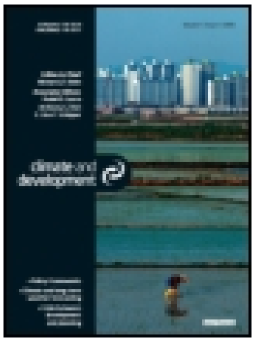

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RESEARCH ARTICLE

Vulnerability of smallholder farmers to climate change in Central America and Mexico: current knowledge and research gaps

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As governments are becoming aware of the potential impacts of climate change on agriculture many are developing adaptation policies targeting smallholder farmers. However, in many cases, governments lack information to develop them. We reviewed the state of knowledge of smallholder's vulnerability to climate change in Central America and Mexico and identified information gaps that may be preventing the development of adaptation actions targeting this group. While there is information on expected impacts of climate change on agriculture and on adaptation measures that could help minimize impacts, information that specifically assess the vulnerability of smallholder farmers to climate change is very limited. To support adaptation policies targeting smallholders in the region, more information is needed on (a) who the most vulnerable smallholders are and where they are located, (b) what is driving the vulnerability of smallholder farmers to climate change in target areas and (c) what are the effectiveness, costs and benefits of adaptation measures recommended for smallholder farmers. Funding and programmes need to be set up to fill those gaps and for adaptation to be effectively implemented. Other regions where smallholder farmers are important for agriculture production may be facing similar issues.

Keywords: adaptive capacity; adaptation measures; adaptation policies; climate change impacts; research needs

1. Introduction

Smallholder farmers represent 75% of the world's farms (Lowder, Skoet, & Raney, 2016), comprise 60% of the agricultural workforce worldwide (Fyfe, 2002) and provide over 80% of the food consumed in the developing world (UNEP, 2013). Even though there are no widely-accepted definition of smallholder farmers (Morton, 2007), most of them depend on their production for both food security and income, cultivate small areas (less than 10 ha) and often use family labour (Cornish, 1998; Nagayets, 2005). Despite the importance of smallholder farmers to the agricultural sector, they often have limited resources to maintain or increase agricultural productivity, live in environmentally fragile and remote locations, and are often marginalized from social and development assistance programmes (Harvey et al., 2014; Vorley, del Pozo-Vergnes, & Barnett, 2012). Many smallholder farmers are also affected by ongoing stressors such as the fragmentation of landholdings (Vorley et al., 2012), the unpredictability in the prices of many agricultural commodities and the existence of regionalized and globalized markets, which brings smallholder farmers into direct competition with industrial-scale farming (Morton, 2007).

Climate change is a threat that further exacerbates the already precarious life conditions of many smallholder farmers. They are considered one of the most vulnerable groups to climate change (Morton, 2007) due to: (i) their high reliance on ecosystem goods and services that are under increasing pressure (Fischlin et al., 2007; Millennium Ecosystem Assessment, 2005) as a result of climate change, (ii) their low capacity to adapt to changes (Adger, Huq, Brown, Conway, & Hulme, 2003), (iii) their dependence on rainfed crops (Eakin, 2005; Lobell et al., 2008) and (iv) their location in marginal landscapes (such as hillsides, deserts and floodplains), where their farms are exposed to a variety of climatic hazards (Morton, 2007; UNEP, 2013). Smallholder farmers are also considered vulnerable to climate change due to the direct and negative impacts of climate change on the suitability (Hannah, Ikegami, Hole, Butchart, & Peterson, 2013) and productivity (Lobell et al., 2008) of crops they rely on for both subsistence and income.

One of the regions where smallholder farmers are expected to be highly impacted by climate change is Central America and Mexico (see Hannah et al., 2013). Despite contributing less to GDP compared to past

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decades, agriculture is still an important economic activity in this region (accounting for 2.7% to 13.5% of GDP across individual countries, data from 2016, http://data.worldbank.org/indicator/NV.AGR.TOTL.ZS), and much of the agriculture production is conducted by smallholder farmers, which are highly depend on this activity for their food security (Tucker, Eakin, & Castellanos, 2010). Smallholder farmers are composed of 2.3 million families in Central America (PRESANCA & FAO, 2011), which are mainly (90%) located in Guatemala, El Salvador, Honduras y Nicaragua (PRESANCA & FAO, 2011).

In Central America, climate change and variability have had significant impacts on agricultural productivity (Salinas-Zavala & Lluch-Cota, 2003; Schroth et al., 2009) and suitability (Laderach et al., 2013) for both cash and subsistence crops. Several modelling suggests that most of the countries in the region will experience a reduction in coffee production (CEPAL & CAC/SICA, 2014a) and in the area suitable for coffee cultivation (Baca, Laderach, Haggar, Schroth, & Ovalle, 2014; Bunn, Läderach, Ovalle Rivera, & Kirschke, 2015; Laderach et al., 2013; Ovalle-Rivera, Laderach, Bunn, Obersteiner, & Schroth, 2015) due to climate change. Climate change have also contributed to past coffee rust crisis in Central America (Avelino et al., 2015). Changes in the production of maize (CEPAL & CAC/SICA, 2014a, 2014b; Gourdji, Laderach, Valle, Martinez, & Lobell, 2015; Schmidt, Eitzinger, & Sonder, 2012) are also expected in the region, but there is limited information on how the suitability and productivity of beans, cocoa, cassava, sorghum, and rice will be affected by climate change in the region (Hannah et al., 2017). As climate change is expected to continue impact this region (Aguilar et al., 2005; Hannah et al., 2013, 2017; Magrin et al., 2007), the adaptation of smallholder farmers to the changing climate is listed as a priority in some national agricultural and climate change policies and programmes (Cuéllar, Luna, Díaz, & Kandel, 2013; Dirección de Cambio Climático, 2014; Gobierno de la República de Honduras, 2015; Ministerio Agropecuario y Florestal, 2013; Ministerio de Agricultura, Ganadería y Ambiente, 2012; República de Guatemala, 2015).

The objectives of this paper are to assess what is known about the climate change vulnerability of smallholder farmers that grow subsistence and cash crops in Central America and Mexico and to identify key information gaps that exist in our understanding of this issue. Using a detailed literature review, we examined: (a) what is known about the impacts of climate change on smallholder farmers in the region?, (b) who are the most vulnerable smallholder farmers and where are they located?, (c) what adaptation measures have been used by smallholder farmers or recommended to reduce their vulnerability?, and (d) what information gaps exist in our understanding of smallholder farmer vulnerability to climate change in the region?

2. Methods

We conducted a literature review to identify studies that address the climate change vulnerability of smallholder farmers that grow subsistence and cash crops to climate change in Central America and Mexico. We found peer-reviewed papers through searches in Mendeley and Google Scholar (see Table A1 for the keywords used), and project reports, dissertations and policy briefs through searches in Google, in the websites of institutions that lead or support climate change adaptation and development projects in the region (IUCN, CIAT, World Vision, World bank, IDB, Catholic Relief Services, CATHALAC, CIRAD, GIZ climate change programme, OXFAM, CATIE and UNAN) and online platforms that list and describe adaptation projects (e.g., CI grasp: http://pik-potsdam.de/cigrasp-2/ and WeADAPT: https://weadapt.org/). We reviewed documents published from 1997 to 2017.

We extracted and summarized the information on the following topics: (a) the impacts of climate change on smallholder farmers, agriculture and water resources, (b) the identification and location of the most vulnerable smallholder farmers, and (c) the adaptation measures used by or recommended for smallholder farmers. Studies that did not present specific information on at least of one of those topics were not used in this review. Studies addressing how climate change may impact farmers, agriculture (i.e. crop suitability and productivity) and water resources were assigned to the first topic, and information summarized included target country and cropping systems, expected or projected impacts and timeframe used. Studies that present information on location and identify the most vulnerable farmers were included in the second topic, and existing information was organized by country, cropping system, identification of who and where the most vulnerable are located, the reason for the high vulnerability, spatial and temporal scales used and the indication of whether spatially explicit information was provided. Studies that present information on adaptation measures either used by farmers or recommended to reduce their vulnerability were assigned to the third topic. We then identified gaps in the information that we summarized related to those three topics that may be preventing the developing of adaptation policies targeting smallholder farmers in the region.

3. Results

We found a total of 52 studies (Table A2) that examined some aspects of the relationship among climate change, smallholder farmers and agriculture in Central America and Mexico. Twenty-six of those studies address current or perceived impacts, twenty-three address future impacts and three studies address both. The documents that we reviewed included 26 projects reports, 22 papers, three dissertations and one policy brief and provided information on at least one of the topics described below.

3.1. *What is known about the impacts of climate change on smallholder farmers in the region?*

Twenty-eight studies describe the impacts of climate change on the agriculture and water sectors. Studies present results on the impacts of climate change in both crop yield and suitability, and in water availability and runoff. Studies have different levels of details, timeframes and scenarios used (see Table 1). Overall, a decrease in suitability and yield is expected in the region for beans, coffee, maize, plantain and rice. Decrease in suitability is expected to be more pronounced towards the end of the century in the region for beans, maize, rice and coffee (CEPAL & CAC/SICA, 2014a, 2014b). Decreases in water availability and runoff are also projected in several studies and for the whole region (ECLAC, 2010; Imbach et al., 2012).

Studies show that coffee yield may slightly increase in Costa Rica, El Salvador, Guatemala, Honduras and Panama (CEPAL & CAC/SICA, 2014a). Maize suitability and bean suitability and yield may also increase slightly in Guatemala, Honduras and Mexico (Bouroncle et al., 2017; Conde et al., 1997; Eitzinger, Laderach, Rizo, Pantoja, & Gordon, 2011; Pazos, 2004; Schmidt et al., 2012). Cassava is expected to increase suitability between 1% and 5% in Guatemala, El Salvador, Honduras and Nicaragua (Bouroncle et al., 2017) and wheat production in Mexico increases during El Niño events and decreases during La Niña events (Chatzopoulos, 2008). Small increases in water availability and runoff are expected in all countries of Central America under certain climate scenarios and timeframes, expect in Costa Rica (ECLAC, 2010; Imbach et al., 2012).

Most of those studies that address the impacts of climate change on crop suitability and yield, and water availability do not, however, mention how those results will lead to the vulnerability of smallholder farmers. One exception is Bouroncle et al. (2017), which presents the results of a vulnerability assessment of smallholder agriculture considering impacts of climate change on crop suitability. Two studies highlight some of the impacts of extreme events on smallholder farmers or rural populations. For example, hurricane Mitch had a stronger impact on population groups with low income and low adaptive capacity (Castellanos & Guerra, 2009) and increases in the frequency of climate extremes led to increases in the food insecurity of rural families in Honduras and Nicaragua (Oxfam, 1998).

3.2. *Who are the most vulnerable smallholder farmers, where are they located and how has their vulnerability been assessed?*

Of the 52 studies we used in this review, only nine measure the vulnerability of smallholder farmers to climate change, and identify farming groups or communities that are most vulnerable to climate change, indicating the reason for the high vulnerability (Table 2). Geographic coverage of those studies includes Mexico, Guatemala, Honduras, El Salvador and Nicaragua, although geographic distribution within those countries is limited, as only two studies show information for all municipalities within a country (i.e. Alayon-Gamboa & Ku-Vera, 2011; Bouroncle et al., 2017). Six studies identify the farming systems in which the work focused on, with maize being the most common crop studied. Other farming systems include coffee, tea, Jalapeño pepper, sweat pea, beans, sorghum, sunflower, soy, rice, plantain and cassava. There is also a variation in the temporal scale used across studies. Four studies consider a future time frame (2020–2050) when assessing vulnerability, whereas three consider vulnerability to hurricanes in past or present time frames (Table 2).

Six studies that measured the vulnerability of smallholder farmers to climate change indicate the definition of vulnerability used (Table 3). Whereas four of the studies consider 'vulnerability' as the combination of exposure, sensitivity and adaptive capacity (Bellon, Hodson, & Hellin, 2011; Bouroncle et al., 2017; CIAT, 2011; Eakin, Webhe, Ávila, Torres, & Bojórquez-Tapia, 2006b), as defined by the IPCC (Parry, Canziani, Palutikof, van der Linden, & Hanson, 2007), the other two considered 'vulnerability' to be the capacity of a group to anticipate, cope with, resist and recover from the impacts of natural disturbance (Alayon-Gamboa & Ku-Vera, 2011), and the combination of sensitivity and adaptive capacity (PNUD, 2013). This is somewhat expected given that there is no widely accepted version of such definition (Tonmy, El-Zein, & Hinkel, 2014) and that IPCC has changed the way vulnerability is defined in the most recent report (see Parry et al., 2007 vs. Oppenheimer et al., 2014). Similarly, there is no consistency in the indicators used to measure each of the components of vulnerability (exposure, sensitivity and adaptive capacity), although most of them use a combination of biophysical and socioeconomic components to assess vulnerability (Table 3).

Two additional studies identified factors influencing the vulnerability of smallholder farmers or smallholder agriculture, but did not use indices to measure vulnerability. In Nicaragua, landscape fragmentation, functional biodiversity, production, and stability of crop productivity in agricultural lands affect ecological resilience of systems; human capital supply, wealth equality, income, food security and profit affect the individual ability to adapt to change, and social ties and safety nets affect local institutional capacity to buffer and respond to crisis (Ravera, Tarrasón, & Simelton, 2011). Eakin (2003b) shows that the interaction of market uncertainty, price volatility and climatic risk may exacerbate the vulnerability of farmers growing irrigated vegetables in Mexico.

Table 1. Information on the impacts of climate change on crop suitability and yield provided by studies found using key words listed in Appendix 1.

Cropping system	Variable	Impacts	Country	Time frame	References
Banana	Yield	Decrease	Central America	Perceived	Adaptation Partnership (2012)
Beans	Yield	Changes between 3% and −66%	Guatemala	2050	MARN (2007)
Beans	Yield	Decrease of 7%	El Salvador	2025	Schmidt et al. (2012)
Beans	Yield	Increase of 4%	Guatemala	2025	Schmidt et al. (2012)
Beans	Yield	Decrease of 14%	Honduras	2025	Schmidt et al. (2012)
Beans	Yield	Decrease of 14%	Nicaragua	2025	Schmidt et al. (2012)
Beans	Yield	Increase	Honduras	NA	Pazos (2004)
Beans	Yield	Decrease of 5% per decade	Nicaragua	Climate variability	Gourdji et al. (2015)
Beans	Yield	Decrease between 14% and 19%	Belize	2060, 2080, 2100	Tzul, Evans, Frutos, and Hulse (1997)
Beans	Yield	Decrease for all countries except Guatemala	Central America	2020, 2050, 2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Yield	Decrease from −1% to −7%, depending on season	El Salvador	2020	Eitzinger et al. (2017)
Beans	Yield	Changes from −2% to + 6%, depending on season	Guatemala	2020	Eitzinger et al. (2017)
Beans	Yield	Decrease between −4 and −9% or no change, depending on season	Honduras	2020	Eitzinger et al. (2017)
Beans	Yield	Changes between −4 and +7%, depending on season	Nicaragua	2020	Eitzinger et al. (2017)
Beans	Yield	Decrease	Central America	2100	ECLAC (2010)
Beans	Yield	Could fall to zero	El Salvador	2100	ECLAC (2010)
Beans	Yield	Could fall to zero	Guatemala	2100	ECLAC (2010)
Beans	Yield	Change between 3% and −17% (depending on timeframe and scenarios)	Guatemala	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Yield	Decrease between 4% and 48% (depending on timeframe and scenarios)	El Salvador	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Yield	Decrease between 3% and 42% (depending on timeframe)	Honduras	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Yield	Decrease between 7% and 47% (depending on timeframe)	Costa Rica	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Yield	Decrease between 5% and 54% (depending on timeframe)	Nicaragua	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Yield	Decrease between 1% and 70% (depending on timeframe)	Panama	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Yield	Decrease between 6% and 53% (depending on timeframe)	Belize	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Beans	Suitability	Decrease of 11%	Guatemala	2030	Bouroncle et al. (2017)
Beans	Suitability	Decrease of 29%	El Salvador	2030	Bouroncle et al. (2017)
Beans	Suitability	Decrease of 23%	Honduras	2030	Bouroncle et al. (2017)
Beans	Suitability	Decrease of 29%	Nicaragua	2030	Bouroncle et al. (2017)
Cacao	Suitability	Change between 20% and −40% in most of the areas (depending on timeframe)	Nicaragua	202,020,302,050	Martinez (2012)
Cassava	Suitability	Increase of 5%	Guatemala	2030	Bouroncle et al. (2017)
Cassava	Suitability	Increase of 1%	El Salvador	2030	Bouroncle et al. (2017)
Cassava	Suitability	Increase of 5%	Honduras	2030	Bouroncle et al. (2017)
Cassava	Suitability	Increase of 4%	Nicaragua	2030	Bouroncle et al. (2017)
Coffee	Suitability	Decrease of 1%	Guatemala	2030	Bouroncle et al. (2017)

Coffee	Suitability	Decrease of 22%	El Salvador	2030	Bouroncle et al. (2017)
Coffee	Suitability	Decrease of 18%	Honduras	2030	Bouroncle et al. (2017)
Coffee	Suitability	Decrease of 18%	Nicaragua	2030	Bouroncle et al. (2017)
Coffee	Suitability	Decrease in the area where coffee has a suitability of 30%–90%	Guatemala	2050	CIAT (2012a)
Coffee	Suitability	Decrease in the area where coffee has a suitability of 10%–90%	Nicaragua	2050	CIAT (2012b)
Coffee	Suitability	Decrease in the area where coffee has a suitability of 30%–70%	Mexico	2050	CIAT (2012c)
Coffee	Suitability	Decrease in the area where coffee has a suitability of 20%–80%	El Salvador	2050	CIAT (2012d)
Coffee	Yield	Decrease	Central America	Perceived	Adaptation Partnership (2012)
Coffee	Suitability	Decrease in 40% or more in a high percentage of the country	El Salvador	2050	Baca et al. (2014)
Coffee	Suitability	Decrease in 40% or more in a high percentage of the country	Nicaragua	2050	Baca et al. (2014)
Coffee	Suitability	Decrease in up to 20% in the highest percentage of land	Guatemala	2050	Baca et al. (2014)
Coffee	Suitability	Decrease in 20% in suitable areas	Costa Rica	2050	Ovalle-Rivera et al. (2015)
Coffee	Suitability	Decrease in 19% in suitable areas	Guatemala	2050	Ovalle-Rivera et al. (2015)
Coffee	Suitability	Decrease in 27% in suitable areas	Honduras	2050	Ovalle-Rivera et al. (2015)
Coffee	Suitability	Decrease in 40% or more in a high percentage of the country	El Salvador	2050	Laderach et al. (2013)
Coffee	Suitability	Decrease in 40% or more in a high percentage of the country	Nicaragua	2050	Laderach et al. (2013)
Coffee	Suitability	Decrease in 40% or more in a high percentage of the country	Costa Rica	2050	Laderach et al. (2013)
Coffee	Suitability	Decrease in up to 20% in a high percentage of the country	Guatemala	2050	Laderach et al. (2013)
Coffee	Suitability	Decrease between 20 and 40% in a high percentage of the country	Honduras	2050	Laderach et al. (2013)
Coffee	Suitability	Decrease in up to 20% in a high percentage of the country	Mexico	2050	Laderach et al. (2013)
Coffee	Suitability	Decrease in for most of the growing area	Guatemala	2050	Bunn et al. (2015)
Coffee	Suitability	Decrease in most of the growing area	Honduras	2050	Bunn et al. (2015)
Coffee	Suitability	Decrease in most of the growing area	Costa Rica	2050	Bunn et al. (2015)
Coffee	Suitability	Decrease in most of the growing area	Panama	2050	Bunn et al. (2015)
Coffee	Suitability	Decrease in most of the growing area	Belize	2050	Bunn et al. (2015)
Coffee	Suitability	decrease in most of the growing area	Nicaragua	2050	Bunn et al. (2015)
Coffee	Yield	Decrease between 6.4% and 38.3%, depending on timeframe	Central America	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)
Coffee	Yield	Decrease between 4% and 45% (depending on timeframe)	Belize	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)
Coffee	Yield	Changes between 2% and −36% (depending on timeframe and scenario)	Costa Rica	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)
Coffee	Yield	Changes between 0.3% and −57% (depending on timeframe and scenario)	El Salvador	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)

(*Continued*)

Table 1. Continued.

Cropping system	Variable	Impacts	Country	Time frame	References
Coffee	Yield	Changes between 2% and −35% (depending on timeframe and scenario)	Guatemala	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)
Coffee	Yield	Changes between 2% and −32% (depending on timeframe and scenario)	Honduras	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)
Coffee	Yield	Decrease between 4% and 53% (depending on timeframe and scenario)	Nicaragua	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)
Coffee	Yield	Changes between 3% and −82% (depending on timeframe and scenario)	Panama	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014a)
Maize	Yield	Decrease between 1% and 21%	Guatemala	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Maize	Yield	Decrease between 3% and 37%	El Salvador	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Maize	Yield	Decrease between 4% and 42%	Honduras	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Maize	Yield	Decrease between 5% and 30%	Costa Rica	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Maize	Yield	Decrease between 6% and 45% in yield	Nicaragua	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Maize	Yield	Decrease between 2% and 43% in yield	Panama	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Maize	Yield	Decrease between 6% and 43% in yield	Belize	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Maize	Suitability	Increase of 14%	Guatemala	2030	Bouroncle et al. (2017)
Maize	Suitability	Increase of 11%	Honduras	2030	Bouroncle et al. (2017)
Maize	Yield	Changes in yield between 8% and −34%	Guatemala	2050	MARN (2007)
Maize	Yield	Decrease	Honduras	NA	Pazos (2004)
Maize	Yield	Decrease in 4% per decade in harvested area	Nicaragua	Climate variability	Gourdji et al. (2015)
Maize	Yield	Decrease in all countries between 4% and 17%	Central America	2020,2050,2040, 2100	CEPAL & CAC/SICA (2014b)
Maize	Yield	Decrease between 17% and 22%	Belize	2060, 2080, 2100	Tzul et al. (1997)
Maize	Yield	Decrease in up to 34%	El Salvador, guatemala, Honduruas and NIcaragua	2025	Schmidt et al. (2012)
Maize	Yield	Decrease	Mexico	Observed	Eakin, Appendini, Sweeney, and Perales (2015)
Maize	Yield	Decrease	Central America	2100	ECLAC (2010)
Maize	Yield	Could fall to zero	Guatemala	2100	ECLAC (2010)
Maize	Yield	Could fall to zero	El Salvador	2100	ECLAC (2010)
Maize	Yield	Could fall to zero	Panama	2100	ECLAC (2010)
Maize	Yield	Changes between −20% and +60% (depending on scenario)	Mexico	NA	Conde et al. (1997)
Maize	Suitability	Increase of 10%	El Salvador	2030	Bouroncle et al. (2017)
Maize	Suitability	Increase of 12%	Nicaragua	2030	Bouroncle et al. (2017)
Plantain	Suitability	Decrease of 31%	Guatemala	2030	Bouroncle et al. (2017)
Plantain	Suitability	Decrease of 28%	El Salvador	2030	Bouroncle et al. (2017)
Plantain	Suitability	Decrease of 23%	Honduras	2030	Bouroncle et al. (2017)
Plantain	Suitability	Decrease of 32%	Nicaragua	2030	Bouroncle et al. (2017)
Rice	Suitability	Increase of 1%	Guatemala	2030	Bouroncle et al. (2017)
Rice	Suitability	Increase of 8%	El Salvador	2030	Bouroncle et al. (2017)
Rice	Suitability	Increase of 3%	Honduras	2030	Bouroncle et al. (2017)
Rice	Suitability	Increase of 2%	Nicaragua	2030	Bouroncle et al. (2017)
Rice	Yield	Decrease	Central America	Perceived	Adaptation Partnership (2012)

Rice	Yield	Decrease between 16% and 27%	Guatemala	2050	MARN (2007)
Rice	Yield	Could fall to zero	Panama	2100	ECLAC (2010)
Rice	Yield	Decrease between 4% and 41% in yield (depending on timeframe)	Guatemala	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Rice	Yield	Decrease between 6% and 50% in yield (depending on timeframe)	El Salvador	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Rice	Yield	Decrease between 7% and 49% in yield (depending on timeframe)	Honduras	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Rice	Yield	Decrease between 7% and 39% in yileld (depending on timeframe)	Costa Rica	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Rice	Yield	Decrease between 11% and 68% in yield (depending on timeframe)	Nicaragua	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Rice	Yield	Decrease between 6% and 48% in yield (depending on timeframe)	Panama	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Rice	Yield	Decrease between 9% and 56% in yield (depending on timeframe)	Belize	2020,2030,2050,2070, 2100	CEPAL & CAC/SICA (2014b)
Water	Runoff	Decrease	Central America	2050, 2070, 2100	Magrin et al. (2007)
Water	Availability	Changes between+ 3% and −64% depending on scenario and timeframe	Belize	2020,2030,2050,2070, 2100	ECLAC (2010)
Water	Availability	Decrease between 3% and 61% depending on scenario and timeframe	Costa Rica	2020,2030,2050,2070, 2100	ECLAC (2010)
Water	Availability	Changes between +2% and −82% depending on scenario and timeframe	El Salvador	2020,2030,2050,2070, 2100	ECLAC (2010)
Water	Availability	Changes between +1% and −62% depending on scenario and Timeframe	Guatemala	2020,2030,2050,2070, 2100	ECLAC (2010)
Water	Availability	Changes between 12% and −69% (depending on scenario and timeframe)	Honduras	2020,2030,2050,2070, 2100	ECLAC (2010)
Water	Availability	Changes between 7% and −71% (depending on scenario and timeframe)	Nicaragua	2020,2030,2050,2070, 2100	ECLAC (2010)
Water	Availability	Changes between 18% and −51% (depending on scenario and timeframe)	Panama	2020,2030,2050,2070, 2100	ECLAC (2010)
Water	Runoff	Decrease	Central America	2070–2100	Imbach et al. (2012)
Wheat	Yield	Increase during El Niño events and decrease during La Niña events	Mexico	NA	Chatzopoulos (2008)

Note: Cropping systems, variable measured, expected or observed impacts, country where the study was conducted, time frame used and references.

Table 2. A summary of the location, target crops, vulnerable groups identified and the reason for high vulnerability, spatial and temporal scales and whether spatially explicit information is provided by studies of smallholder farmer vulnerability to climate change in Central America and Mexico.

Reference	Mexico	Guatemala	Honduras	El Salvador	Nicaragua	cropping system	Who and where are the most vulnerable	Reason	spatial scale	temporal scale	spatially explicit information
Alayon-Gamboa and Ku-Vera (2011)	X					Maize, jalapeno pepper	Commercial agriculture oriented farmers are considered the most vulnerable when compared to subsistence farmers	Household subsistence farmers better manage resilience mechanisms, as they emphasize maize production and invest more family labour in maize cultivation, without reducing family labour in their cash crop, than commercial oriented farmers	Municipality level (one municipality)	Climatic variability	No
Aguilar, Pacheco, Tobar, and Quñónez (2009)				X		NA	Geographic areas where most vulnerable farmers are located are identified	Communities with high climate exposure, low resilience and low adaptability	Regional level (2 regions)	2020	No
Bellon et al. (2011)	X					Maize	Communities located in the highlands of eastern Mexico are the most vulnerable	Communities located in the highlands of eastern Mexico lack local maize seeds that are adapted to predicted climate change	Regional level (1 region)	2050	yes
CIAT (2011)		X				Broccoli, Sweet pea, corn	Guatemalan frozen vegetables farmers (moderate vulnerability by 2030 and high vulnerability by 2050)	Most vulnerable farmers have low adaptive capacity but are located in places with high exposure in the future	Country level	2030; 2050	No
Schmidt et al. (2012)		X	X	X	X	Beans, Maize	In El Salvador, communities with high vulnerability are El Rosario, San Felipe and San Rafael; in Guatemala, the community with high vulnerability is Patzisia; and in Honduras, the community with high vulnerability is Orica	Communities with high vulnerability high climate impact and low adaptive capacity	Regional level (3 regions)	2020; 2050	Yes

Eakin et al. (2006a)	X					Sorghum, Maize, Safflower, soy, irrigated vegetables, fruit trees	Private farmers were found in higher percentages in the high vulnerability category when compared to communal farmers	Private smallholders have higher adaptive capacity (more educated, younger and had more land) but also higher sensitivity (to crop pests and diseases and to their dependence on crop income) making them more vulnerable when compared to communal farmers	Municipality level (one municipality)	Climatic variability	No
Holt-Gimenez (2002)					X	NA	Farmers using conventional practices when compared to farmers using sustainable practices	Conventional farmers do not use sustainable practices that help farmers to suffer less damage during extreme events, making them more vulnerable than neighbours using sustainable practices	Regional level	Climatic variability	No
PNUD (2013)			X			NA	Farmers located in the south west portion of the country, in the border with El Salvador and Guatemala	They have low capacity to adapt	Country level	NA	Yes
Bouroncle et al. (2017)		X	X	X	X	Coffee, maize, beans, rice, sorghum, plantain, cassava	Farmers located in agricultural frontier areas and in those prone to drought, and farners that grow basic grains	Areas where crops are expected to experience changes in areas suitable for production and where farmers have low adaptive capacity. Areas under subsistence crops tend to have less resources to promote innovation and action for adaptation	Country level	2050	Yes

Note: N/A indicates that the information was not provided in the study.

Table 3. Definition of the vulnerability used, the variables used to assess vulnerability and how the variables were combined to assess vulnerability in each study (N/A indicates that the information was not provided in the study).

Reference	Definition of vulnerability used	How vulnerability was measured	Variables used to assess vulnerability		
			Exposure	Sensitivity	Adaptive capacity
Alayon-Gamboa and Ku-Vera (2011)	Capacity of the farmer to anticipate, cope with, resist and recover from the impacts of natural disturbance	Comparison of crop area, grain harvest, days spent in family labour for corn, and crop area, fruit harvested, family labour and wage labour for jalapeno between before and after Isidore hurricane and between the household subsistence agriculture and household commercial agriculture	NA	NA	NA
Aguilar et al. (2009)	NA	A function dependent on 3 sub-indices: Climate exposure, resilience and adaptability	Temperature related climate extremes, dry and wet climate extremes	NA (used resilience instead, measured by organization flexibility, mechanisms of control and structural coupling)	Potential of resources, innovation and experimentation and organization complexity
Bellon et al. (2011)	Exposure to climatic stressors and the sensitivity to those stressors, which is determined by complex set of social, economic, and institutional factors that collectively determine adaptive capacity	Absence of local maize seeds adapted to predicted climate change, which was assessed through the origin and history of the seed used to reproduce and its management	NA	NA	NA
CIAT (2011)	Function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity	Vulnerability index, which is the sum of exposure, sensitivity, minus adaptive capacity, and was represented in three categories (low, moderate and high)	Changes in suitability of crops under climate change using modelling work	Water access, credit access, organization affiliation, technical assistance, level of affect by pest, topography, training about markets and the presence of hedgerows against erosion.	Technical assistance, organization affiliation, access to training, water access, distance to market, access to pest control, car owner, house owner.

Schmidt et al. (2012)	NA	Vulnerability index, which is based on impact (combination of exposure and sensitivity) and adaptive capacity. Each of those 2 indicators were scored as high, medium and low, which generated a composite vulnerability class (high, medium, low)	Changes in relative yield predicted at the municipality level by the bio-physical model (combined for maize and beans), and information on the terrain inclination and whether at least one conservation technology for soil preparation was used at the household	Combination of the potential impacts of the change in the maize-beans production system on food consumption (which was considered the exposure indicator) and income level (if maize and beans are the main sources of income)	Combination of different variables for different indicators (Physical and natural capital: land quantity and quality, water quantity and quality, quality of farm access, farm/irrigation equipment; Financial capital: credit access level; Human capital: family labour, education level; and Social Capital: social participation, information level and reactive capacity).
Eakin et al. (2006b)	Function of the exposure to climate shocks and extreme events, the sensitivity of the farm to such events in terms of both direct crop impacts and indirect livelihood impacts and the capacity of the households to adapt and adjust to protect themselves from future harm.	Vulnerability index by combining the values of a single multivariate indicator of adaptive capacity and of a single multivariate indicator of sensitivity	Not assessed because the authors think that differences in exposure are captured in differential sensitivities to climate impacts	Variables measuring direct climate impacts on crops and variables that were hypothesized to indicate greater sensitivity of the farm livelihood to climate shocks.	Measured as human resources, material resources, financial resources, information access and use, and economic and agricultural diversity
Holt-Gimenez (2001)	NA	Measured by top soil depth, rill and gully erosion, percent vegetation, crop losses and structural damage	NA	NA	NA
PNUD (2013)	Possibility that the system will be affected by something that is related to climate, and is the function of sensitivity and adaptive capacity	NA	NA	Effects of climate change on agriculture production and the dependence of people on those affected crops	Economic, poverty, inflation, proportion of people with disability, proportion of deforested areas, unemployment rate, human developed index, number of beds in hospital, proportion of groups especially vulnerable, number of TV per person and the capacity to response
Bouroncle et al. (2017)	Expected change in agricultural livelihoods over a given timeframe, as a function of exposure, sensitivity and adaptive capacity	Combination of exposure and sensitivity (potential impact), and adaptive capacity of farmers	Changes in crop suitability	Changes in crop suitability	Function of human, natural, built and financial capitals.

3.3. *What adaptation measures have been used by or recommended for smallholder farmers?*

Thirty-one studies provide information on adaptation measures used by smallholder farmers (n = 10, Table 4) or recommended to reduce their vulnerability ($n = 21$, Table 5).

3.3.1. *Adaptation measures used by smallholder farmers*

Studies showed that farmers are responding to climate change, mainly by using coping strategies. For example, in Mexico, smallholder coffee farmers have adopted crop and livelihood diversification, applied mulches, fertilizer, herbicides, and pesticides, have made alterations in tillage practices, and have used shade, sturdier crop varieties and seasonal forecasts and inter-cropped maize with drought-tolerant crops (Anderzen, 2015; Eakin, 2000; Eakin, Castellano, & Haggar, 2003). In Honduras, farmers have coped with climate change impacts by installing rainwater harvesting systems and, in Nicaragua, by diversifying crops and using agroforestry systems in coffee farms (Adaptation Partnership, 2012).

Some of the mechanisms used by farmers to cope with the stresses caused by droughts, and in response to coffee leaf rust outbreaks, include increasing wild food harvest, increasing consumption of fruits to substitute basic grains that they could not harvest, selling fire wood and animals as an alternative income-generation strategy, reducing food consumption and household expenditures, selling crops for lower prices, selling assets and seeking help from programmes and organizations (Bacon, 2017; Bielecki, 2015; Oxfam, 1998; Ruiz, 2015). In the context of droughts and coffee least rust outbreaks, some farmers have taken more drastic measures such as migrate to other areas (Bacon, 2017; Bielecki, 2015; Oxfam, 1998; Ruiz, 2015) measure that can be considered transformative adaptation (see Richards & Howden, 2012) (Table 4). Some of those measures are however, not necessarily in response to climate change per se, but to disease outbreaks that are not exclusively associated with climate change (see Avelino et al., 2015).

3.3.2. *Adaptation measures recommended to reduce the vulnerability of smallholder farmers*

Twenty-one studies provide adaptation measures recommended for smallholder farmers. Although most of measures can be considered coping strategies, some such as migration, the establishment of payment for ecosystem services, the promotion of agroforesty and forest restoration can be considered transformative measures (see Richards & Howden, 2012). Most of the recommendations that we found in the studies we reviewed focus on coffee and basic grains farmers and are related to changes in practices, including those that focus on soil conservation and aim to improve soil fertility, and the use of agroforestry (Adaptation Partnership, 2012; Alonso, 2011; Cafedirect & GTZ, 2008; Cathalac, 2008; Eitzinger et al., 2017; Holt-Gimenez, 2002; Laderach et al., 2013; Morris, Méndez, Van Zonneveld, Gerlicz, & Caswell, 2016; Schroth et al., 2009) (Table 5). Regarding farmer's livelihoods and capacity, measures recommended in most of the studies we reviewed include crop diversification, the use of more resistant plants and seeds, the improvement in the capacity of farmers on climate change resilience and climate change adaptation, and establishment of farmers organizations (Adaptation Partnership, 2012; Alonso, 2011; Cafedirect & GTZ, 2008; Castellanos & Guerra, 2009; Cathalac, 2008; Eakin, Tucker, & Castellanos, 2006a; Eitzinger et al., 2017; Laderach et al., 2013; Martinez, 2012; Mercer, Perales, & Wainwright, 2011; Oropeza, 2007; PNUD, 2013; Saldaña-Zorrilla, 2008; Schroth et al., 2009; Schmidt et al., 2012).

Measures related to technology include the improvement of irrigation systems and the use of water storage techniques, and the establishment of early warning systems (Adaptation Partnership, 2012; Avelino et al., 2015; Cafedirect & GTZ, 2008; Laderach et al., 2013; PNUD, 2013; Retana, 2012; Saldaña-Zorrilla, 2008; Schroth et al., 2009). Several measures on finance and policy are mentioned in the studies we reviewed. Those include the establishment of financial mechanisms to support the producer and promote a more efficient market (Cafedirect & GTZ, 2008; Castellanos & Guerra, 2009; CATHALAC, 2008; Eakin et al., 2006a; Laderach et al., 2013; PNUD, 2013; Schroth et al., 2009), and the development and implementation of management plans for catchment areas (Cafedirect & GTZ, 2008; PNUD, 2013). The development or implementation of payment for ecosystem services has also been highlighted as an adaptation measure for smallholder farmers (Laderach et al., 2013; PNUD, 2013).

Five studies are more specific in their recommendations. For example, Schmidt et al. (2012) present a list of recommendations to be implemented in locations with specific combinations of sensitivity, exposure and adaptive capacity of famers to climate change and Eitzinger et al. (2017) do so based on the impacts of climate change on crop suitability. Adaptation Partnership (2012) evaluates different adaptation measures based on their cost, feasibility, effectiveness, and additional social, economic and environmental benefits provided, and shows that the introduction of agroforestry systems, the strengthening of local capacities and the installation of improved irrigations are the most cost-effective measures in reducing the vulnerability of smallholder farmers to climate change among those that they reviewed.

Table 4. A summary of adaptation measures used by smallholder farmers in Central America and Mexico, organized in four topics, presented in the studies we reviewed.

Reference (country, copping systems)	Adaptation measures used by smallholder famers			
	Farm practices	Farmers' livelihood and behaviour	Technology	Finance and policy
Chatzopoulos (2008) (Nicaragua, Sugar, wheat, maize, palm oil, oilseed rape)	Sustainable land management			
Eakin et al. (2003) (Mexico, maize)		Crop diversification (switching from more sensitive crops – mainly maize; sensitive to both drought and frosts to more resilient options like oats and barley)	Irrigation	
Eakin (2000) (Mexico, maize)	Application of mulches Alterations in tillage practices Incorporation of shade Stagger planting times Inter-cropping maize with drought-tolerant crops Application of fertilizer, herbicides, and pesticides	Crop diversification Use of new crop varieties	Using seasonal forecasts	
Adaptation Partnership (2012) (Honduras, Nicaragua, beans, rice, coffee, corn, banana, sugarcane, livestock)	Using agroforestry systems in coffee farms	Crop diversification	Installation of micro hydro systems and rainwater harvesting systems	
Oxfam (1998) (Nicaragua and Honduras, maize, beans, sorghum)		Increasing the consumption of fruits to substitute basic grains Reducing food consumption Migration (T)		Selling animals to increase income Selling fire wood to increase income
Anderzen (2015) (Mexico, coffee)	Pruning and transplanting new coffee trees Use of copper sulfate	Livelihood diversification Using a variety believed to be resistant to coffee rust		
Bacon (2017) (Nicaragua, coffee)		Migration (T) Increasing wild food harvest from forest		Reducing household expenditures Off farm day labour Selling crops for lower price Selling assets Seeking help from others and organizations
Bielecki (2015) (Guatemala, coffee)		Reduction of food consumption Migration (T) Crop diversification		Taking loans Off farm labour Receiving assistance from organizations
Magrin et al. (2007) (Central America, NA)	Soil conservation	Crop diversification		Economic diversity
Ruiz (2015) (Mexico, coffee)		Introducing fruit trees in plantation Migration (T) Diversification of coffee varieties		Seeking help from programmes and subsidies

Note: Measures that can be considered transformative adaptation are represented by (T).

Table 5. A summary of adaptation measures recommended to reduce the vulnerability of smallholder farmers in Central America and Mexico, organized in four topics, presented in the studies we reviewed. Measures that can be considered transformative adaptation are represented by (T).

Reference (country, copping systems)	Adaptation measures recommended for smallholder farmers			
	Farm practices	Farmers' livelihood and capacity	Technology	Finance and policy
CATHALAC (2008) (Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama)	Intensify agriculture activity Establish soil conservation practices Establish agroforestry systems (T)	Diversify by using more tolerant species and varieties Develop capacities regarding management capacities Promote crop diversification Strengthen local capacities and organization strength Provide technical assistance	Improve seed bank to produce material that are more adapted to future climate	Establish commercial channels that support the producer Provide finance Establish a soil improvement programme Improve the social and productive infrastructure Establish commercial channels that support the producer
Adaptation Partnership (2012) (Central America, Coffee, Maize, Rice, Sugarcane, Bananas)	Introduce agroforestry systems (T)	Strengthen local capacities	Improve irrigation systems	
Alonso (2011) (El Salvador)	Establish agroforestry systems (T)	Promote capacity on climate change and management of ecosystems Promote crop diversification Use more resistant seeds		
Oropeza (2007) (Mexico)	Incorporate good farming practices	Use of drought-tolerant crops	Recover traditional technologies Promote efficient use of energy	
Retana (2012) (Costa Rica)	Incorporate good farming practices	Use new crop varieties	Improve irrigation systems	
Castellanos and Guerra (2009) (Guatemala, basic grains)		Improve the organization of basic grain producers Crop diversification		Increase funding, Promote a clear legal framework for cultivation and marketing, Increase producer access to new technologies Promote a more efficient market
Mercer et al. (2011) (Mexico, maize)		Strengthen the social relations of maize production Promote seed exchange		
Haggar and Scheep (2012) (Guatemala, coffee)		Train farmers to increase resilience to climate change in their production systems Diversify strategies		
Bellon et al. (2011) (Mexico, maize)		Establish new links within farmers' seed – sources, linking farmer groups in different locations, Foster the exchange of germplasm, knowledge, and practices among different locations		

(*Continued*)

Table 5. Continued.

Reference (country, copping systems)	Adaptation measures recommended for smallholder farmers			
	Farm practices	Farmers' livelihood and capacity	Technology	Finance and policy
Cafedirect & GTZ (2008) (Nicaragua and Mexico, coffee)	Mulching, Establish sustainable cultivation that controls for fungal attacks and loss of soil fertility Promote the use of hedges Establish natural barriers Implement terraces in slopes Introduce agroforestry systems (T)	Strengthen local institutions Improve cooperation, knowledge management, access to information and local data pools, Train and build awareness on climate change and impacts Strength capacity on adaptation strategies Promote farmer-to-farmers exchanges Promote crop diversification Use alternative crops	Breed suitable varieties less susceptible to water shortage and pests, Use water storage techniques, Establish early warning systems, Implement irrigation systems	Establish crop insurance (T) Establish micro credits for farmers (T) Establish a management of catchment areas Fund community organizations
Schmidt et al. (2012) (El Salvador, Guatemala, Honduras and Nicaragua, beans, maize)	Agriculture expansion Intensify production using sustainable measures	Change to non-agricultural activities (T) Crop diversification		
Eakin et al. (2006a) (Mexico, Sorghum, Maize, Safflower, Soy, Irrigated vegetables, Fruit trees)		Crop diversification		Access to financial and material resources that can buffer a large-scale producer against climatic risk (for commercial producers)
Saldaña-Zorrilla (2008) (Mexico, maize, bens)		Use improved seeds	Establish warning systems Implement Irrigation systems	Establish loans of machinery and more credit
Holt-Gimenez (2001) (Nicaragua, Honduras and Guatemala)	Apply soil and water conservation methods Reduce or discontinue the use of chemical inputs Implement Cover crops Introduce agroforesty (T) Use row tillage Apply organic fertilizer and pesticides Use integrated pest management			

(*Continued*)

Table 5. Continued.

Reference (country, copping systems)	Adaptation measures recommended for smallholder farmers			
	Farm practices	Farmers' livelihood and capacity	Technology	Finance and policy
PNUD (2013) (Honduras)		Establish watershed committees in dry areas in the south and west, Strengthen smallholder farmers associations Support the women associations in all regions Promote land organization in all regions Strengthen the capacity of the communities to manage resources in the areas that are more vulnerable to flooding, Improve the administration and coordination capacity at the local level	Establish irrigation and water retention systems, Establish, broaden and interconnect early warning systems	Solve land tenure issues Improve the credit access of smallholder farms in all regions Manage water at the micro watershed level in the dry areas Develop payment for ecosystem services (T)
Schroth et al. (2009) (Mexico, coffee)	Promote Agroforesty (T) Restore degraded, flood prone and ecologically sensitive areas (T)	Strengthen community organization, Promote capacity building on resource management, forest conservation and fire control Promote agricultural diversification Promote crop diversification, by using new coffee varieties	Increase water efficiency in coffee production and processing	Promote more effective commercialization of products Develop and implement fire management plans
Avelino et al. (2015) (Costa Rica and Mexico, coffee)			Early warning systems	
Eitzinger et al. (2017) (El Salvador, Guatemala, Honduras, Nicaragua, beans)	Soil fertility management (in adaptation spots, where yields will decrease but still economically feasible to grow)	Diversify to other crops or migrate (where yields will be too low to be economically feasible) Sowing better adapted cultivars (where yields will decrease but still economically feasible to grow)		Seek off farm income
Martinez (2012) (Nicaragua, cacao)		Technology transfer regarding coffee production associated with cacao in agroforestry systems (where increase in temperature is expected) Farm diversification Farmer exchange programmes to highlight effective measures Promote farmers associations		
Laderach et al. (2013) (Central America, coffee)	Use of shade cover	Migration or moving to high altitude areas (T) Crop diversification Use of drought and hear resistant varieties	Irrigation	Payments for ecosystem services or watershed services (T) Subsides to implement practices or technologies
Morris et al. (2016) (Central America, coffee)	Promote agroforestry (T)			

4. Discussion

Our review shows that there is a need to generate geographically explicit information on who are and where the most vulnerable smallholder farmers are located, and to identify effective adaptation measures for smallholder farmers working in different crop systems, which could support the development of adaptation, climate change and agriculture programmes and plans targeting smallholder farmers. Donors, policy makers and researchers working in this region need to set up funding, programmes, and knowledge-sharing mechanisms to enable those gaps to be filled and for adaptation actions targeting smallholder farmers to be effectively implemented.

4.1. *Information related to the vulnerability of smallholder farmers in Central America and Mexico*

Smallholder farmers in Central America and Mexico are expected to be particularly vulnerable to climate change (Ortiz, 2012) and the region is one of the top ten priorities for climate change adaptation worldwide (Hannah et al., 2013). The existing literature indicates that extreme events are impacting farmer's food security and agricultural production. The literature we reviewed also indicates that climate change will negatively impact the suitability and yield of several crops in the region, including beans, coffee, maize, plantain and rice and likely exacerbate the already existing vulnerabilities and inequalities in access to food and health. Studies that we reviewed also provide insights on key factors that influence farmers and agriculture vulnerability, including the way farmers interact with the landscape and the way that crops respond to changes, farmer's income, profit and adaptive capacity, the available livelihood activities, the existence of social ties and safety nets, as well as the interaction among market uncertainties, price volatility and climatic risk.

Even though this big picture exists, information on the vulnerability of smallholder farmers to climate change is still patchy and incomplete (see Table 2). Methodologies used in the assessments we reviewed vary across studies, as well as the definition of vulnerability used, which is somewhat expected given that there is no widely accepted version of such definition (Tonmy et al., 2014). In fact, the different definitions observed in the literature could reflect in part the changes in ways to measure vulnerability in the last years. For example, 'vulnerability' in the latest IPCC report (Oppenheimer et al., 2014) is used to define climate risk, and could have affected the way that different studies defined and measured vulnerability. Most of the assessments consider, however, vulnerability as the result of changes in crop suitability or production (which often represent the combination of exposure and sensitivity) combined with the information on the adaptive capacity of farmers. Even though these studies use a similar approach, it is difficult to combine and compare studies given the differences in spatial scale, timeframes and aggregation methods used (see Tonmy et al., 2014). In any case, the fact that the assessments only address expected impacts and that adaptive capacity are mainly based on proxy indicators are two limitations that need to be highlighted.

Many adaptation measures are suggested to reduce the vulnerability of smallholder farmers to climate change, but the extent to which those may be efficient in doing so is not well known. Our review shows that farmers are responding to changes in climate and extreme events, with responses ranging from establishment of soil conservation practices to changes in eating behaviour and social organization. However, studies that present adaptation measures used by or recommended for smallholder farmers are limited geographically, some do not specify the crops they refer to and there is a lack of information regarding the factors that motivate specific adaptation responses.

Most of the adaptation measures recommended for smallholders provided in studies we reviewed are also broad and extensive, ranging from changes at the farm level (from the use of soil conservation practices to intensification) to those related to the capacity of farmers to respond to shocks. The use of agroforestry and resistant seeds were the most recommended measures. The adaptation measures recommended in studies we reviewed were not, overall, tailored to different socioeconomic and ecological contexts and collectively did not include information on the wide diversity of farming systems present in the region. The value of these broad recommendations for policy making on climate change adaptation is probably limited, given the lack of specific recommendations for different agroecological zones or regions, or the limited information on how such measures can reduce vulnerability. However, the fact that some of those recommendations are the same as those resulting from development assessments (e.g. strengthen local institutions, fund community organizations, give property titles to smallholders, promote a land organization in the region) could be beneficial as adaptation could be addressed by tackling development challenges. In fact, currently, there is a strong emphasis in providing development aid to the region more than to adapt to climate change, and therefore, it can be advantageous to have recommendations that may address development and climate change issues at the same time.

Recommendations that are likely helpful to target adaptation action for smallholder farmers are provided in Schmidt et al. (2012). This study identified specific adaptation measures based on the level of exposure, sensitivity and adaptive capacity of farmers. For example, measures aimed primarily at change of activities (maize/bean) as sources of livelihoods are appropriate where the impact (combination of exposure and sensitivity) of climate change is high, the adaptive capacity of farmers is low and their vulnerability is high. In contrast, sustainable intensification and agriculture expansion are recommended where impact is medium, adaptive capacity is low and vulnerability is high. Unfortunately, this information is not available for all geographies and farming systems. Therefore, gaps also exist regarding adaptation measures used by farmers working on specific crop systems, and those specifically recommended for a variety of crops to reduce the vulnerability of smallholders to climate change.

The limited spatially-explicit information on where vulnerable smallholder farmers are is likely preventing policy makers and donors from being able to strategically target their funds to the most vulnerable. Furthermore, the lack of consistency in both the definition of vulnerability used and the different ways to interpret and measure the components of vulnerability makes it hard to combine results to prioritize communities, areas or regions, and/or to identify adaptation actions to be implemented. Information on the vulnerability of smallholder farmers in Panama, Costa Rica and Belize was entirely missing.

There are several potential reasons for the lack of detailed and specific studies on smallholder farmer vulnerability to climate change in the region. First, climate risk, both in the present and in future, is not always seen as a priority for farm households or by farmers in this region (Eakin, 2000, 2005), despite frequent and even increasing losses of agriculture production to climatic hazards. Instead, farmers and research institutions are maybe concerned about vulnerability to other risks, such as market shocks (Bacon, 2005; Eakin et al., 2006b; Tucker et al., 2010), environmental degradation, market failures and state fragility (Morton, 2007), inequities in land and wealth distribution (Ravera et al., 2011), land tenure, and costs and uncertainties associated with certain practices (Eakin, 2003a). Another possible explanation for the lack of studies on the vulnerability of smallholder farmers to climate change in this region is the limited government investment in agricultural research and smallholder farmer agriculture (Boggs & Thale, 2013). International support for climate change adaptation in the region has also been limited (Caravani, Barnard, Nakhooda, & Schalatek, 2014).

4.2. *What knowledge gaps exist in our understanding of smallholder farmer vulnerability to climate change in this region?*

Based on our review, we suggest three main areas that require additional research that could support the development and implementation of adaptation programmes and plans for smallholder farmers (Table 6).

4.2.1. *Consistent and comparable information on who the most vulnerable smallholder farmers are and where they are located*

There is an important need to measure the vulnerability of smallholder farmers to climate change in different communities and/or municipalities, especially in Mexico, Costa Rica and Panama, so there is a consistent, complete, and geographically explicit data of which farmers are in greatest need of adaptation support. Such information could be generated with existing climate projections (temperature and precipitation), climate impacts on crop suitability and productivity and ecosystems services and census information, such as education levels, income and dependence on agriculture and ecosystem services, to assess adaptive capacity of smallholder farmers. Simple maps could be generated indicating areas of high, medium and low vulnerability of smallholder farmers to climate change. A methodology already exists for calculating smallholder vulnerability to climate change (see Lindoso et al., 2012), which could be adapted and applied across the region. Vulnerability maps should be regularly updated, as new climate projections, national censuses and related data become available.

4.2.2. *Information on adaptation measures that can reduce vulnerability*

There is a need to identify what is driving the vulnerability of smallholder farmers in a specific context, and how different measures can help reduce such vulnerability. Schmidt et al. (2012) present specific adaptation recommendations that could be implemented in locations that will experience high climate change impact and where farmers have low adaptive capacity to reduce the vulnerability of those farmers. Likewise, they identify recommendations for locations that will experience high climate impacts and where farmers have high adaptive capacity. Furthermore, governmental policy and agricultural programmes that exist to assist farmers in adapting to variable climatic conditions should be considered when identifying the possible adaptation measures for smallholder farmers. Interactions with other drivers of change should also be considered while identifying adaptation measures as climate change can exacerbate already exiting stressing conditions.

4.2.3. *Information costs, benefits and effectiveness of adaptation measures used by smallholder farmers or recommended to reduce their vulnerability*

This information could help policy makers to narrow down the number of adaptation options, prioritize those that are more relevant to the target area and avoid maladaptation, as some measured may be beneficial for a group of

Table 6. Types of information that are needed to guide adaptation actions for smallholder farmers in Central America and Mexico, the description of the information, the reason why this information needs to be assessed and ideas on how this information can be generated.

Information needed	Description	Reason	How to generate this information
Index that show the vulnerability of smallholder farmers for communities, municipalities or regions in Mexico, Costa Rica and Panama	Climate change vulnerability index (i.e. number) or category (i.e. Low, medium, high) that can be used to compare two or more communities, areas, regions and/or countries to identify the most vulnerable ones, calculated for both short- and long-terms. Maps should show areas of low, medium and high vulnerability of smallholder farmers to climate change	To prioritize communities, municipalities or regions for which the needed adaptation actions could be identified and implemented	Through already existing data, such as census data that indicate where smallholder farmers are located, climate projections that indicate exposure and information of impacts of climate change that indicate sensitivity, combined with existing data, household surveys and/or interviews with experts and focus groups to assess adaptive capacity. Underlying pre-existing vulnerabilities besides climate should also be considered
Information on what is driving the vulnerability of smallholder farmers and how different measures can help reduce it	Indication of what is driving the vulnerability of smallholder farmers in a context, and how the proposed measures can help reduce such vulnerability	To identify the adaptation measures that are more relevant to the target area	Through the identification of which components that describes vulnerability is the highest and the adaptation measured that can be used to reduce it, considering the context of the target area
Information on the cost, benefits and effectiveness of adaptation measures used by smallholder farmers or recommended to reduce their vulnerability to climate change	Identification of the costs, benefits and effectiveness of each potential adaptation measure to reduce the vulnerability of smallholder farmers to climate change	To prioritize measured among those that are more relevant to the target area, and to avoid maladaptation	Through economic analysis of proposed measures, field work and interviews with experts or focus groups

farmers but not for others or may affect non-targeted groups that are part of the agricultural chain. Information on the effectiveness of these adaptation measures is sorely missing, as is the information on the costs of implementing and maintaining adaptation strategies (but see Holt-Gimenez, 2002; Adaptation Partnership, 2012).

5. Conclusions

A large body of work exists regarding the impacts of climate change on agriculture (i.e. crop suitability and yield) and water, which is a great contribution as is part of what is needed to understand the vulnerability of smallholder farmers to climate change. However, the existing information on smallholder farmer vulnerability to climate change *per se* in Central America and Mexico is incomplete and likely insufficient to guide effective and efficient adaptation actions targeting this important livelihood group. Even though we recognize that there are many political and economic barriers that prevent adaptation initiatives to be developed, there is still a need for detailed, geographically explicit information on who and where the most vulnerable smallholder farmers are located, and for evidence-based recommendations on adaptation strategies and practices (or potential new adaptation strategies) for smallholder farmers working in different crop systems. As Central American countries and Mexico are in the process of designing and refining their climate change strategies and national adaptation plans, there is an important window of opportunity to generate this information to ensure strategies and plans effectively reduce the vulnerability of smallholder farmers across the region, and that adaptation measures specific for smallholder farmers are included in sectoral plans. In addition, information generated should be package in a way that can reach decision makers in the region and appropriate channels should be used to reach that audience (see Donatti, Harvey, Martinez-Rodriguez, Vignola, & Rodriguez, 2017). Donors, policy makers and researchers should recognize the importance of better understanding the vulnerability of smallholder farmers to climate change and which adaptation strategies are most likely to be effective, in order to help this important livelihood group adapt to climate change. Therefore, funding, programmes and knowledge-sharing mechanisms should be put in place to fill up those key gaps and to effectively implement adaptation actions targeting smallholder farmers. Other regions where smallholder farmers are important for agriculture and where climate change is likely to impact their livelihoods may be facing similar issues.

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Supplemental data

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