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Towards smallholder food and water security: Climate variability in the context of multiple livelihood hazards in Nicaragua

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ABSTRACT

Climate variability and change affect both food and water security, as do other hazards, such as shifting food prices, plant pathogens, and political economic changes. Although household food and water insecurity affect billions, most studies analyze them separately. This article develops a relational approach to explaining household access to food and water in a multi-hazard context. We identify pathways linking hazards to livelihood vulnerability and assess the relative importance of climate-related hazards. Analyzing longitudinal data collected from two surveys of the same 311 smallholder households in northern Nicaragua, conducted in 2014 and again in 2017, we find that peak seasons of food and water stress are asynchronous across the agricultural calendar, resulting in a total of five to six months of food and/or water stress. Across households, we find a significant positive relationship between water and food insecurity, even after adjusting for household fixed effects. Households experienced less food and water insecurity in 2017 than in 2014, due in part to the end of a severe drought in 2016, but remained concerned about damage from a severe coffee leaf rust outbreak and unfavorable agrifood prices that reduce income and threaten food security. Higher incomes and larger farm areas correlated with improved food and water security. We propose a generalizable approach for the joint assessment of household food and water security, which foregrounds the influence of seasonality and climate variability in the context of multiple hazards. This approach and our findings can contribute to developing integrated risk reduction strategies, building resilient livelihoods, and informing policy changes and partnerships with organized smallholders to improve resource access and sovereignty.

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1. Introduction

After more than a decade of decline, global hunger is again on the rise, affecting more than 820 million people in 2018, with smallholder families and rural residents comprising more than 50% of the global food-insecure population (FAO, 2019). Inadequate access to drinking water, sanitation, and nutrition affects more than 2, 3, and 2.5 billion people, respectively (Hirvonen et al., 2020; UN, 2019). Despite improvements in some regions prior to 2020, climate disruption, pandemic, and conflicts have continued to intersect with vulnerabilities within the dominant food, water, and agricultural systems to threaten people's access to healthy food and safe water (FAO et al., 2020; Devereux et al., 2020; Herrera et al., 2017; Masson-Delmotte et al., 2018; Wheeler & Braun, 2013). These threats compound existing drivers of food and water insecurity, such as food price fluctuations, unsustainable water use and management, land and water resource appropriations, existing patterns of uneven social vulnerabilities, and persistently precarious rural livelihoods (Birkenholtz, 2016; Borras et al., 2020; Clapp, 2014; Johansson et al., 2016; Wutich & Brewis, 2014). Stronger theory and empirical research are needed to explain the relationship between household water and food insecurity in hazard-prone environments (Brewis et al., 2020), and to inform adaptation to these persistent challenges (Adger et al., 2013).

We study the linkages among vulnerability to multiple hazards, food systems, and household food and water insecurity, using an

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interdisciplinary analysis of smallholder livelihoods in northern Nicaragua's coffee-growing highlands. Our goal is to situate climate variability's impacts on food and water security within the broader vulnerability context. Our study documents an improvement in measured food and water security between 2014 and 2017, a period that coincided with the receding of the most severe regional drought in 30 years. The evidence thus appears to implicate climate-induced production entitlement failure as the driver of the earlier insecurity (Sen, 1981). However, a more nuanced analysis of household surveys and the local precipitation record suggests that a climate-based explanation must be augmented with an analysis of seasonality, vulnerability to plant pathogens, and volatility in terms of trade that strongly affect farmer exchange entitlements to food.

Recent research has called attention to the need to improve methods to assess household food and water insecurity and their interconnections (Brewis et al., 2020; Wutich & Brewis, 2014; Jepson et al., 2017), address research gaps identifying actionable knowledge for agricultural climate adaptation (Davidson, 2016; Donatti et al., 2019), and explain smallholder vulnerability in multi-hazard environments (Guido et al., 2020; Bacon et al., 2017). Robust household-level water insecurity indicators have only recently appeared in the published literature (Brewis et al., 2020; Wutich et al., 2017; Venkataramanan et al., 2020). Additionally, there is a need for explanatory theories that relate household food and water insecurities and connect livelihood insecurities to the vulnerability context and document resilience-building adaptations (Hinkel, 2011; Scoones, 2015). Although integrated studies addressing these challenges continue to emerge (Adger et al., 2013; Eakin et al., 2014; McCubbin et al., 2015; Perfecto et al., 2019a), more research is needed to refine theories and explain relationships with actionable precision (Brewis et al., 2020; Wise et al., 2014).

Important contributions of our work to filling these research gaps include the development of an integrated framework for assessing household food and water insecurity using both perceptual and climate measurements and careful spatial and temporal analysis of household responses to hazards. Through this detailed place-based study using generalizable methods, we identify local determinants of food and water security and explore the adaptations likely to reduce the risk of shortages and hardship, thereby informing local action and wider policy responses for both incremental and transformative adaptations (Donatti et al., 2019; Eakin et al., 2014; Wilson et al., 2020).

Coffee-growing smallholders are compelling partners for researching these issues. Coffee is a global commodity involving more than 26 million smallholder producers and more than 125 million workers, traders, pickers, and processors across a value chain extending from crop to cup, with a total estimated export value from producing countries of $39 billion (Hirons et al., 2018; Jha et al., 2014). Most coffee producers manage small parcels of land, often located on remote mountainsides, and frequently face multiple hazards, including hurricanes, droughts, pests, and disease outbreaks (Bacon et al, 2017; Avelino et al., 2015; Diaz & Hunsberger, 2018). Like the tens of millions of other smallholders involved in tropical commodity production and export (Talbot, 2004), coffee producers sell their crops into global value chains subject to power relations that favor larger corporations in the Global North and frequent commodity price fluctuations (Guido et al., 2020; Bacon, 2015; Richey & Ponte, 2020; Bennett, 2017; Goodman et al., 2012; Perfecto et al., 2019b). Additionally, millions of smallholders are organized into cooperatives and producer associations built from ongoing and sometimes conflicted relationships of solidarity and commercial activity among their members (Mutersbaugh, 2002; Wilson & Mutersbaugh, 2020). Many smallholders and their organizations are also engaged in partnerships with nongovernmental agencies, roasters, importers, researchers, activists, and governments to launch and scale a range of sustainability initiatives (e.g., organic, fair trade, shade grown, and many others) that claim to promote corporate responsibility and address the environmental, social, and economic conditions in coffee-growing communities (Richey & Ponte, 2020; Bennett, 2017; Goodman et al., 2012; Perfecto et al., 2019b).

The article proceeds as follows. The next (second) section proposes an integrated framework for the joint assessment of household food and water security. Drawing on this framework, we develop a conceptual approach identifying hazards and other key drivers and the pathways that link them to livelihood vulnerability and food and water insecurity. The third section reviews our empirical methods and data sources, which include qualitative ethnographic research, a longitudinal survey of smallholder households, and related climatological and socioeconomic data. The fourth section presents our main results. We document the correlation of food and water insecurity across households and the prevalence of multiple months of seasonal food and water stress. We then assess the impact of key drivers of food and water insecurity through a series of regressions as well as qualitative and contextual research, finding that climate variability, income, and farm size play significant roles. We explore farmer perceptions of the severity of a variety of hazards, noting that the coffee leaf rust pathogen as well as terms of trade in agricultural prices compete with climate variability in their impact on livelihoods. The fifth, concluding section summarizes our findings, reviews recent developments in the region, and draws implications of our work for adaptation research, planning, and policy.

2. Conceptual framework

We propose an integrated framework for the joint assessment of household food and water security among rural residents navigating multiple hazards. We draw on the well-established definition of food security, which states that it "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). The four pillars of food security – availability, access, utilization, and stability – can be extended to structure an analysis of both food and water security (Wutich et al., 2017).

Table 1 summarizes our unified approach. The first dimension of food or water security is availability, which for food could include local production, storage, markets, and government assistance, and for water, precipitation, surface and groundwater capture, and storage. Access, the second dimension, refers to the social and institutional context that determines household and individual claims to available food or water supplies. Utilization, the third, entails the actual household practices that transform accessible food and water into use value (Burchi et al., 2011).

Stability over time and risk reduction constitute the fourth dimension of food and water security (Devereux et al., 2008; Mason, 2015). This dimension interacts with the first three, emphasizing their temporality, including anticipated seasonal patterns, intermittent events (such as El Niño), and unanticipated hazards (such as hurricanes). The predictability of seasonal patterns allows households to plan for enhanced stability in access; however, uncertainty about interannual events (e.g. hurricanes or global price shifts) and variation in seasonality can contribute to the use of severe coping responses that often undermine resilience to future hazards (e.g., selling the farm or pulling children out of school) and highlight the need for mitigation strategies to reduce risk exposure (e.g., crop diversification, community-based

Table 1
A framework for assessing household and individual food and water security.

	1. Availability		2. Access		3. Utilization	
Dimensions of individual & household ability to access and use food & water	**Food** – Regional & national production – Local distribution – Storage & processing – Food trade, aid, & sharing	**Water** – Precipitation & surface H_2O – Storage and filtration – Water capture – Transfers & sharing	**Food** – Income – Institutions – Entitlements – Intrahousehold dynamics – Gender relations	**Water** – Income – Institutions – Infrastructure – Entitlements – Intrahousehold dynamics – Gender relations	**Food** – Dietary diversity – Nutrition security – Preparation & knowledge	**Water** – Sufficient quantity and quality for drinking, cooking, cleaning, & bathing – Water for agriculture
4. Stability and Coping Responses (over time)	- Seasonality of crop harvests & precipitation patterns – Impacts of periodic hazards – Accumulation of stocks/storage – Coping responses (Gov/Trade) to shortages in availability		- Seasonal vs. constant employment (income) – Diversity of income sources – Shifting exchange entitlements (e.g, Markets, price, terms) – Shifting production entitlements – Diversity food & water source – Access to safety nets (Gov.) – Coping & adaptive capacities		- Seasonal patterns in use & quality - Water, sanitation & hygiene - Water quality/contamination - Food quality/contamination - Capabilities and health status - Access to healthcare (Gov.) - Bodily nutrient absorption - Coping & adaptive capacities	

Sources: Authors. Food security framework from Burchi et al. (2011), complemented by authors to include water security and integration of both food and water security.

insurance, or precautionary asset accumulation) (Béné et al., 2017; Hill & Porter, 2017).

We use a livelihoods perspective to assess the vulnerability of households to hazards that could exacerbate food and water insecurity across the four dimensions (Scoones, 2015; Wutich et al., 2017). Within this perspective we focus on Sen's entitlement theory (Devereux, 2001), human capabilities analysis (Burchi & De Muro, 2016), and local institutions (Agarwal et al., 2012; Smucker et al., 2015). Entitlements (e.g., landholdings for production or market access for exchange) and capabilities (e.g., education and skills) encompass the various claims and resources that individuals, households, and communities can marshal in response to hazards, and thus help determine their vulnerability, defined as the "propensity or predisposition to be adversely affected, encompassing a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC, 2014).

Building on the conceptual framework from Table 1 as well as knowledge of local conditions based on qualitative and survey work, Fig. 1 illustrates the key pathways connecting preconditions and multiple hazards to household food and water insecurity. This figure places climate-related hazards – in our study, predominantly precipitation events – in the broader context of additional drivers that may induce or exacerbate food and water insecurity. On the left side of the diagram, we start with both social and biophysical states and processes that may be taken as (provisionally) exogenous preconditions, shocks, or hazards. These include natural forces or conditions (e.g., climatic events or pathogen outbreaks), asset endowments that help determine household adaptive capacities (e.g., landholdings or human capital), market conditions (e.g., global coffee prices), and the political and institutional context (e.g., presence of local cooperatives, political unrest, and community water committees).

Moving from left to right in Fig. 1, natural and social conditions co-determine the availability (overall local supply) of food and water resources, which in turn affects access, mediated by household entitlements. In the case of food access, we emphasize production and exchange entitlements, notably food production and the exchange of coffee, other crops, or labor for purchased food. The political-institutional context influences multiple dimensions of food availability and access, in addition to crop and food prices (Agarwal et al., 2012; Smucker et al., 2015; Ostrom, 2009;

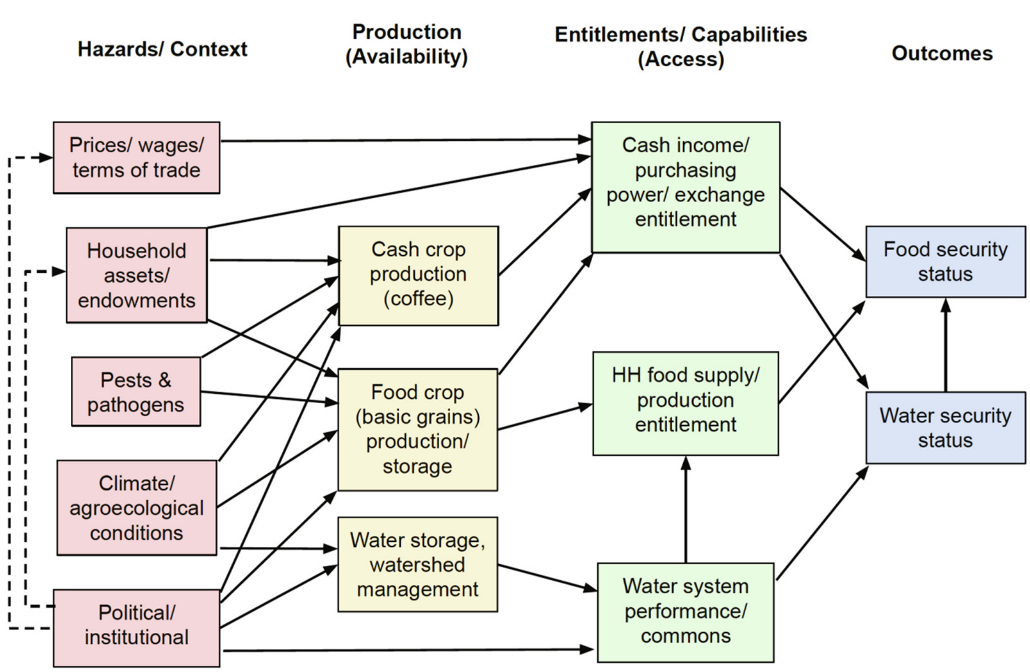

Fig. 1. Pathways linking hazards and context to food and water security.

Guthman et al., 2006). For example, government agencies and coffee companies have incentivized farmers to replant coffee plots after the coffee leaf rust outbreak (e.g., Keurig-Green Mountain coffee roasters in our study area), while others have also prioritized the programs that partner with co-ops and other farmer associations to invest in corn and bean production (e.g., Community Agroecology Network, WeEffect). Over time, political institutions often help shape household asset endowments, such as smallholder access to land – whether to enhance access, for example through agrarian reform policies (which significantly influenced smallholder land tenure in northern Nicaragua), or to reduce access, for example through land policy support for investments that can lead to land grabbing and smallholder displacement (Puig & Baumeister, 2017; Enríquez, 1991; Bacon, 2015).

With respect to water access and security, community water systems supply most households in our study area. These systems are dependent on surface water sources that are sensitive to precipitation and local topography and hydrology, but their functionality is also contingent on built infrastructure and local management of this common resource, which shape community entitlements to water (Dapaah & Harris, 2017). Most agriculture in the region is rain-fed, but the arrow connecting water systems to food production acknowledges the significance of irrigated home gardens and fruit trees.

Finally, moving to the right-most column, household access – coupled with household patterns of utilization – help determine the household's food and water security status. The vertical arrow linking water and food insecurity acknowledges the potential direct effect of water insecurity on household food utilization operating through insufficient quantity or quality of water for maintaining human health and preparing food.

3. Methods and data sources

To assess the importance of the posited drivers and the pathways linking them to food and water insecurity, we integrate multiple sources of qualitative and quantitative evidence, drawing on more than a decade of research in northern Nicaragua, informed by a community-based participatory action research (CB-PAR) approach (Bacon, 2015; Chevalier & Buckles, 2019; Nyantakyi-Frimpong et al., 2016). In the longitudinal survey analysis reported below, we estimate multiple regression models that capture the reduced-form relationships linking hazards and context to measurable household food and water security outcomes, and explore some of the mediating pathways. We also integrate information on seasonal and secular trends in rainfall and relative prices as well as other reported hazards and stressors to assess the relative importance of climatic and other factors in contributing to household vulnerability.

Our team's long-term partnerships with farmer cooperatives and local development associations facilitated the identification of the research population and the field research. Sources of evidence include (i) in-depth interviews and focus group discussions; (ii) extensive surveys of smallholder households on livelihoods, land use, and food and water security for a sample of the same households in 2014 and 2017; (iii) precipitation estimates from an established database that incorporate both remotely sensed data and on-the-ground observations; and (iv) relevant socioeconomic data, such as price series.

3.1. Study site

We conducted this study in Nicaragua's north central highlands, an area with a high concentration of smallholder farmers and part of Central America's dry corridor, which is a global hotspot for food and water security risks (Bouroncle et al., 2017). The landscape includes low mountains, rolling hills, and plateaus, with altitudes of 550–1600 masl (Fig. 2), average daily temperatures of 20–32 °C, and an average annual rainfall rate of 991 mm (Funk et al., 2014). The uplands are primarily forests, pastures and mixed crop production, with evergreen forests representing around 15% of the land cover in the higher altitudes (Kelley et al., 2018). The annual agricultural calendar is structured by a rainy season expected from May through November, with a mid-summer drought occurring in July and August, and a dry season from December through April. Although there is a degree of spatial variation in precipitation and drought severity, the physical geography of these lowland mountains remains broadly similar across the study area.

Nicaragua's vulnerability context is characterized by multiple hazards, many of which converged and exacerbated risk exposure in Central America during our study period from 2013 to 2017, including a strong El Niño (ENSO) event and associated drought (2014–16), an outbreak of a powerful plant pathogen known as coffee leaf rust (CLR) beginning in 2011, and rapid and dramatic fluctuations in the prices of coffee and crops harvested (especially in 2014). All of these events threatened the availability, access, and/or stability of food and water. In Central America, histories of imperialism, violence, and state-building have marginalized smallholders. Their displacement from fertile valley floor soils to mountainsides has increased their exposure and sensitivity to environmental hazards (Wisner et al., 2012). Risk from climate warming is anticipated to increase (Depsky & Pons, 2020), resulting in the region being labeled a climate change "hotspot" (Giorgi, 2006; IPCC, 2014). The persistence of social vulnerability coupled with exposure to climatic hazards led Germanwatch to rank Nicaragua #6 in their global Long-Term Climate Risk Index (Eckstein et al., 2018).

Although poverty and food and water insecurity decreased significantly in Nicaragua from 1997 to 2015, many challenges remain, and since 2018 economic conditions have worsened. A civil society-led national survey in 2017 that calculated poverty based on the cost of food and other necessities found a general poverty rate of 42.1% (and extreme poverty of 8.4%), with significantly higher rates of 55.9% overall and 14.5% extreme poverty in rural areas (FIDEG, 2018). Multilateral institutions relying on government data estimated lower poverty rates, and found that 17% were undernourished in 2017 (World Bank, 2017), while also confirming that about 48% or 3.065 million urban and rural residents lacked access to safely managed drinking water in the same year (WHO-UNICEF, 2020).

Access to safe water and consistent food is especially difficult in rural communities, which in Nicaragua's north central region are often a patchwork of small and large farms. In addition to agricultural production, off-farm livelihoods activities (e.g., day labor or salaried work) and local institutions (e.g., food systems, village water committees, and cooperatives) influence household access to food and water. Smallholders account for approximately three out of every four farmers, and manage an average of less than 3.5 ha of land, while collectively producing over half of agricultural exports and most of the food consumed within the country (IFAD, 2012). More than 95% of the 44,000 coffee producers in Nicaragua manage smallholdings of less than 10 manzanas (about 5.9 ha), but due to concentration in ownership they account for less than a quarter of the coffee lands (Martinez et al., 2012). Despite selected gains for landless workers and smallholders during the 1979–1990 agrarian reforms implemented through Sandinista-led government programs, highly concentrated patterns of farm land ownership (especially in agricultural export sectors) have increased since 1990, and persisted during the Sandinistas' second period in power, which started in 2007 (Puig & Baumeister, 2017).

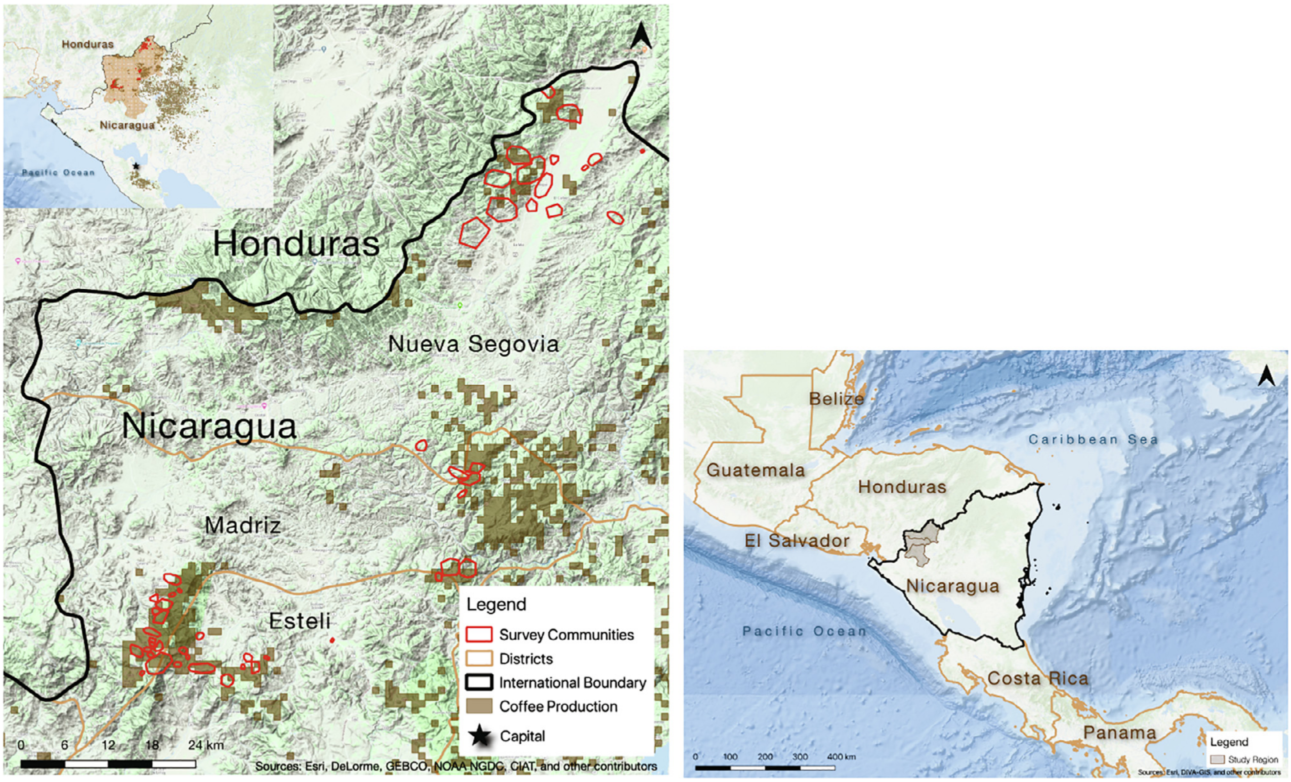

Fig. 2. Map of study area and survey communities (left) and region's location in Central America (right).

3.2. A participatory action research approach

Participatory and mixed methods approaches are increasingly common strategies for understanding the complex context, livelihoods, and farming practices of smallholder farmers and rural civil society institutions (Kerr et al., 2019; Perfecto et al., 2019a). Our team's long-term partnerships with farmer cooperatives helped identify the research population and conduct field research, including the 2014 baseline survey and the 2017 follow-up. The research team coordinator formed these partnerships through the co-design of a community-based participatory action research approach that aims to co-produce new scientific knowledge addressing the persistence of seasonal hunger and poverty among farmers linked to organic and fair trade certified sustainable coffee markets, while simultaneously creating a space for learning about local adaptation practices and building capacity with researchers and farmers and across different institutions (e.g., cooperatives, NGOs, and national and international universities).

Our first partner is a well-established multi-service farmer cooperative focused on coffee marketing and export. Pioneer organizers and smallholders formed this cooperative several decades ago, and it now represents thousands of farmers. Our second partner is a smallholder sustainable agriculture association within Nicaragua's national farmers and ranchers association, known as the Campesino-a-Campesino (farmer-to-farmer) program (Holt-Giménez, 2002); many of these farmers participate in broader social movements that share diversified agroecological farming and promote food sovereignty and have contributed to the formation of local, regional, and global smallholder civil society organizations (Edelman, 2014; Raynolds, 2012).

3.3. Study design and household surveys

The first stage of the study included participant observation, multiple focus groups, and interviews conducted with smallholders in the region from 2010 to 2014, which informed the baseline survey design (Bacon et al., 2017). The two farmer-led organizations, with professional staff to support the spread of appropriate technology and knowledge sharing, provided critical access to registries of affiliated farmers that facilitated the stratified sample design of the 2014 baseline survey. From these registries we identified a representative population of households affiliated with one or the other organization within six municipalities, and then used random numbers to select a roughly 30% sample. We then matched this sample with equal numbers, to the extent possible, of randomly selected producers from the other association, and from a third set of local farmers unaffiliated with either organization. To be included, households needed to have produced coffee in areas no larger than 10 *manzanas* (5.9 ha) and – for the affiliated farmers – have maintained at least three years of membership in their farmer organization (see Table 2).

Our original sampling strategy – stratifying by organizational affiliation – was in part motivated by an interest in studying potential differences in vulnerability and adaptive capacity across members of the different farmer organizations as well as unaffiliated farmers. In practice, these differences turned out to be relatively minor. This pattern could be due to the fact many of these farmers live in the same communities and commonly share sustainable agriculture and social organizing practices with each other as well as nearby unaffiliated farmers. To facilitate longitudinal analysis, the original sample of households was surveyed again in 2017.

Table 2
Study population and samples from 2014 and 2017 surveys, by organizational affiliation.

	Fair trade cooperative			Campesino a Campesino			Unaffiliated	
	Population	Sample 2014	Sample 2017	Population	Sample 2014	Sample 2017	Sample 2014	Sample 2017
Jalapa	160	33	28	0	0	1	20	15
Telpaneca	216	56	51	63	35	29	13	11
San Lucas	131	29	29	77	28	28	27	27
Pueblo Nuevo	62	14	14	80	13	16	15	9
Las Sabanas	62	24	21	80	26	23	20	19
Total	631	156	143	300	102	97	95	81

Sources: Household surveys 2014 and 2017.

The second intensive stage of field research occurred in June and July of 2014, when our team trained community promoters and collected survey responses from 368 households. The initial data quality controls for duplication or incomplete surveys resulted in four omitted records. Furthermore, an additional 11 households claimed affiliations with other or both organizations and were dropped from the sample, leaving 353. We immediately started to analyze survey data, complemented it with the qualitative and hydrological research findings, shared results with Nicaragua-based partners, and then published findings.

In the third stage, in 2016, a research team member selected two case study communities in northern Nicaragua to conduct focus groups, interviews, and a survey that piloted questions aimed at integrating food and water security with 80 individuals. Finally, our full team (faculty, collaborating Nicaraguan researchers, and several undergraduate students) conducted the fourth stage of field research in 2017. Continuing our partnerships with the same local organizations and survey enumerators, we returned to as many of the households sampled in 2014 as possible to share results from the previous study and conduct a new follow-up survey, focus groups, local water quality monitoring, and personal interviews. Our team of community-based promoters completed 336 surveys in July of 2017; using names and locations, the principal investigator identified 311 households that were interviewed in both 2014 and 2017. In accordance with the approved research protocol (IRB 15-06-679), the data were then anonymized for subsequent statistical analysis and archiving. The two surveys completed by each of these 311 households constitute the core longitudinal sample for our analysis. Among survey respondents, the average age was 51 in 2014, and 33 percent were female. Additional household demographic and livelihood characteristics are presented in Table 3 and discussed below.

3.4. Multipurpose household survey

The design of our integrated household survey followed a livelihoods framework (Scoones, 2009), prioritizing the multidimensionality of smallholder activities to "make a living and make it meaningful" (Bebbington, 2000). We combined elements from the Living Standards Measurement Studies (e.g., household demographics, house construction, and income) with questions focused on food and water security, smallholder agriculture (Bouroncle et al., 2017; Niles & Brown, 2017), land use/management (CCAFS, 2015; Garlick et al., 2019; IFRI, 2017), vulnerability and coping responses (Bacon et al., 2017; Blaikie et al., 2014), local institutions, and adaptation to climate variability and change (Agrawal, 2008; Douxchamps et al., 2016). We also drew from previous studies conducted with smallholders in Mexico and Central America (Bacon, Sundstrom, Stewart, & Beezer, 2017; Jaffee, 2014; Lyon, Mutersbaugh, & Worthen, 2017; Méndez, Bacon, Olson, Morris, & Shattuck, 2010). Our team and local collaborators reviewed, culturally adapted, field tested, and finalized many questions from past survey instruments, updated old questions, and included new questions focused on the joint assessment of food and water security in the context of drought and other stressors and hazards.

3.5. Assessing food insecurity

Household-level questions assessing several dimensions of food security have been validated in multiple contexts worldwide (Pérez-Escamilla, 2012; Zezza et al., 2017), although challenges remain. A recent study that reviewed more than 100 different surveys used to assess poverty, food consumption, and nutrition in low and middle income countries found, among other things, that nearly 50% of the surveys did not take into account seasonality (Smith et al., 2014). In this study, we measure seasonal food insecurity by the reported number of "lean months" or times when food was scarce during the preceding year. This is a common indicator for assessing one of the most frequently reported forms of food insecurity (CCAFS, 2015; Devereux et al., 2008; Niles & Brown, 2017). Experience-based measures such as these are useful to identify "hidden" or "silent" hunger, which is often overlooked by other measures focused on nutrition or dietary diversity.

We complemented measures of seasonal hunger with indicators to assess the severity of food insecurity as well as a proxy measure of food and nutrition quality. To assess severity we culturally adapted a global set of common household coping mechanisms frequently reported during periods of hardship (Maxwell et al., 2014), such as the typical number of times per week during the previous month that household members skipped meals, rationed food, borrowed money to buy food, or ate seeds stored to plant. The frequency of these 16 coping responses among households responding to the 2017 survey – along with analogous coping responses for water insecurity – is shown in Appendix Table A1. These responses were discussed, ranked, and scored in focus groups conducted in December of 2017 following established methods (Maxwell & Caldwell, 2008), and the scores were then used to weight the incidence of coping responses by each household to calculate a coping index of household food insecurity.

3.6. Assessing water insecurity

Like food security, our strategies to assess water insecurity focused on the temporality of access, coping mechanisms due to water-related stress, and perceptions related to quality. Despite ambitious recent efforts (e.g., UN Sustainable Development Goals) (Biermann et al., 2017), systematic and comparable household level indicators that measure water access, coping, and quality remain methodologically underdeveloped in comparison to those associated with food security (Jepson et al., 2017; Tsai et al., 2016).

To assess the seasonality of water access, we asked about households' primary and secondary water sources for designated uses (e.g., drinking, cooking, and bathing, as well as irrigation) during the wet and dry season, as well as the months of perceived water scarcity – resulting in a measure analogous to lean months for food (WHO/UNICEF, 2006). We also assessed basic water infras-

Table 3
Key livelihood characteristics of matched survey households, 2014–2017.

Variable	2014 Median	2014 Mean	2014 SD	2017 Median	2017 Mean	2017 SD	Change in mean
Household size							
Number of persons (total)	5	4.66	1.91	5	4.85	2.06	0.19
Number of persons under 15 years old	1	1.24	1.2	1	1.43	1.42	0.19
Agriculture							
Farm size (land area, ha)	3.70	5.82	7.21	3.52	5.07	5.87	−0.75
Produced more than half of food on farm (binary)	0	0.27	0.44	0	0.21	0.41	−0.06
Grows corn and/or beans (binary)	1	0.76	0.43	1	0.70	0.46	−0.06
Corn production (kg) [m = 0]	460	970	1734	322	936	2050	−33
Red bean production (kg) [m = 0]	230	405	591	92	405	831	0.6
Number of fruit trees inc. bananas and plantains [m = 0]	199	365	511	165	376	702	11
Coffee production positive in latest cycle	1	0.64	0.48	0	0.44	0.50	−0.20**
Produces coffee or has land with coffee in development	1	0.96	0.21	1	0.89	0.31	−0.06**
Coffee production (kg) [m = 0]	46	142	457	0	276	588	134**
Coffee production (kg) among positive producers	92	222	555	327	623	752	401**
Produces certified organic coffee (among producers)	1	0.66	0.48	1	0.51	0.50	−0.14**
Greater than half of coffee affected by CLR (binary)	1	0.70	0.46	1	0.66	0.48	−0.04
Income							
Sum of income from top 5 sources last 12 mo (US$)	706	1272	1971	652	1319	1751	47
Sells coffee (binary)	1	0.69	0.47	0	0.49	0.50	−0.20**
Sells corn (binary)	0	0.25	0.44	0	0.20	0.40	−0.06
Sells beans (binary)	0	0.46	0.50	0	0.37	0.48	−0.09*
Has labor or salaried job (binary)	0	0.41	0.49	0	0.43	0.50	0.02
Food and water insecurity							
Number of food lean months (food scarce)	3	3.12	1.26	3	2.62	0.90	−0.51**
Dietary diversity Berry index = 1 − sum(share^2)	0.85	0.83	0.07	0.84	0.84	0.04	0.00
Number of water lean months	4	3.53	3.05	3	3.07	3.24	−0.46
Total precip 14 mo preceding survey (May-June) (m)	1.45	1.37	0.22	1.48	1.40	0.20	0.03*

** and * indicate significant change in mean between 2014 and 2017 at 1% and 5% critical levels respectively. Full sample N = 311. [m = 0] indicates missing value set to 0.
Source: Household surveys, 2014 and 2017.

tructure (e.g., presence of improved water sources, household water storage, and sanitation facilities) and any water collection activities (Dickson et al., 2016). To understand the severity of water shortages we asked how families are coping with water-related stress, drawing from ongoing efforts to develop a globally comparable set of survey questions to assess coping responses, such as frequency of conflicts over water access, bathing in less preferred places, or going to bed thirsty (Hadley & Wutich, 2009; Jepson et al., 2017; Stevenson et al., 2016). For the water coping question we asked about coping mechanisms over the preceding year rather than month; given the strong seasonality of water availability in the study area, 12-month recall window allows us to identify coping responses during the driest periods. Frequency of coping responses is reported in Appendix Table A1. Using the 13 coping mechanism responses in the survey and severity weights derived from focus-group scoring exercises, we calculated a water insecurity coping index analogous to that for food insecurity.

Finally, we included questions about community water systems infrastructure, monthly water fees, and individual participation in the collective management of village water systems and local watersheds (Herrera et al., 2017). Many of these questions were piloted in our 2016 survey, analyzed and refined based on farmer feedback during subsequent focus groups, and then updated for this survey in 2017.

3.7. Qualitative research

We employed qualitative research methods to inform our study's hypotheses, research design, survey, and the interpretation of quantitative findings. We drew from a decade of one author's ethnographic research in the study area to establish trust with partner organizations, who shared data and helped recruit community promoters that served as survey enumerators. Qualitative field research activities include 20 focus groups from 2013 to 2017, five months of participant observation conducted in July and December of each year, one or two field visits from all co-authors, participatory workshops for sharing results, and key informant interviews. In June of 2019, the research team conducted an additional series of five focus groups to develop the agricultural calendar shown in Fig. 5c below.

Themes explored in the semi-structured interviews and focus groups included perceptions and responses to drought, coffee rust, commodity price changes, and other stressors and hazards (IFRI, 2017); identifying, discussing, and ranking food and water shortage-related coping mechanisms (Maxwell & Caldwell, 2008); and the degree to which the collective management of agricultural land and water followed design principles for sustainable governance (Agrawal, 2001; Ostrom, 2009; Romano, 2017; Tucker, 1999). In several cases focus groups were separated by sex in an effort to document the gendered impacts of drought, interpretations of coping responses, and broader strategies for adaptation to multiple stressors and hazards (Bee et al., 2013; Segnestam, 2009). Our research team transcribed interview recordings, and then we thematically coded them.

3.8. Assessing climate variability and change

To assess climatic patterns and drought severity, we extracted daily precipitation from the widely-used UC-Santa Barbara Climate Hazards Center CHIRPS data (Funk et al., 2014) for the 1981–2018 period. CHIRPS is a 30+ year quasi-global precipitation data set that incorporates 0.05 resolution satellite imagery with in-situ station data to create gridded rainfall time series. From these data, we calculated average monthly precipitation, total annual precipitation, and the Standard Precipitation Index (SPI) (McKee et al., 1993) for each community. The SPI is a widely used index to measure precipitation extremes, allowing a reliable comparison between locations and climates, and represents the number of standard deviations that observed period precipitation deviates from the climatological average. It can be calculated for any time scale and is based on multi-decadal precipitation records. We focus on SPI for the rolling three-month time window (SPI-3) as best suited to capturing critical periods in the local agricultural calendar.

4. Results

4.1. Household characteristics

Our longitudinal sample includes 311 smallholder households surveyed in both 2014 and 2017. Key livelihood characteristics of the sample households are summarized in Table 3. Households had a median of 5 members, and farms were typically small, with a median land area of about 3.5 ha. Median household cash income for the 12 months preceding the 2017 survey was $652 (US), implying per capita cash incomes of less than one dollar per day; these figures do not account for the value of own food production or any other in-kind income sources. Mean household cash income did not change significantly between 2014 and 2017.

Although coffee is the principal economic activity among surveyed smallholders, income sources are diversified, with a majority of households also growing corn and beans (basic grains). Sales revenue from coffee was the top source of cash income reported for the plurality of households and accounted for 42% of total household income in 2017. Revenues from selling basic grains and from off-farm labor were the next most important cash income sources, accounting for 16% and 12% of total income respectively. Subsistence production is also key to securing food entitlements, as a quarter of households reported growing at least half their own food.

Between 2014 and 2017, a significant fraction of farms curtailed coffee production (from 64% to 44%) as a consequence of factors such as coffee leaf rust (CLR) related crop losses. Many of these farmers plan to resume active coffee production: of 200 households reporting coffee production in 2014, only 92 reported production in 2017, but 87 more reported coffee land in development. Despite the large drop in the fraction of farms actively producing coffee, total coffee production actually increased substantially, as active producers nearly tripled their total output.

4.2. Joint assessment of household food and water insecurity

Most households reported the presence of seasonal hunger, as indicated by months experiencing difficulty feeding the family (lean months). Ninety-six percent of households reported nonzero lean months, with a mean of 2.6 months, median of 3, and IQR of [2,3]. Among the households in our paired longitudinal sample, mean food lean months fell by about half a month between 2014 and 2017, from 3.1 to 2.6, a change significantly different from zero ($p < 1\%$). These magnitudes are consistent with previous findings by the authors among smallholders in this area.

Seasonal scarcity of water for direct consumption can be measured analogously using reported months without sufficient water for household uses. By this metric, seasonal water insecurity affected some 71% of households in the 2017 survey, with a mean of 2.1 months, median of 2, and IQR of [0,3]. Using a consistent measure of water lean months available in both surveys for the matched households, the mean number of water lean months also fell by about 0.5 between 2014 and 2017.

Food and water insecurity are positively correlated across households, as indicated in Fig. 3a, which plots food lean months against water lean months for the cross-section of households in 2017. The estimated OLS regression slope of 0.07 is statistically different from zero ($p < 1\%$) but is rather small in magnitude, implying that households that experienced one additional month of water scarcity experienced on average about two more days of food scarcity.

The inter-household association of food and water insecurity is also exhibited by the indexes of the severity of household coping responses (Fig. 3b) (Jepson et al., 2017; Maxwell et al., 2014). The median household in 2017 did not report any coping responses for either food or water, and thus the median coping index is 0; Fig. 3b uses a sample restricted to the subset of observations with nonzero values of both index numbers. The positive relationship between water and food lean months across households also holds (weakly) in first differences (changes) between 2014 and 2017 (Fig. 3c), implying that the relationship is not merely a consequence of time-invariant household characteristics (fixed effects) correlated with both food and water insecurity.

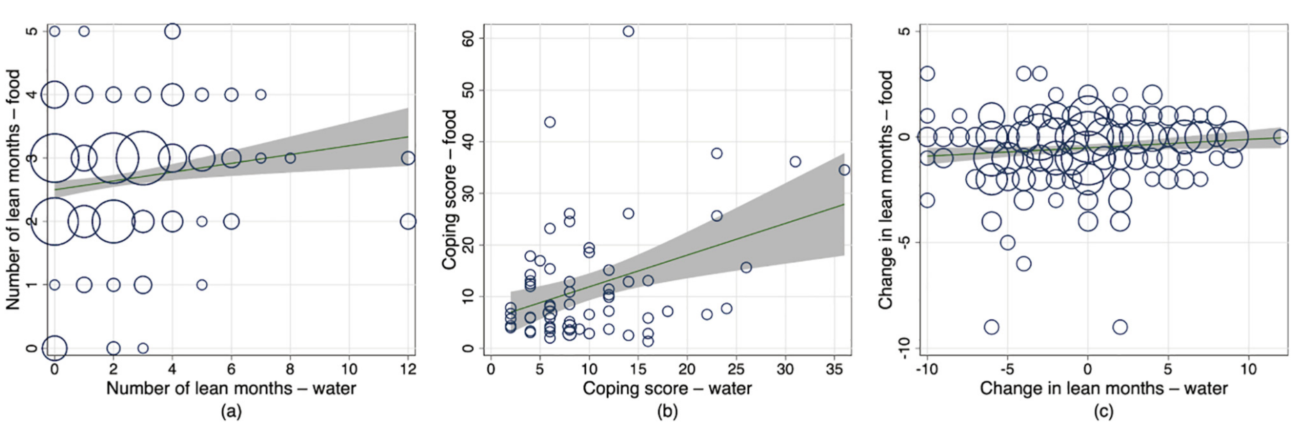

Fig. 3. Relationship between measures of seasonal water insecurity and food insecurity across survey households. Source: Household survey samples from June-July 2014 and June-July 2017. See text and methods section for details on lean month and coping index variables. Notes: Point size scaled to number of observations. Shaded area is 95% confidence (prediction) interval around the OLS linear prediction. a. Food and water lean months, 2017 household survey. OLS regression line: $\hat{Y}$ = 2.50 (0.08) + 0.069 (0.025) X, R^2 = 0.027, N = 334. b. Food and water coping index scores, 2017 household survey, sample restricted to observations with nonzero coping scores. OLS regression line: $\hat{Y}$ = 5.76 (1.78) + 0.61 (0.17) X, R^2 = 0.149, N = 65. c. 2014–2017 change in food and water lean months for matched households surveyed in both 2014 and 2017 with non-missing lean months both years. OLS regression line: $\hat{Y}$ = −0.515 (0.081) + 0.040 (0.018) X, R^2 = 0.014, N = 299. Robust standard errors in parentheses.

4.3. Drivers of household food and water insecurity

The pathways illustrated in Fig. 1 posit some key common drivers of food and water insecurity. Although data limitations do not permit estimation of a full causal model, we use multiple regressions to estimate the associations between key measurable household characteristics and food and water insecurity outcomes across households.

Core regression results are presented in Table 4. The estimating sample is the cross section of household survey responses from 2017. The dependent variables are the lean month and coping index measures of food insecurity (upper panel) and water insecurity (lower panel). All regressions include as regressors measures of household assets (farm area) and endowments (education), local precipitation, and impact of the coffee leaf rust; additional specifications add household cash income, which is a potentially important mediating factor, or the farm's output of three key crops – coffee, corn, and red beans. The latter specification captures household resources by accounting for the principal cash crop (coffee) along with production of the two staple basic grain crops, which may be directly consumed by the household and/or sold. The first three columns (lean months) report OLS regression coefficients, while the latter three (coping index) report coefficient estimates for a tobit specification, which adjusts for the left-censoring of coping scores at zero (Maddala, 1986).

Examining the results for the food insecurity regressions, the negative and statistically significant coefficients for land area in the first two regressions confirm the importance of farm size for livelihoods. The −0.03 coefficient in the first column implies that a one-standard deviation increase in farm size (about 6 ha) corresponds to a reduction in predicted food lean months of about 0.2 (roughly 6 days), conditioning on the other regressors. Because the impact of farm size on food security should operate primarily through its effect on crop production, the inclusion of controls for coffee and basic grain production (third column) not surprisingly reduces the farm size coefficient to insignificance. The coeffi-

Table 4
Drivers of food insecurity (upper panel) and water insecurity (lower panel), 2017 survey.

Food	Lean mo	Lean mo	Lean mo	Coping	Coping	Coping
Farm land area (ha)	−0.0308***	−0.0185**	−0.00767	−0.781**	−0.413	−0.248
	(0.00803)	(0.00849)	(0.00843)	(0.332)	(0.352)	(0.383)
Respondent education: at least some secondary	−0.148	−0.0559	−0.118	−3.699	−1.106	−2.896
	(0.132)	(0.138)	(0.124)	(3.868)	(3.942)	(3.868)
Community 14-mo total precip (meters)	0.194	0.334	0.161	−4.507	0.337	−2.450
	(0.228)	(0.226)	(0.220)	(6.795)	(6.720)	(7.079)
Proportion coffee affected by CLR	−0.203	−0.170	−0.160	6.604*	7.700*	8.430**
	(0.130)	(0.131)	(0.128)	(3.986)	(3.958)	(3.894)
Household cash income in $1000		−0.0994**			−3.678***	
		(0.0418)			(1.055)	
Corn production last 12 mo. (1000 kg)			−0.00714			−3.703**
			(0.0222)			(1.691)
Bean production last 12 mo. (1000 kg)			−0.191***			−0.554
			(0.0737)			(2.408)
Coffee production last 12 mo. (1000 kg)			−0.342***			−6.655**
			(0.110)			(3.313)
R-sq, pseudo-R-sq	0.061	0.089	0.121	0.008	0.017	0.020
Observations	311	311	311	311	311	311
Water	**lean mo**	**lean mo**	**lean mo**	**coping**	**coping**	**coping**
Farm land area (ha)	−0.0194	0.0143	0.0297	−0.0680	0.103	0.163
	(0.0266)	(0.0327)	(0.0374)	(0.149)	(0.167)	(0.177)
Respondent education: at least some secondary	−0.413	−0.162	−0.367	0.667	2.093	1.011
	(0.274)	(0.284)	(0.271)	(2.287)	(2.338)	(2.285)
Community 14-mo total precip (meters)	−0.0484	0.333	0.00328	−19.94***	−18.19***	−18.68***
	(0.535)	(0.549)	(0.555)	(3.418)	(3.413)	(3.559)
Proportion coffee affected by CLR	−0.165	−0.0730	−0.0453	−0.798	−0.399	0.0136
	(0.306)	(0.309)	(0.311)	(2.145)	(2.111)	(2.157)
Household cash income in $1000		−0.272***			−1.504**	
		(0.0829)			(0.627)	
Corn production last 12 mo. (1000 kg)			−0.0799**			−0.565
			(0.0361)			(0.536)
Bean production last 12 mo. (1000 kg)			−0.286**			−0.343
			(0.145)			(1.361)
Coffee production last 12 mo. (1000 kg)			−0.657***			−4.631***
			(0.227)			(1.662)
R-sq/ pseudo-R-sq	0.009	0.047	0.051	0.022	0.028	0.029
Observations	311	311	311	311	311	311

Notes: * $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$. All regressions estimated with intercept term, not reported here. The first three columns (lean months) report OLS regression coefficients, while the latter three (coping index) report coefficient estimates for a tobit specification. All regressions use household-level cross-section data from the 2017 survey. Community precipitation is the sum of community-level estimates of monthly precipitation for the 14-month period May 2016-June 2017; May of the year preceding the survey year is the earliest month for which past precipitation would have directly affected agricultural production during the survey period of June-July 2017, given the local agricultural calendar. Coffee leaf rust is assessed by the household's reported percentage of the coffee plantation affected; non-responses are largely households not currently producing coffee and are coded as zero. Household cash income is the sum of income from the household's top five sources over the preceding 12 months, converted to US dollars at the prevailing official exchange rate. For the crop production variables, non-responses are coded as zero. Source: Cross-section regressions using household survey sample from June-July 2017 for matched households.

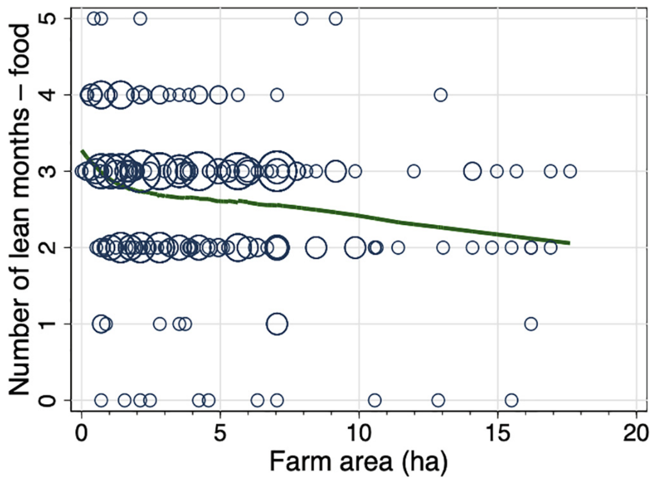

Fig. 4. Farm size and food insecurity across households, 2017. Notes: N = 325. Scatter plot with lowess smoothed relationship; point size scaled to number of observations. Plot excludes 9 observations with very large farm areas exceeding 20 ha; size pattern is not sensitive to including them. Source: Household Survey 2017.

cient on farm size in the coping index regressions is also negative and significant in the specification without income or crop production controls.

As have previous studies, we found that the smallest farms experienced the highest levels of food insecurity (McKune et al., 2018). In Fig. 4, we show that the bivariate relationship between farm size and food lean months is nonlinear: As farm size increases, food insecurity declines, with a steep decline as reported farm size goes from zero to approximately 1.5 ha, and a continued but more gradual decline beyond that point. This pattern suggests that the negative relationship estimated in the regressions presented in Table 4 might be even stronger for the smallest farms.

Like farm size, household cash income is also associated with reduced food insecurity, as expected. These findings are consistent with the role of farm size and poverty in perceptions of adaptive capacity among Nicaraguan coffee farmers documented by Quiroga et al (Quiroga et al., 2020). The coefficients on education and local precipitation are not significantly different from zero in any specification, although education is associated with higher income, as noted below. A higher reported incidence of coffee leaf rust is not significantly associated with food lean months, but is associated with greater food insecurity in the coping index regressions.

Increased production of both coffee and food crops is associated with lower food insecurity (third and sixth columns of Table 4). The coefficient on coffee production in the lean months regression implies that a one-standard deviation increase in coffee output would be associated with approximately five fewer days of food shortage, other things equal. When cash income is included as a control along with the crop production variables (not reported here), the food crop coefficients are not significant, suggesting that diversification into the production of basic grains during this period enhanced food security predominantly through its effect on overall household resources.

The lower panel of Table 4 presents coefficients from analogous regressions of water insecurity on the same set of drivers. In contrast with the food insecurity regressions, the farm size effect is not statistically significant in any specification, but household income is significantly associated with reduced water insecurity: a one-standard deviation increase in annual income (~$1750) is associated with a reduction in water lean months of about 0.5 (2 weeks per year). The regressions also indicate that households in communities experiencing more rainfall over the 14 months leading up to the survey reported less severe coping responses to water shortage. The coefficients on crop production are all negative and significant in the lean months regression; both the income and crop production effects here are consistent with the idea that greater household resources increase entitlements to water, whether through better water system access or investment in rain capture or wells, etc.

The core regression results presented in Table 4 are largely robust to various alternative regression specifications, presented and discussed in the Appendix (Tables A2 and A3). For example, the estimated coefficients are of similar magnitude and significance using a Poisson count regression for the lean month regressions. Results are also similar when household income is adjusted for family size, and when we log-transform both income and land area to take account of potential diminishing returns to household resources. Additional controls for farmer organization and household demographics are mostly statistically insignificant and do not substantively affect the main results.

Climatic and other preconditions influence household food and water security via multiple pathways, including farm production and household cash income (Fig. 1). We assess the importance of some of these mediating links by regressing annual production of coffee, corn, and beans, as well as total cash income, on key drivers (results in Appendix Table A4). These regressions confirm the importance of farm size, which unsurprisingly is strongly positively associated with income and production of all three key crops. Respondent educational attainment is significantly (and positively) associated with cash income, perhaps reflecting the role of off-farm skilled employments as a source of income for more educated householders.

4.4. Seasonal vulnerability to food and water insecurity

In our study area, the seasonal patterns of water and food scarcity are quite distinct, resulting in multiple months of exposure to one or the other kind of seasonal stress for many households. Fig. 5a summarizes the patterns revealed in our survey, showing the percentage of households reporting each type of insecurity during that month. The gray line shows the percentage of households reporting *either* water or food insecurity (or both) for the indicated month. In each of the six months from March through August, more than a quarter of households report seasonal water stress, food stress, or both; in five months of the year more than half report one or both.

Water lean months are associated with the latter part of the dry season – March and April in particular (Fig. 5b) – whereas seasonal lean months for food come during June, July, and August, before the harvest of the first planting of beans and corn (Fig. 5c), and when staple food prices (corn in particular) are high and household exchange entitlements correspondingly low (Fig. 5d).

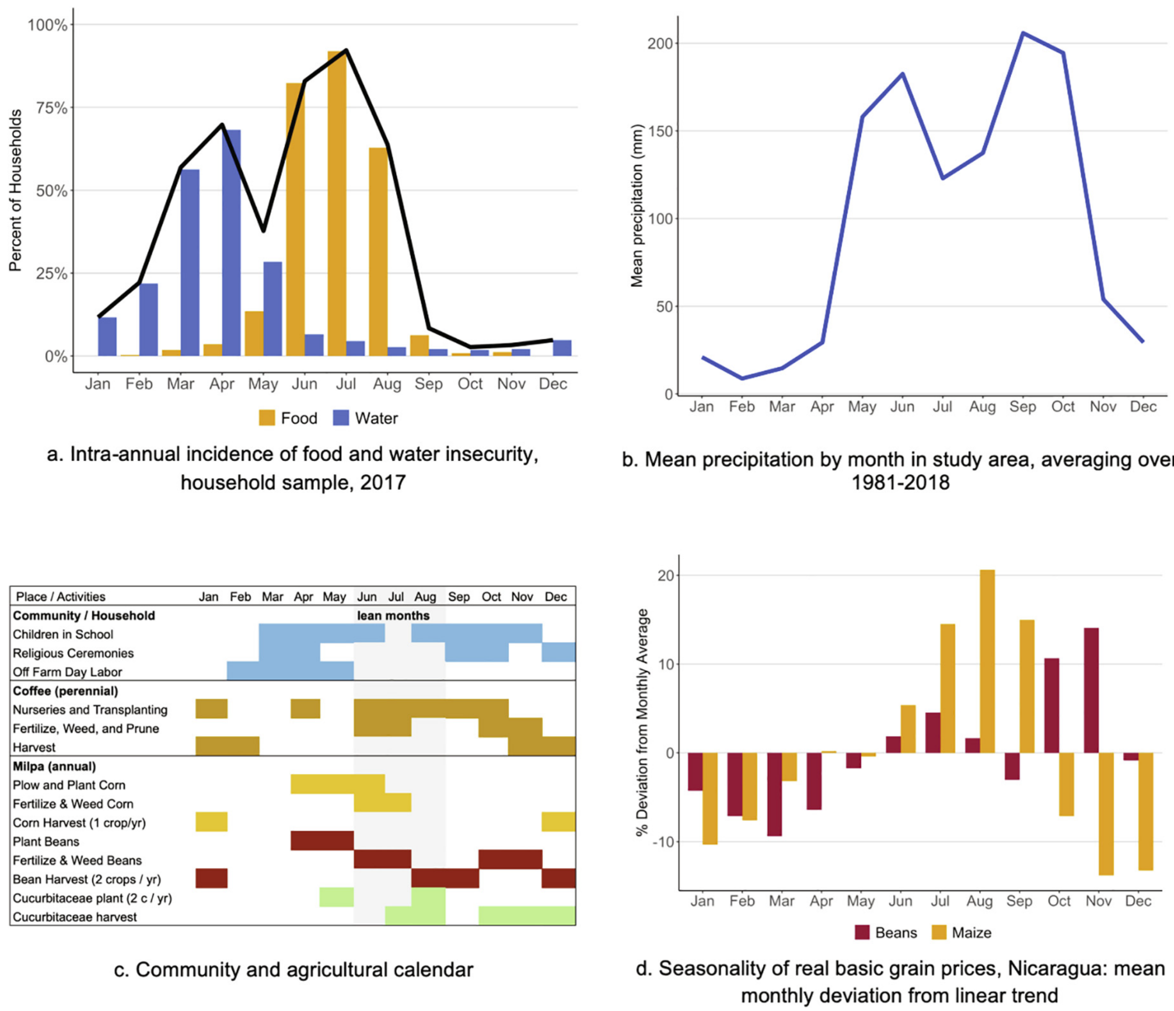

Fig. 5. Seasonality of food and water insecurity, precipitation, and agriculture. Notes and sources: a. Percent of households reporting specific months of difficulty providing enough food or water to family during preceding 12 months. Dark line indicates difficulty providing either. Source: Household survey sample from June-July 2017 for matched households (Full N = 311). b. Unweighted mean precipitation by month for the period 1981–2018, for communities in the study region using CHIRPS data. c. Community and agricultural calendar summary for the study area – additional detailed activities such as pest control, seed selection, and post harvest activities not included due to lack of space. Harvests shown in January and February are from the corn and bean plantings in May and June. Cucurbitaceae refers to the gourd family often planted as an intercrop with corn and beans in the *milpa*, commonly including squash, pumpkin, zucchini, and selected gourds. Source: Interviews and focus groups with farmers and cooperative officials. d. Mean monthly deviation from linear time trend of real prices of maize and beans, January 2000–December 2016. See text and methods section for additional details.

4.5. Climate threats and adaptation in the context of multiple hazards

Between 2014 and 2017 the surveyed households reported an improvement in food and water security, with a mean reduction in both food and water lean months of about 0.5 months (see Table 2). The return of the region to relatively normal precipitation levels following an earlier severe drought period that coincided with a strong El Niño/Southern Oscillation (ENSO) event from 2014 to 2016 (NOAA's Climate Prediction Center, 2016) – as indicated in Fig. 6a – may help account for this change. As of March 2014, the SPI had fallen below −1 in all communities, indicating dry conditions, whereas the months leading up to the 2017 survey were generally a period of historically normal precipitation.

Climate-related fluctuations in weather patterns are but one of a number of important hazards contributing to livelihood vulnerability. In our 2017 survey we asked respondents to identify the events with greatest adverse impact over the preceding 12 months (see Fig. 6b). Coffee leaf rust (CLR) and drought were the most frequently mentioned in households' three most severe hazards – drought was mentioned even during a relatively normal precipitation year. The survey also reveals the significant impact of changing exchange entitlements: although farmers ranked the effects of CLR and drought higher than price changes for either food bought or crops sold, when taken together, adverse shifts in these prices were second only to CLR in perceived importance. Concerns of crop loss due to both drought and flooding indicate the importance of climatic extremes on livelihoods.

The salience of shifting exchange entitlements is unsurprising given the volatility in terms of trade between food and coffee. Fig. 6c exhibits indexes of the ratios of maize and dry bean prices (at monthly frequency) to the price of coffee on global markets at the typical time of coffee harvest and sale in our study area (January-February). The indexes capture the inverse of a coffee farmer's relative purchasing power over food. Terms of trade are highly volatile: a doubling of relative food prices over the course of a few months is not uncommon. Relative prices of both corn and beans were down substantially in 2017 relative to 2014, a drop that may help account for the reduction in reported food insecurity, despite only marginal increases in per capita cash income over the same period and decreased production of corn and beans by

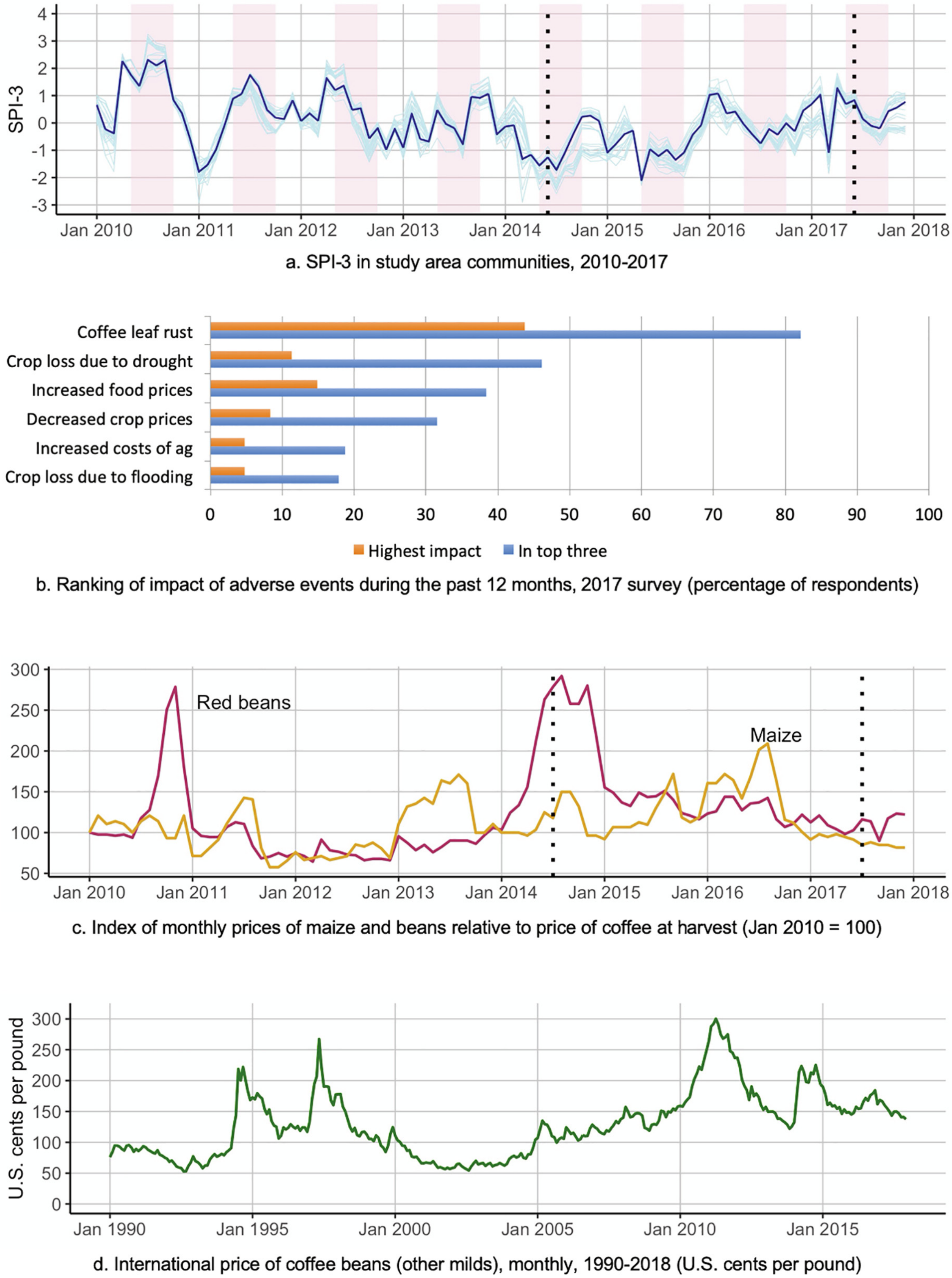

Fig. 6. Hazard and stressor exposures. Notes: a. Monthly series of the SPI-3 precipitation anomaly index at the local community level. A separate SPI-3 series was estimated for each community from monthly precipitation data for the period January 1981 - December 2018, using the SPEI package in R and the default gamma distribution. Light blue lines represent the series for each community, the dark blue line is the SPI-3 for the median community in that month, the vertical dotted lines represent the survey periods (June and July in 2014 and 2017), and the pink shaded areas are the typically wetter months of May-October. b. Percent of households reporting the event at indicated rank of impact, for adverse events ranked in top three by at least 10% of households. Source: 2017 household survey. N = 334. c. Index number = 100 $(P_{ft}/P_{fb})/(P_{ct}/P_{cb})$, where P_{ft} = price of food (maize or beans) at time t, P_{fb} = price of food at base period (January 2010), P_{ct} = mean price of coffee in January and February of each year (U.S. cents per pound), P_{cb} = mean price of coffee in January and February 2010. Vertical dotted lines at survey months. Data sources: International Coffee Organization (ICO), ICO Composite & Group Indicator Prices – Monthly Averages, "Other Milds" series http://www.ico.org/new_historical.asp; Food and Agriculture Organization (FAO), Wholesale prices of maize (white) and beans (red), Managua http://www.fao.org/giews/food-prices/tool/public/#/dataset/domestic; data downloaded 5/18/2018. d. Data source: International Coffee Organization (ICO), ICO Composite & Group Indicator Prices – Monthly Averages, "Other Milds" series http://www.ico.org/new_historical.asp; data downloaded 5/18/2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the median farm. In general, however, the relative prices of corn and beans are not highly correlated with each other over time, suggesting that diversification of staple food crops could be a viable risk-reduction strategy (on the correlation of commodity prices and the value of diversification in a country-level panel, see Merener and Steglich (2018)). Farmers reliant on coffee sales for income are at the mercy of well-known dramatic fluctuations in global coffee prices, displayed in Fig. 6d.

The importance of coffee leaf rust (CLR) as a hazard and perceived stressor for these farmers raises the question of the recent and potential future relationship between the incidence of CLR and climate change. Interactions among coffee plant conditions, *Hemileia vastatrix* (the fungal disease that causes CLR), and the environment have contributed to CLR outbreaks in Latin America and the Caribbean (Avelino et al., 2015; McCook & Vandermeer, 2015). Variability in the coffee plant's microenvironment can contribute to spread of CLR, but plant health (including the age of the coffee bushes), coffee varieties, sunlight exposure, and the use of different treatment strategies have also been strongly correlated with the intensity of the CLR outbreaks occurring in the region since 2008 (Avelino et al., 2015; Bebber et al., 2016; Castillo et al., 2020; Vandermeer & Rohani, 2014; Ehrenbergerová et al., 2018). Weather likely played a role in the 2012 CLR epidemic in Central America: above-average precipitation during the dry season and early stages of the rainy season (see Fig. 6a) may have maintained a high level of initial inoculum; below-average rain in the last two trimesters likely reduced the number of CLR spores washed away, thereby leaving more available for new infections; and lower diurnal temperatures could have decreased the duration of CLR's latency (Avelino et al., 2015).

Although climate change increases the likelihood of warmer temperatures and increased precipitation variability in our study area (Maurer et al., 2017), attributing a specific outbreak directly to climate variability's influence on meteorological conditions that favor CLR is complex. While there is some evidence pointing to a role for climate change in CLR outbreaks, the picture is mixed, and climate is far from the sole factor shaping CLR epidemics, with farmer management strategies, landscape context, market volatility, state withdrawal from investment in smallholder production, and rising input costs equally or more important in structuring where, when, and with what intensity CLR epidemics take shape.

Regarding the role of climate change, a study conducted in Colombia, which used climate reanalysis to test the hypothesis that climate change increased the likelihood of the 2008–2011 CLR outbreak, rejected the hypothesis (Bebber et al., 2016). In contrast, a recent review article that focused on organic coffee smallholders in the higher altitudes of Mexico concludes that climate change "generated instability in the flowering and fruit generation cycles and has favored the proliferation of CLR in areas above 1400 m above sea level" (Castillo et al., 2020: 13).

Evidence for the importance of crop variety and management is strong. For example, neither Brazil nor Vietnam, both of which have high percentages of CLR resistant *robusta* coffees (*Coffea canephora*), have experienced CLR damage to the same degree as Central and South American countries that have a higher percentage of CLR-susceptible *arabica* coffee varieties. A study in Peru concluded that coffee farm design and management were key drivers of its recent CLR outbreak (Ehrenbergerová et al., 2018). Other researchers have noted that CLR outbreaks are strongly influenced by weak plant health, linked to lack of agricultural investment, and frequently occur shortly after periods of low coffee prices and/or rising input expenses – factors leading some to label the recent rust outbreaks a "neoliberal epidemic" (McCook & Vandermeer, 2015).

We have several takeaways from this research. First, these studies highlight the complex causal relationships that help explain CLR outbreaks. Second, the evidence points to the importance of coffee farm design and management, especially strategies related to crop varieties, plant health, and the management of the microenvironment through shade tree vegetation. Third, declines in coffee plant health, the presence of older plants, and the slow adoption of CLR-resistant varieties are all related to systematic underinvestment in agriculture, caused in part by low revenues and returns in coffee associated with very low international coffee prices in the decade leading up to the 2011 rust outbreak (see Fig. 6d). Since 2012, however, many producers in our sample have received support and also used their own resources to invest in planting more coffee and replacing dead and damaged plants. Fourth, while several studies predict that projected climate change – especially warming temperatures – will significantly reduce the areas that are optimal or even suitable for coffee production (Läderach et al., 2017; Harvey et al., 2018), there is mixed evidence about the role of climate change in the 2008 to 2013 CLR outbreaks in Latin America.

5. Concluding discussion

How important are climate-related impacts on household food and water insecurity in the context of multiple hazards affecting northern Nicaragua and Central America? We expected the influence of climate would be significant, given that over 90% of farmers rely on rainfall and over 85% use community water systems dependent on surface water sources. Worldwide, climate variability explains about a third of observed yield outcomes for maize, rice, wheat, and soybean crop yields (Ray et al., 2015). Climate change is already affecting the region, as farmers in our study and across Central America contend that they are experiencing increased intensity and frequency of droughts, irregular precipitation patterns that interrupt traditional cropping patterns, hotter days, and warmer nights (Harvey et al., 2018). Climate projections predict warmer temperatures and longer midsummer dry periods (Maurer et al., 2017). In the Central American Dry Corridor, "annual-scale, longer-term droughts are projected to lengthen by 68% under moderate emissions, potentially triple in length under high emissions, and to intensify by 27–74%" (Depsky & Pons 2020: 1), with implications for agricultural calendars, crop loss, seasonal hunger, and water access.

In our survey, farmers expressed more concern about CLR and unfavorable prices (taking food and crop prices together) than about drought, echoing findings in other contexts that immediate concerns related to maintenance of livelihoods may eclipse climate-related threats (Fischer, 2018; Rhiney et al., 2020; Taylor & Bhasme, 2020). Still, climate variability and change remain a pressing concern, as both drought and flood impacts were identified among the six most serious threats to livelihoods. In focus group discussions of our study's findings, farmers attributed household food security improvements from 2014 to 2017 to the end of the 2014–16 drought, which agricultural extension agents reported contributed to 50–70% losses of maize and bean crop harvests by December 2014.

A cursory read of these findings suggests a case of climate-induced production entitlement failure leading to food insecurity (Niles & Salerno, 2018; Sen, 1981), with a subsequent partial recovery; however, precipitation was actually near-normal during the 15 months preceding our survey in June 2014 (Fig. 4a). Our explanation focuses on seasonality and exchange entitlements. By May and June most producers exhaust food stored from the December harvests and must purchase corn and beans in local markets. Cash is scarce during these lean months, and CLR damage to coffee harvests has exacerbated this dynamic over the past decade. Furthermore, the drought had already started by July 2014, and the anticipated bean crop failures and local grain trader speculation contributed to a bean price spike. Thus, farmer livelihood vulnerabilities intersected with environmental hazards and unfavorable terms of exchange, contributing to food insecurity levels not seen since Hurricane Mitch rocked the region in 1998. In contrast, the context leading up to the July 2017 survey period included some support for CLR recovery, relatively stable food prices, and the expected precipitation patterns. Our finding that water insecurity is also related to household production and incomes suggests a similar explanation for the observed decline in water insecurity over the same period.

Since our survey in summer 2017, additional hazards have further exacerbated a challenging vulnerability context. In 2017 Nicaragua's GDP grew at a 4.6 percent annual rate, before an interconnected combination of political unrest, geopolitical shifts, domestic responses, falling international coffee prices, and a plunge in tourism contributed to GDP growth rates falling to −3% in recent years, according to World Bank estimates (World Bank, 2020). Efforts to build adaptive capacity to maintain household food and water security in the face of threats from prospective climate variability and change will have to take place within the context of these political economic challenges.

In November 2020, back-to-back Hurricanes Eta and Iota blasted the Atlantic Coast before moving through the study area, the strongest storms ever to hit the country so late in the season and inflicting the most severe hurricane-related damage since Hurricane Mitch in 1998. After meeting immediate needs for alleviating the humanitarian emergencies, recovery and reconstruction efforts could be informed by research findings that identify the specific household capacities and farm characteristics – such as income and access to larger farm areas – that correlate with improved food and water security.

In the longer term, addressing the chronic problems of seasonal hunger and malnutrition and securing sustained access to safe drinking water will require access to relevant technologies and broader political economic changes, including transformations of the adverse terms of resource access (e.g., prices received by farmers, land tenure policies, drinking water delivery systems) that smallholders in Nicaragua and elsewhere have faced for decades (Anderson et al., 2019; Gliessman, 2013; Béné et al., 2017; Bacon et al., 2017). Civil society and social movement-led campaigns that advance these agendas and aim to shift power relations to favor organized smallholder interests – often under the banner of food sovereignty and the human right to food – hold potential to address some of these inequalities; such food sovereignty approaches must still contend with the fact that most of these producers also sell cash crops, purchase some of their food, and may rely on off-farm income (Diaz & Hunsberger, 2018; Perfecto et al., 2019b; Zimmerer et al., 2020).

Farmers affiliated with both the fair trade cooperative and the Campesino-a-Campesino organizations in our region have advocated for policy changes that advance agroecology based approaches to farm diversification, organic agriculture, and food sovereignty, which they see as an approach that could lead to improved exchange entitlements and greater access to land and locally adapted seeds (Bacon, 2015; Holt-Giménez, 2002; Bacon et al., 2014). Support for village water committees to strengthen their administrative capacity, power, and access to technology for water delivery and purification is an analogous strategy that could improve water security (Romano, 2019). Building the institutional capacity within and across farmer organizations and rural social movements (Holt-Giménez et al., 2010; Starobin, 2021; McCune & Sánchez, 2019), strengthening village water and sanitation committees (Romano, 2019), and investing in community-based public health efforts (George et al., 2009) are additional potentially powerful responses to these multiple hazards.

We close by noting several implications of our study for adaptation research, planning, and policy in rural areas worldwide. First, the connection between water security and food security underlines the need for integrated planning that breaks the siloed approach of focusing on just one or the other (Brewis et al., 2020; Wutich et al., 2017). Second, our findings suggest several strategies for building adaptive capacity with smallholders. This study highlights the importance of access to more land, especially among the smallest landholders. Farm area correlated with larger harvests of cash and subsistence crops, improved food security outcomes, and higher incomes, while higher incomes and farm production correlated with greater food *and* water security. Given the risks associated with coffee production and changing markets, diversified farming practices that include the production of food crops (e.g., corn and beans) for household consumption and local sales remain an important strategy for food security in this case and elsewhere (Bacon et al., 2017; Kremen et al., 2012; Zimmerer et al., 2020; Méndez et al., 2010). Third, the exchange entitlement analysis shows again the importance of creating local food systems and markets that offer better terms and greater land access to marginal farmers (Devereux et al., 2008; Frison, 2016; Ingram et al., 2012). Ultimately, we argue for transformative adaptation strategies combining existing social-ecological knowledge, detailed assessment of what works in response to different hazards, and broader efforts to address inequalities in ways that improve the terms of household access to food, water, and land (Roy et al., 2018; Johansson et al., 2016).

Data and replication code availability

The survey instrument, anonymized survey data, and files required for replication and statistical analysis are available upon request and will be posted to Harvard Dataverse archive (Bacon, Sundstrom, Stewart, Maurer, & Kelley, 2020), after this article is published.

Conflict/declaration of interest statement

All authors must disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

Declarations of interest

None.

CRediT authorship contribution statement

Christopher M. Bacon: Conceptualization, Writing - original draft, Visualization, Methodology, Formal analysis, Data curation, Investigation, Writing - review & editing, Supervision, Funding acquisition. **William A. Sundstrom:** Conceptualization, Writing - original draft, Visualization, Methodology, Data curation, Formal analysis, Investigation, Writing - review & editing, Funding acquisition. **Iris T. Stewart:** Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **Ed Maurer:** Conceptualization, Investigation, Writing - review & editing, Funding acquisition. **Lisa C. Kelley:** Conceptualization, Methodology, Writing - review & editing.

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Appendix A. Supplementary data

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