmers in the Ocoa watershed in the Dominican Republic. Results showed that extension, credit access, and attitudinal measures of the farmer's orientation to change (an index of positive responses to questions about taking risks and considering migration) and propensity to adopt (an index of positive responses to questions about willingness to attend trainings on conservation and to invest in conservation) were all significant and positively correlated with adoption.

The most comprehensive study on soil and water conservation adoption in LAC is Jansen et al. (2006), who tested factors affecting adoption of four different conservation practices (live barriers, contour planting, terraces, and tree planting) in hillside communities in Honduras. Although several factors were included in the regression analysis, the largest effort was directed toward estimating the effect of a "livelihood strategy" on adoption; that is, the income sources of the farmer (coffee + basic grains, basic grains + off-farm work + livestock, etc.). Results showed that the adoption of live barriers was increased by the number of community-based organizations in an area and the number of external organizations focusing on integrated development, but decreased by market access. The same results were observed for contour planting, except that external organizations did not have a significant effect. Terrace construction was significantly higher among farmers with the livelihood strategy coffee + basic grains. Construction also had a U-shaped relationship to population density, increased with local community organizations, and decreased with higher market access.[5]

Swinton's (2000) analysis of conservation practices in Peru's altiplano included a regression analysis of the two practices found to decrease soil erosion in that region: fallows and

[5] See Section 4 for a review of the results on tree planting.

vertical furrows. Results revealed that the length of the fallow period was increased by the value of well equipment available to a farmer, the number of adults in the household, membership in farmer associations, the existence of a previous natural resource project in the village, and the amount of land in a traditional collective crop rotation scheme. An increase in nonfarm income decreased fallow period length. The proportion of land planted to vertical furrows increased with association membership and for land in the footslope, but decreased for farmers with higher access to farming equipment and higher poverty levels, indicating adoption was highest for farmers with intermediate wealth levels.. Surprisingly, crop prices were insignificant in both regressions and the effect of access to equipment was not consistent across regression variables. It is notable that the social capital variable (association membership) was the sole variable positively correlated with adoption of both conservation measures (Swinton 2000).

Posthumus (2005) also conducted regression analysis of the factors affecting adoption of bench terraces, slow-forming terraces, infiltration ditches, and conservation practices as a whole in two villages in the Peruvian Andes. In the village of Pacuca, she found that:

- Steeper slopes increased adoption of bench terraces and soil and water conservation practices as a whole;
- Larger farm area increased adoption of both types of terraces;
- Both family size and percentage of farmland without stones decreased adoption of bench terraces and soil and water conservation practices in general;
- Education and age increased adoption for a subsample of farmers enrolled in one program (MARENASS);
- Farmers enrolled in MARENASS were much more likely to adopt soil and water conservation technologies than those enrolled in another program (PRONAMACHCS), though participants in both programs had higher adoption rates than nonenrolled farmers; and
- Market access increased the adoption of slow-forming terraces.

In the village of Piuray-Ccormarca the determinants of adoption were somewhat different. The most important factors included:

- Percentage of agriculture without irrigation access, which was positive for adoption of both general soil and water conservation and irrigation ditches;
- Long-term perspective of the head of household (positively correlated) and age (negatively correlated) for bench terraces;
- Farm area for slow-forming terraces;
- Risk-taking preference of the head of household; and
- Average distance from the house to the field for infiltration ditches.

5.3. Lessons for Future Soil and Water Conservation Structure Projects and Impact Analyses

A number of lessons can be drawn from this review of adoption of soil and water conservation structures. First, there are many different types of conservation structures, some of which have completely different effects and are appropriate in some conditions but not others. For example, adoption of terraces and grass strips was generally found to have a higher positive effect in dry areas, but structures like diversion ditches are more useful in high rainfall areas (Shiferaw and Holden 2001; Hellin and Haigh 2002; Posthumus 2005;).

In terms of factors affecting adoption specifically, risk-orientation and the long-term versus short-term view of farmers were found to play a significant role in perceived profitability of conservation structures and thus the level of adoption (Hansen et al. 1987; Ellis-Jones and Mason 1999; Shiferaw and Holden 2001; Posthumus 2005; Antle et al. 2006). Where attempts were made to evaluate the impact of the farmer discount rate on adoption of soil and water conservation structures, it was found to be a robust predictor of adoption. Future studies should make sure to take discount rates into account, but also need to take care to determine a reliable way of estimating them. The current literature has either assumed various discount values for the purpose of theoretical simulations (Ellis-Jones and Mason 1999; Shiferaw and Holden 2001) or used a qualitative index of attitudinal questions to estimate it empirically (Hansen et al. 1987; Posthumus 2005).

A number of case studies also suggested that the use of participatory methods in the development of soil and water conservation structures and their extension significantly increases the level of adoption, as do social network connections and group membership (Hansen et al. 1987; Ashby et al. 1996; Witter et al. 1996; Cramb 2000; Posthumus 2005; Oliveira et al. 2012). This can be particularly important given the evidence that expected returns and the rate of adoption vary dramatically by location (e.g., in the case of the dramatically different results between the two villages analyzed by Posthumus [2005] in Peru). However, no rigorous impact evaluation has been undertaken of the effects of this largely anecdotal, but well-motivated, evidence.

The current research on soil and water conservation structures in LAC tends to be limited mostly to Peru and certain Central American and Caribbean countries such as Honduras and the Dominican Republic (Hansen et al. 1987; Lutz et al. 1994; Witter et al. 1996; Swinton 2000; Posthumus 2005). To some extent it is necessary that this research be geographically limited, since conservation structures are most appropriate for highland areas with steep slopes. In fact, evidence suggests that economic returns and thus adoption levels are higher on more steeply sloped land (Posthumus 2005). However, empirical studies of both the effects and factors affecting adoption of conservation structures could be usefully expanded within LAC to more thoroughly cover more highland and hilly areas in the region.

In terms of impact assessment, as discussed above, there are many different types of structures and practices that fall under soil and water conservation, some of which have short-term benefits, but others whose benefits are delayed. For the latter, a longer time frame is needed to assess impacts and/or intermediate outcomes with clear links to the ultimate impacts that need to be identified. Given the location-specificity of many expected benefits, selecting controls will require relatively more information than is the case with other interventions. To a lesser extent, positive externalities are likely to be quite pronounced with many soil and water conservation interventions. As before, this has two main implications. The first is that understanding the range of these externalities will be crucial to determining where control farmers will be located (outside of the range of the externalities but still facing similar circumstances). The second is that community-level factors are also likely to be critical in fostering adoption of soil and water conservation structures, the more so the stronger are the externalities. This also argues for having the "treatment" level be at a higher level than the individual farmer.

Many soil and water conservation interventions require significant upfront investments by the farmer. This poses some issues for randomization. Take-up without subsidies can be low, but subsidies can be seen as unfair if randomly assigned within a community. At the same time, certain plots will generate greater public spillover benefits than others. In fact, some of the greatest benefits can be "downstream," which would then make a soil and water conservation intervention a candidate for a payment-for-environmental-services scheme, which is discussed in the next section.

6. Market and Governmental Institutions that Affect the Adoption of Climate-Smart Agriculture

6.1. Carbon Contracts and Other Payments for Environmental Services

For decades, some country governments and donor agencies have sponsored payment-for environmental-services (PES) programs that compensate farmers who adopt practices that support ecosystem services like biodiversity conservation or watershed protection. With the advent of global carbon markets under the Kyoto Protocol as well as voluntary carbon market schemes, there are an increasing number of PES programs that pay farmers to adopt practices that sequester carbon, including agroforestry and zero tillage.

PES programs take a number of different forms, but they tend to focus on channeling payments from various donors and the private sector, particularly hydroelectric companies, ecotourism operators, and businesses purchasing carbon offsets (Balvanera et al. 2012). In 2005, there were 287 ongoing PES programs aimed specifically at forest environmental services, watershed protection, landscape beauty, biodiversity, and carbon sequestration (Grieg-Gran et al. 2005). Currently only afforestation and reforestation projects qualify for funding under the UNFCCC's CDM program, with nine such projects in LAC as of February 2011 (Locatelli et al. 2011). Other international programs that focus on forestry PES programs include REDD+,[6] which has more than 40 active pilot projects in LAC alone, and the UNFCC Adaptation Fund, of which one of the first projects, initiated in September 2010, was a water management project in Honduras (Locatelli et al. 2011). The Adaptation Fund, which is financed by a 2 percent levy on CDM carbon offsets, is the only mechanism under the UNFCCC that explicitly links climate change mitigation and adaptation.

PES programs are currently on the rise in LAC, where they are actually more common than in any other region in the world. Costa Rica was the first country in LAC to establish such a program, in 1997, and the country currently has 29 such programs that have promoted conservation practices on a total of 251,124 hectares (Balvanera et al. 2012). Other countries in the region with a large number of PES programs include Mexico, which has 15 such programs covering 2.44 million hectares, Colombia (19 PES programs covering 1.16 million hectares, Brazil (11 PES programs covering 2.07 million hectares), and Bolivia (nine PES programs covering 609,305 hectares) (Balvanera et al. 2012). The highest payment rate among the programs was in Costa Rica, but as a share of income it was highest in Ecuador, where farmers earned up to 30 percent of income from PES payments (Grieg-Gran et al. 2005).

Carbon mitigation projects are the most common PES programs directly relevant to climate change. Payment for Environmental Services (*Pago por Servicios Ambientales* – PSA) in Costa Rica compensates land users for new plantations, sustainable logging, and conservation of natural forests. The costs of PSA are covered by a national tax on fossil fuels, which covers 80 percent of costs, and by the government sale of carbon credits originating from public protected areas, which covers the other 20 percent (Montagnini and Nair 2004). Unfortunately, most analyses of the program's impact in terms of reducing deforestation show it to be limited (Sierra and Russman, 2006; Sills et al., 2008). The primary reason seems to be that Costa Rica had put in place strict legal restrictions on deforestation before the PSA program got off the ground, so deforestation rates on "control" plots were also quite low.

The government of Mexico operates a similar program that focuses on forest conservation in hydrologically critical watersheds (Pagiola et al. 2005). There are NGO-based PES programs as well, including Fondo Bioclimatico in Chiapas, Mexico, which was set up in 1995 through a partnership between the El Colegio de la Frontera Sur (ECOSUR) and a coffee producers' union. It currently serves 450 farmers in 21 communities. ECOSUR scientists monitor and measure carbon sequestration and organize contracts between the producers and various European countries seeking to purchase carbon offsets (Nelson and de Jong 2003).

[6] An extension of the United Nations' program for Reducing Emissions from Deforestation and Forest Degradation (REDD).

Very few studies have evaluated the impact of PES programs on participants, but existing qualitative studies report positive effects that include improved local natural assets (soil, windbreak protection, water quality, tourism), increased knowledge and access to training, and increased income diversification (Grieg-Gran et al. 2005). However, PES programs face a number of challenges, including expensive monitoring and other implementation costs, the fact that administratively attractive flat payment rates often have limited adoption where land has differing opportunity costs in the target region, lack of clear directives and achievement criteria for participants, insecure land tenure, and weak legal support (Nelson and Chomitz 2002; Hall 2008; Southgate and Wunder 2009; Murillo et al. 2011). Furthermore, though many see PES programs as a way to improve the environment while also fighting poverty, others say that the programs can exacerbate poverty, particularly in regions with insecure land tenure, because they exclude landless workers from the land, and may cause land values to increase beyond the purchasing power of many poor farmers (Landell-Mills and Porras 2002; Kerr 2002; Grieg-Gran et al. 2005; Kosoy et al. 2008). Still others argue that programs aimed at preventing deforestation or afforestation are likely to simply displace deforestation to other areas, as reported by Alix-Garcia et al. (2012). The point of PES programs is in fact to generate positive spillovers, which need to be accounted for. The argument by Alix-Garcia et al. highlights the need to consider potential negative spillovers as well.

Nonetheless, a number of studies on the adoption of climate-smart agriculture have found a significant effect of subsidies and incentive programs. Several studies report a positive effect on the adoption of soil conservation practices (Ashby et al. 1996; Ellis-Jones and Mason 1999; Pagiola 1999; Posthumus 2005; Frangi et al. 2003; de Herrera and Sain 1999). A review of conservation agriculture adoption by Knowler and Bradshaw (2007) found four cases in which government subsidies had a positive effect (Napier and Camboni 1993; Swinton 2000), but a number of other cases where subsidies had no significant effect (Traoré et al. 1998; Soule et al. 2000). Several case studies suggest that input support programs, particularly subsidies for no-till equipment, have had a positive effect on the adoption of conservation tillage among smallholders (Erenstein et al. 2008, Kassam et al. 2009), though empirical evidence is slim for LAC. On the other hand, particularly for avoided deforestation or afforestation, Sills et al. (2008) determined that having land with little conversion value (i.e., having standing forests with little pressure to convert in the first place), along with the ability to convert nonenrolled land, increased participation, obviously muting the impact of the program on increasing forest cover.

Overall, there are few rigorous empirical studies specifically in Latin America on the effect of PES programs and subsidies in general for the four different target technologies. For most PES projects, the primary effects evaluated are the environmental services provided. The unit of analysis is then generally some land area or watershed, not the households that supply these services. This is not surprising, as the primary objective of these projects is to supply environmental services, though many programs have secondary objectives including improving the livelihoods of suppliers (Pattanayak et al. 2010). Studies that seek to assess both increases in environmental services and effects on supplying households must design a sampling framework for both levels. Finding suitable controls is often problematic at both levels. Payment programs want to target what preexisting information indicates are lands or watersheds that provide the highest environmental services, and also prefer to enroll motivated landowners who they believe will adopt and sustain practices that generate those services. Spillovers are of course widespread (Arriagada et al. 2012; Pfaff et al. 2008).

One method to identify controls arises when more landowners enroll in a program than can be inscribed. If landowners provide a similar quality of services—which is indeed a big "if" —then random selection could be used. Randomized roll-outs may also be possible, but, again, they are far more difficult to justify in the absence of a large number of landowners supplying relatively similar services. Alternatively, if the program explicitly wishes to include high-value land (in terms of environmental services to be provided), then a "discontinuity" design based on eligibility criteria may be employed. In this case, matched controls can be found among those who enrolled but nonetheless were denied entry, but who were close to matching the required criteria for participation. For example, in Mexico, a program called Payments for Hydrological Environmental Services used eligibility criteria to determine program participation, and Alix-Garcia et al. (2012) used information on those denied entry to match controls.

Nonetheless, those interested in designing an impact assessment need to be aware of how difficult it is in particular to find controls ex ante and to determine if multiple methods can be used in the event that randomization of treatment and controls does not work as expected. A case in point is the Regional Integrated Silvopastoral Approaches to Ecosystem Management Project that ran from 2002 to 2008 and was funded by the Global Environment Facility and the World Bank. This was a carefully designed project with the explicit objective of measuring impact and employing quasi-experimental techniques in Costa Rica, Nicaragua, and Colombia. However, the project was also innovative and complex in its implementation and in its requirements of participants. As documented in Vaessen and van Hecken (2009), the sophisticated impact evaluation design combined with a new and complex project led to a number of unintended responses by both farmers and project implementers that made comparisons of the treated and control groups quite difficult.

6.2. Agricultural Insurance Programs for Climate Change Risk Mitigation

Another economic institution factor that could play a major role in farmer adaptation to climate change is insurance. Weather insurance, whether private or government-sponsored, helps to mitigate farmers' risk from climate change. This could either serve as a complement to promoting climate-smart agriculture practices—since both help with adaptation—or it could slow such adoption, since those with insurance are more susceptible to moral hazard. It is important to understand the different existing and potential insurance instruments, some of which avoid the moral hazard problem, and to analyze their effects on adoption of climate-smart agriculture and adaptation to climate change as a whole.

Climate change presents both new threats and new opportunities to the global insurance industry. Threats include the compounding of climate change risk across the entire portfolio, particularly for agricultural insurance and emerging markets, which raises costs of operations. Opportunities include the increased need and willingness to pay for insurance among developing-country farmers and the advent of a number of new products like weather derivatives, cat bonds, microinsurance, and hedge funds that invest in greenhouse gas emission credits (Mills 2007). Weather derivatives are put-and-call options based on weather indices, which can be purchased by farmers or other actors to hedge climate risk. Cat bonds, or catastrophe bonds, are sold either by the government or insurance companies and pay investors 3 to 20 percent interest in years without a natural disaster, but in years with a natural disaster the investors forfeit their interest, which is used to pay claims to policyholders. Microinsurance targets low-income people and involves small premiums and low coverage caps to reduce the level of risk to insurance companies.

The UNFCCC specifically calls on the parties of the agreement to consider insurance-related instruments to help low-income countries adapt to climate change. Disaster-related losses globally were $54 million annually in 2004, and as a share of national income losses in developing nations are double the losses in developed nations (Arnold and Kreimer 2004). As an example of the huge risks posed by weather, Hurricane Mitch increased the number of poor people in Honduras by 165,000, and four years after the storm GDP was 6 percent lower than what had been projected prior to the disaster (Linnerooth-Bayer and Mechler 2006). Insurance schemes could help reduce the impact of storms and other disasters exacerbated by climate change.

More than 40 percent of farmers in developing countries face threats to their livelihoods from adverse weather, but only 1 percent of households in low-income countries and 3 percent of households in middle-income countries have catastrophe coverage, compared to 30 percent in high-income countries (Linnerooth-Bayer and Mechler 2006). Currently, LAC has a very low penetration of agricultural insurance, with only 1.5 percent of world market premiums (Candel 2007). The insurance coverage that does exist is not equitably distributed among income classes or across countries. Within LAC, Brazil accounts for 27 percent of insurance coverage, Mexico for 25.7 percent, and Puerto Rico for 13.4 percent, although residents of Puerto Rico have access to the U.S. National Flood Insurance Program, so coverage is disproportionately high (Candel 2007). A review by Mills (2007) of agricultural insurance in LAC reveals additional differences across countries. For example, Argentina insures 30 percent of its total area, all through private insurance, and the majority of plans pay 60–90 percent of the difference between actual and historical yields. By contrast, only 2 percent of cropped area in Chile is insured, through a mix of public and private insurance with subsidized premiums.

LAC countries, in fact, have been the pioneers of multi-peril insurance, with programs established in Brazil in 1954, Costa Rica in 1970, Mexico in 1971, Chile in 1980, and the Dominican Republic and Venezuela in 1984 (Wenner 2005). Multi-peril insurance is the most attractive type of insurance for farmers, but it also entails much higher losses and requires much higher overhead costs, because of the need to monitor many claims, and it is often cost-prohibitive without government subsidies (and leads to high deficits for the government). Those countries that have higher insurance penetration tend to be those which have supported the development of alternative instruments that reduce moral hazard and risk. This is the case in Mexico, which has one of the largest and most successful government crop insurance programs in LAC. Unlike many of the other government insurance programs in the region, Mexico's program has been operating profitably since 2000 (Mills 2007). Over 15 percent of cropped area is insured, and many different products are offered, including yield loss, revenue loss, and cost coverage insurance, as well as a weather-based index insurance option. In the 1960s the Mexican government offered 45–61 percent premium subsidies for crop insurance, making the purchase of insurance a prerequisite to obtain a bank loan. The system was liberalized in the 1990s and currently offers a 30 percent subsidy, provides cat bonds and index insurance options, and reduces moral hazard by only insuring 70–90 percent of losses (Mills 2007; Linnerooth-Bayer and Mechler 2006).

A number of studies explore the role that insurance can play in helping low-income countries adapt to climate change. Some scholars have found that insurance is a superior way to deal with climate risk when compared with ex-post disaster relief programs, since the latter are often ad hoc, untimely, not properly organized and targeted, increase public deficits and/or dependence on foreign aid, and increase moral hazard (Mills 2007). On the other hand, crop insurance may potentially increase moral hazard and thus decrease adoption of climate-smart agriculture practices. That is, when farmers know that they will receive a pay-off if their production is low, they have an incentive not to invest in labor time, inputs, and adaptation technologies that can help keep yields high. This is particularly a problem of multi-hazard insurance with general premiums based on individual crop losses. The problem can be mostly avoided if index insurance is used, where all farmers in an area receive an automatic payout based on general weather patterns in their region (Besley 1995; Hess 2003; Carter et al. 2004; Barnett and Mahul 2007; Collier et al. 2009). When moral hazard is reduced, insurance may actually help stimulate adoption of climate-smart agriculture practices by serving as a price signal. That is, where farmers have no concept of the monetary value of adaptation, insurance premiums act a as a gauge of this value and farmers are in some cases more likely to adopt climate-smart agriculture if the cost is below that of the insurance premiums (Collier et al. 2009).

In addition, insurance companies actually support climate change adaptation and mitigation efforts in order to help reduce the level of risk in their portfolios. For example, Storebrand, Norway's largest insurance company, has invested in sustainable forestry practices, and the insurance company Swiss Re has contributed to reforestation efforts in Haiti (Mills 2007). The Caribbean Disaster Mitigation Project is an example of a successful public-private partnership to support climate change adaptation efforts: United Insurance partnered with the U.S. Agency for International Development and several local NGOs to help homeowners retrofit their homes against hurricanes, and they received reduced insurance premiums as a result (Mills 2007). Though this particular example is not in the agricultural sector, similar programs could be designed for agriculture in the future.

7. Concluding Comments

There are numerous types of projects that can contribute to climate change adaptation and/or mitigation in the agricultural sector. This paper has reviewed four major types of land use and management projects: conservation agriculture, irrigation, agroforestry, and soil conservation structure. It has also examined two prominent institutions that affect adoption of land management: payment-for-environmental-services programs, and weather-related insurance. The aim of the paper has been to synthesize the empirical evidence on the likely farm-level effects of various land management techniques and on participation in PES contracts schemes or insurance, and to identify which factors are most important in explaining adoption. Information on likely effects and the most important conditioning factors inform the types of data collection that should be included in the monitoring and evaluation frameworks and impact evaluations for future projects. In addition, different types of projects have unique characteristics that need to be taken into consideration when designing the impact evaluation strategy.

While there is a good deal of empirical evidence on likely effects and on the most important conditioning factors affecting adoption of most of the practices discussed in this paper, evidence does tend to be concentrated in just a few countries (e.g., Mexico and Brazil). Because effects tend to be rather site-specific, future impact evaluations outside of Mexico and Brazil should aim to generate valuable information to help guide policies on how to best promote adaptation to climate change in the agriculture sector, and on how to best capture potential mitigation benefits. On the other hand, there has been limited success in evaluating the effects of PES schemes and weather insurance products. PES projects tend to be quite complex and highly dependent on self-selection, making random allocation into “treatment” quite complex. The few attempts to evaluate insurance programs have also run into difficulties. Often, in the initial stages, the actual product offered changes every season, making it difficult to isolate factors affecting up-take. There is thus a wide scope for drawing on lessons learned to better design and implement impact assessments for both PES and weather insurance, which should be of great interest to Latin American governments.

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