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Social-ecological interactions in a disaster context: Puerto Rican farmer households' food security after Hurricane Maria

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E-mail: lrodrig2@uvm.edu**Keywords:** small island developing states, food insecurity, extreme weather events, vulnerability, adaptive capacity**Abstract**

Islands are uniquely vulnerable to extreme weather events and food insecurity, and have additional response challenges due to their limited landmasses and economies, isolation, colonial legacies, and high dependence of food imports. Domestic farmers have a key role in producing food for island communities like Puerto Rico, which can safeguard food security when food importation may be challenging. Nevertheless, in the context of disaster, farmers themselves may be vulnerable to food insecurity and unable to contribute to domestic markets. This paper examines Puerto Rican farmers households' food security in the aftermath of 2017's Hurricane Maria using a social-ecological lens. Survey data from 405 farmers gathered eight months after Maria, coupled with biophysical data from the hurricane's impacts (winds, rains, and landslides), were analyzed. Overall, 69% of farmers experienced at least one month of food insecurity in the aftermath of Hurricane Maria, and 38% reported persistent food insecurity (three months or more). A multinomial logistic regression suggests that biophysical impacts, but especially social factors, such as age and constraint access to external sources of support, are linked with persistent food insecurity. This suggests that the biophysical impacts of the hurricane interact with existing infrastructure and social resources to affect farmer vulnerability and the food environment in different ways. Thus, strengthening adaptive capacity in multiple domains can help farmers and vulnerable populations better navigate the disruptions faced during disasters to alleviate food insecurity.

1. Introduction

Extreme weather events, such as hurricanes, are becoming more intense in the growing climate crisis [1, 2]. These events can trigger disasters, often prompting disruptions in the built and natural environments affecting livelihood activities [3–6]. Such disruptions can generate a period of transitory or episodic food insecurity, where people's consecutive access to adequate food that supports their wellbeing is hindered [7, 8]. During these periods, often unexpected or seasonal [9–11], people lack or have difficulty accessing nutritious and culturally-appropriate foods [7]. The length of these effects on people's food security may vary, due to the magnitude of the

impact, coupled with an affected populations' vulnerability stemming from social-ecological characteristics, such as race, sex, geography, economics, politics, ecosystem services, and biophysical aspects of a place, among others. Social-ecological characteristics may predispose some populations to be at higher risk of harm, and may reduce their ability to recover from disaster impacts [5, 12–14]. This assertion is increasingly true of small island developing island states (SIDS) and territories (as well as low-income societies), which have higher exposure and sensitivity to extreme weather events [1, 15–18].

In island systems, physical and economic access to food at all times is often challenging due to several characteristics: high dependence on imports and

marine supply chains, limited land to produce food, small economies, high costs of food, critical infrastructure and high population density in coastlines, as well as trade and colonial histories with power inequities [16, 19–28]. Furthermore, most SIDS are located in the tropics, and are facing the climate crisis's effects disproportionately [1]. These characteristics may shape people's adaptive capacity—the assets and abilities that allow people to mitigate and prepare for shocks, as well as to recover from them, and transform their environment to better sustain impacts [12, 29–34]—which may contribute to lengthening negative effects on food security after an extreme weather event [35]. Yet, despite the unique social-ecological characteristics of SIDS, very little research has explored island food security following disasters [20, 27, 28, 36]. This paper examines Puerto Rican farmer households' food security in the aftermath of 2017's category four: (Saffir-Simpson Hurricane Wind Scale) Hurricane Maria. The analysis is focused on farmers, who face high vulnerability to natural hazards' impacts due to their dependence on natural resources, which mediates the sensitivity and exposure they face to shocks [37].

Prevalent social (e.g. structural inequities, income inequality) and biophysical conditions (e.g. housing disruption due to hurricane damage) generate obstacles for people to have consecutive access to food following a disaster [8, 38–41]. For example, risk factors, such as gender or poor physical health, as well as difficult access to social or structural support, were linked to food security levels after Hurricane Katrina in the United States [39]. Impacts to infrastructure and agricultural landscapes also shape the length of negative effects to food security by hindering local production, and household's food access and sources of income [35, 42, 43]. In the case of SIDS and other net-importers, their susceptibility to market fluctuations and impacts of extreme weather events abroad also have an impact on food security [44, 45]. As such, understanding food security following a disaster must encompass the multidimensionality of food security in a social-ecological system, where natural (e.g. climate patterns, ecosystem services, agricultural resources) and social components (e.g. economic, inequality, colonial legacies) intertwine and influence individual outcomes [46–51]. Assessing farmers' food security over time during the recovery period from an extreme weather event can provide an understanding of how social-ecological dynamics shape disasters [37, 52, 53], and what may contribute to reducing vulnerability to future extreme weather events and other natural hazards more broadly [48, 54]. This is important in SIDS where domestic production can buffer against supply chain challenges following a disaster [36, 44, 55].

Farmers are an important unique group of focus to understand disasters and food security, given their

livelihood reliance on natural resources and their potential ability to provide locally available food post-disasters. Studies focused on continental smallholder farmers, who often farm less than 10 hectares—while employing different approaches and measures of food security—show that farmer food security outcomes are driven by a combination of social (e.g. support networks, income), physical (e.g. infrastructure assets), agricultural (e.g. farm size), and demographic characteristics (e.g. gender, income) [10, 53, 56–59]. For example, agricultural diversity—production diversity, as well as access to different markets and sources of support—have been shown to decrease farmer household food insecurity [10].

Research on Caribbean farmers has shown that social factors play a key role in food security outcomes. Studies have shown that Caribbean farmers with land tenure, access to diverse markets and sources of income and support, see less negative effects on their food security and thus, cope better with extreme weather events [19, 36, 60–63]. Yet, studies in the Caribbean have mainly focused on Cuba, and the Caribbean Community (CARICOM)—to which Puerto Rico is not a part of [19, 60, 61, 64, 65]. It is important to note that the Caribbean is composed of islands of diverse landmasses, many of which are not sovereign and that are embedded in neocolonial relationships with former metropolis [21, 22, 27]. Hence, studying this issue in Puerto Rico, an unincorporated territory of the United States, can increase our understanding of how food security manifests in the context of disaster beyond sovereign SIDS.

Besides the general research on (smallholder) farmer food security, there is a growing body of evidence exploring food security more generally during and after extreme events, such as drought [66, 67], monsoon and floods [68], and hurricanes or cyclones [59]. Many studies have shown clear links between experiencing natural hazards and decreased food security or diet diversity. Findings show that a combination of household assets coupled with broader structures of support play a key role in people's access to food when a shock creates a disruption in livelihood activities [9, 47–50]. Most of the existing work on food security and extreme events is focused on continental countries, not in SIDS. The limited studies that have been done in the context of disaster in Latin America and the Caribbean mostly focus on farm resiliency and recovery (e.g. returning the farm to production or to pre-event state), showing that production diversity, access to diverse markets and sources of support, correlate with better farm recovery from extreme weather events [45, 54, 55].

Given the dearth of research focused on farmer food security in SIDS following extreme events, this paper will assess farmer households' food security in the aftermath of Hurricane Maria in Puerto Rico

to understand the social-ecological components that relate to adaptive capacity in an island setting. This paper combines farmer survey data with biophysical and climate data from Hurricane Maria to assess the factors associated with short and long-term food insecurity. Especially, after extreme weather events and the disasters they trigger, where food security is understudied in island contexts. The research questions are the following:

- (a) How food secure were Puerto Rican farmer households after Hurricane Maria? (RQ1). It is expected that food security will decrease following Hurricane Maria, and persist for several months, given extreme weather events' role in triggering transitory food insecurity (H1).
- (b) How do socioeconomic, political, agricultural factors of farmers and farms versus the biophysical impacts of Hurricane Maria predict food security outcomes? (RQ2). Following findings from the Caribbean (mainly CARICOM countries) and Latin America [31–35], it is expected that farmers with higher levels of education, income, and access to external resources will be more food secure (H2). It is also expected that farm assets, such as size and level of production will be linked positively to better food security outcomes (H3). Lastly, given the extensive nature of Hurricane Maria's impact to the built environment (e.g. infrastructure), it is expected that social and agricultural factors, rather than geographical and biophysical factors, will predict food security outcomes (H4).

2. Materials and methods

2.1. Place and context

Puerto Rico is an archipelago in the Caribbean that is part of the Greater Antilles and is an unincorporated territory of the United States. Similar to the broader islands of the Caribbean, Puerto Rico's food system focuses mostly on domestic markets, and has seen a decline in farms in the past 20 years. From producing around 45% of its food in the 1980s, the US territory produces 15% today, with the majority of food imported from the continental United States. Most Puerto Rican farmers' household income is less than \$20 000, according to the recent agricultural census [69]. That contrasts with their counterparts' household income in the United States, which averages over \$60,000 [70]. A 2019 report found 33% of Puerto Rican adults to be food insecure prior to Hurricane Maria [71].

Hurricane Maria had widespread impacts across Puerto Rico's agriculture and infrastructure. It decimated 80% of Puerto Rico's agricultural production and infrastructure, is linked to 2975 deaths [21, 72], and triggered the longest blackout in United

States history [73]. All 3.4 million Puerto Ricans faced a general power outage [74]. In many places, power was not restored for more than a year; after 15 months, only 65% of Puerto Rico had electricity [74]. Other prominent effects over the agricultural sector included loss of phone, internet communication, access to farms, and impassable roads. Farm management issues, electricity, and fuel shortage, as well as obstacles for access and transportation complicated farmlands' recovery after Hurricane Maria [29, 75, 76].

2.2. Survey development and data collection

A survey was developed in collaboration with the Extension Service of the University of Puerto Rico-Mayagüez (UPRM), and focused on understanding how Hurricane Maria impacted farmers, and their perceptions around climate change, adaptation, policy, and food security, among other elements of adaptive capacity [77]. The survey was built following other farmer surveys related to climate change [56, 78]. The research was conducted in accordance with the principles embodied in the Declaration of Helsinki and in accordance with local statutory requirements. The Committees on Human Subjects Serving the University of Vermont and the UVM Medical Center at the Research Protections Office approved this study on 04 December 2017 (CHRBSS: 18-0258). It received Exemption Category 2. The survey booklet included a statement of consent that was facilitated to participants by the enumerators. A pilot study was conducted in February 2018 with a pool of farmers ($n = 31$), which resulted in survey refinement and clarifications on structure and language. Puerto Rican farmers were surveyed across the archipelago in May-June 2018 by agricultural agents of the UPRM Extension Service. Paper copies of the surveys were distributed to central offices of the five regions of the Puerto Rican Extension Service (Arecibo, Caguas, Mayagüez, Ponce, and San Juan). Based upon Extension's recommendation to assess diverse farmers (e.g. dairy, plantain, coffee, mixed, etc.), all regions received 100 copies, except Arecibo and Mayagüez, which received 70 copies, based on the distribution path of the hurricane (i.e. this area of Puerto Rico was impacted less by the Hurricane, which made landfall in the southeast of the main island). Extension agents randomly surveyed farmers within their regions that receive or had received services from Extension. Overall, 405 farmers (87% response rate) responded to the survey.

2.3. Variables

This paper uses a subset of variables from the deployed survey. To assess respondents' experiences with food security (dependent variable), the survey asked, 'In which months, if any, does your household tend to not have enough food to consume or have

struggled to acquire food. Please select the month for which you have face a struggle to acquire food or a shortage of it.' This question was based on the baseline survey developed by the Climate Change, Agriculture, and Food Security (CCAFS) Program, and allows for assessing the time frame in which food security was affected (period of transitory or episodic food insecurity). Respondents were given the option to select between 12 binary variables representing months (May 2017—April 2018) [78, 79]. Months before September 2017 were not included in the analysis due to minimal response (<1%) of people indicating food insecurity. Food security was categorized in three groups: (a) food secure (0 reported months); (b) immediate food insecurity (1–2 months); (c) persistent food insecurity (three months or more).

To assess factors associated with food security outcomes among farmer households, a suite of questions from the survey which represent social-ecological components were selected (table 1) [29, 30]. These variables reflect several social-ecological factors that correlate with Caribbean farmers' food security [29, 60, 62–64, 80], and are relevant to food security in disaster contexts [38, 40, 80, 81]. In some cases, new variables were generated or simplified. For example, the variable 'education' was modified to have a reduced set of options (from ten to two). The variable 'network' is an aggregated variable of the number of organizations and groups farmers reported having received information and services regarding climate change adaptation, which serves as a proxy for access to social and support networks. 'Farm production' is also an aggregate variable of the number of agricultural products farmers reported to be producing before Hurricane Maria, which serves as a proxy for agricultural diversity, ecosystem services, and economic aspects of a farm operation. The variable 'damages' aggregates farmers who reported 'total loss' and 'significant damages or less' in a binary variable. Farm size is shown in *cuerdas*, Puerto Rico's traditional land measurement, which is also how the U.S. Department of Agriculture (USDA) Agricultural Census for Puerto Rico reports farm size. This variable is also a proxy for agricultural and economic assets. One *cuerda* is approximately 0.97 acres or 0.39 hectares. The binary variable *bona fide* describes a farmer who is certified as a *bona fide* farmer by the Puerto Rico Department of Agriculture. To be *bona fide*, a farmer must show evidence that 51% or more of their income comes from farming. This certification provides farmers with direct access to the Puerto Rico Department of Agriculture's incentives and farming assistance programs. This variable was positively highly correlated with household income. The 'metropolitan' (binary) variable was created based on the municipality where farmers reported their farming operations. Using a guide by the Puerto Rico Planning Board, municipalities were categorized

as 'metropolitan' (significant population centers and proximity to metropolitan areas) or as 'not metropolitan' (less population, closer to rural areas). Coastal and metropolitan municipalities in Puerto Rico have higher access to highways, critical infrastructure, and governmental institutions. The variable 'food assistance' (binary) describes people that participate in the Puerto Rico Nutrition Assistance Program (*Programa de Asistencia Nutricional, PAN* in Spanish). This program provides eligible members nutrition assistance benefits to the purchase of food in certified retailers and cash for the purchase of food in certified and non-certified retailers through the governments electronic transfer system. This program is funded by a block grant, different from the USDA's Supplemental Nutrition Assistance Program (SNAP) that US states receive.

To account for the effect of critical, hurricane-related biophysical features on the reported level of food security, two additional independent variables were included. First, the straight-line distance from the municipalities where a farm is located to the tracking line of the hurricane's eye ('distance to eye') was evaluated, an indicator for the intensity of wind force and other indirect effects associated with the proximity to the most severe disturbances caused by the hurricane's passage [82]. Second, the density of hurricane-induced landslides at the municipality level (number of landslides per square kilometer or 'landslides') was included to account for their *in-situ* impacts on farmlands and surrounding areas as well as the challenges they pose for access to and from the farms (e.g. road blockages). Landslides are also related to total storm precipitation [83], another potential hurricane effect on food security. These spatial variables were derived from official or peer-reviewed layers and summarized at the municipality level using geographic information systems (table 1). 'Landslide' data was retrieved from the Science Base-Catalog of the United States Geological Service [84]. It was developed using a spatial inventory of Hurricane Maria landslides points. 'Distance to eye' data was retrieved from the tropical cyclone tracks data from the NOAA National Hurricane Center portal [85].

2.4. Statistical analysis

A multinomial logistic regression was carried out to understand how different social-ecological factors relate to food security outcomes because the dependent variable is categorical (three unordered categories of food security status). Moreover, the data use does not follow multivariate normality, which this model resolves because it does not assume normality, linearity, or homoscedasticity. The model was carried out in Stata 15.1 using maximum likelihood and clustered robust errors [86, 87]. The dependent variable compares food insecure groups with people

Table 1. Variables included in the analyses of this study.

Variables	Question/Statement or description	Measure	Rationale
Dependent variable			
Food insecurity	In which months, if any, does your household tend to not have enough food to consume or have struggled to acquire food. Please select the month for which you have face a struggle to acquire food or a shortage of it.	Categorical (1 = no food insecurity, 2 = immediate food insecurity, 3 = persistent food insecurity)	Time frame of food security outcomes in relation to the event (Hurricane Maria).
Independent survey variables			
Age	In what year were you born?	Continuous	Vulnerability
Bona fide	Are you a 'bona fide' farmer of the [Puerto Rico] Department of Agriculture?	Binary (0 = No, 1 = Yes)	This program provides farmers with economic incentives and tax exemptions. The variable was also positively correlated with household income.
Damages	How would you describe the damages, if any, caused by Hurricane Maria to your farm?	Binary/Dummy (0 = not total loss, 1 = total loss)	Proxy for infrastructure and farm damage (e.g. physical assets).
Education	What is the highest level of education you have completed? Mark one:	0 = High school diploma or less 1 = Some college or more	Formal education attainment reflects economic and social network assets.
Farm production	What agricultural products have you produced, currently produce or plan to produce in the future on your farm? Check all that apply.	Count	Proxy for agricultural diversification, relates to higher ecosystem services and access to diverse markets or diet diversity.
Farm size	How many <i>cuerdas</i> of terrain do you manage in your farm?	Continuous	Farm size can reflect physical and economic assets, as well as agricultural outputs.
Food assistance	Do you receive services from the Nutrition Assistance Program (PAN)?	Binary (0 = No, 1 = Yes)	Proxy for preexisting obstacles to household food security. This program is based on household income.
Gender	What is your gender?	Binary (0 = Male, 1 = Female)	Vulnerability
Metropolitan	In what municipality your farm is located?	Binary (0 = Not metropolitan, 1 = Metropolitan)	To reflect population, urban centers, and access to critical infrastructure.
Network	Which of the following organizations and institutions, if any, have you received or would like to receive information from related to adapting to climate-related impacts? Check all that apply.	Count	Proxy for social networks of support.
Independent added biophysical variables			
Distance to eye	Straight-line distance (in km) from municipality centroid to the hurricane Maria track line.	Continuous	Wind speed and potential damages or impacts.
Landslides	Number of landslides normalized to the km ² of the municipality.	Continuous	Incidence related to rainfall intensity and infrastructure impacts.

not experiencing any food insecurity (reference/base group). Kruskal–Wallis rank tests (for continuous dependent variables) and Chi Square tests (for categorical dependent variables) were used to evaluate differences between groups.

3. Results

3.1. Participants' characteristics

Descriptive statistics for all independent variables of all respondents are shown in table 2. Respondents are

Table 2. Descriptive statistics of study's variables. Frequency, mean, standard deviation (SD), and responses (n) are included.

Variables	Scale	Frequency (%)	Mean \pm SD	$n =$
Survey variables				
Age	Continuous	—	54.0 \pm 13.5	391
Bona fide	Yes	210 (52.8%)	—	398
	No	188 (47.2%)	—	
Damages	Total loss	170 (42.6%)	—	399
	Not total loss	229 (57.3%)	—	
Education	Less than high school	49 (12.2%)	—	401
	High school diploma	82 (20.5%)	—	
	Some college	42 (10.5%)	—	
	Technical/Associate degree	66 (16.5%)	—	
	Bachelor's degree or more	162 (40.4%)	—	
Farm production	Count	—	3.1 \pm 2.5	402
Farm size (<i>cuerdas</i>)	Continuous	—	58.1 \pm 99.0	383
Food assistance	Yes	65 (18.0%)	—	359
	No	294 (82.0%)	—	
Sex	Female	55 (14.0%)	—	395
	Male	340 (86.0%)	—	
Metropolitan	Metropolitan	229 (57.5%)	—	398
	Not metropolitan	169 (42.5%)	—	
Network	Count	—	2.3 \pm 2.1	398
Biophysical variables				
Distance to eye (km)	Continuous	—	21.7 \pm 14.0	379
Landslides (km ²)	Continuous	—	9.8 \pm 13.4	338

comparable to Puerto Rico's agricultural census data on sex, farm size, income, and education levels [69]. However, data shows an overrepresentation of *bona fide* farmers (53%, compared to 24% in Puerto Rico [88]). Respondents had an average age of 54; 53% were 55 years or older. The majority were male (86%). Average farm size was 58 *cuerdas* (55 acres or 22 ha). Moreover, the majority reported attending some college or more formal education (67%). Almost half of farmers reported total loss of their farms due to Hurricane Maria's impact (43%). The majority of farmers farmed in metropolitan municipalities (58%), produced two or more agricultural products (65%), and had a network of one or more organizations and groups (75%). On average, municipalities corresponding to the location of the respondents' farms are 22 km from the passage of Hurricane Maria and had ten hurricane-triggered landslides per squared kilometer.

3.2. Food security

Figure 1 shows the number of months farmer households experienced negative effects on their food security prior and after Hurricane Maria's landfall. Overall, farmers reported an average of 2.0 ± 2.1 months of negatively impacted household food security ($n = 401$). Most farmer households (69%) reported at least one month of not having enough food to consume or having struggled to acquire food. High levels of affected food security were reported in the month of September 2017, when Hurricane Maria hit Puerto Rico (September 20,

2017; two weeks after category 5 Hurricane Irma hit the eastern side of Puerto Rico), increasing in October (59%), and slowly decreasing in November (49%), December (30%), and the following months (all <15%). Among respondents, 31% reported immediate food insecurity (1–2 months of affected household food security), 38% reported persistent food insecurity (three months or more), and 31% of farmers did not report experiencing any negative effects on their food security. These results support H1.

The characteristics of households reporting varying levels of food security differed significantly (table 3). Low levels of food security were significantly ($p \leq 0.05$) more prevalent among older respondents, those that were not *bona fide* farmers, those with smaller land holdings, those outside of metropolitan areas, and those with closer distance to the eye of the hurricane. These results suggest that a number of social, agricultural and biophysical factors affected food security in the months following Hurricane Maria, largely supporting H2 and H3. Farmers in the persistent food insecurity category were closer to Hurricane Maria's track, and farmed in municipalities that experienced higher volume of landslides in comparison to the other two groups (table 3, figure 2), partially supporting H4.

3.3. Multinomial model

Table 4 shows the results of the multinomial logistic regression in which the comparison reference group are food secure. The multinomial logistic regression shows that farmers receiving food assistance

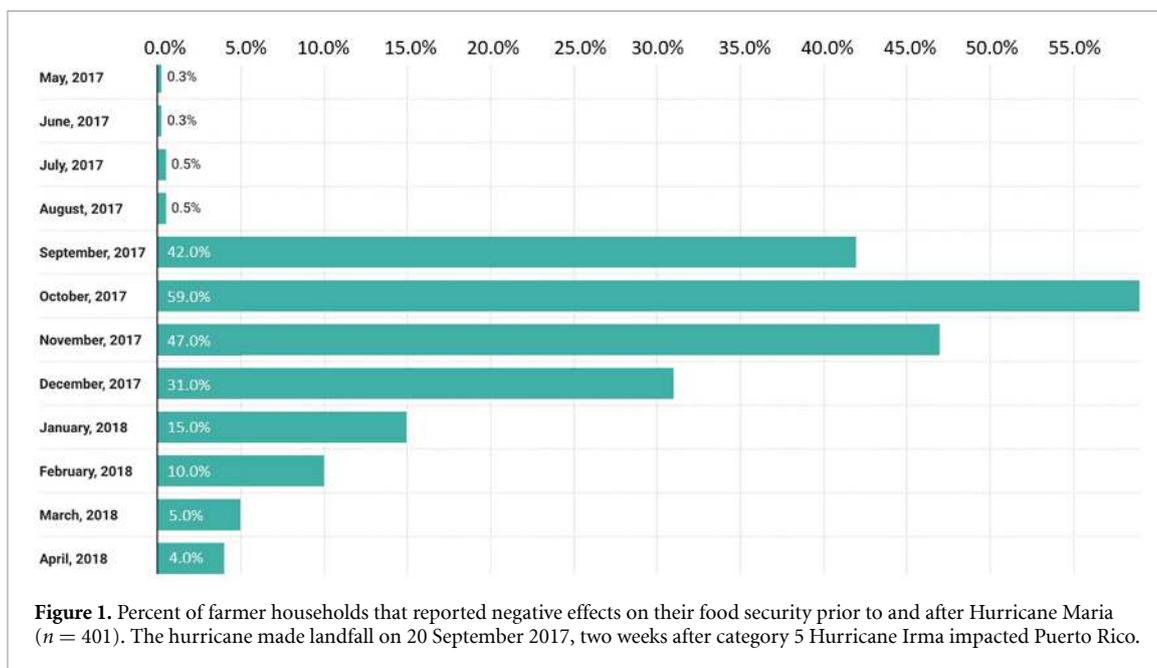


Table 3. Descriptive statistics and statistical analyses by food security categories.

Variables	Food insecurity category			Statistical test significance (p)	
	Food secured ($n = 124$; 31.0%)	Immediate food insecurity ($n = 123$; 31.0%)	Persistent food insecurity ($n = 154$; 38%)	Kruskal–Wallis	Chi Square
Survey variables					
Age	52.5 ± 13.5	52.6 ± 13.0	56.4 ± 13.0	0.053	—
Bona fide ^a				—	0.002
Being bona fide	79 (37.6%)	65 (31.0%)	66 (31.4%)		
No	43 (22.9%)	57 (30.3%)	87 (46.3%)		
Damages				—	0.630
Total loss	57 (33.5%)	50 (29.4%)	62 (36.5%)		
Significant loss or less	67 (29.3%)	71 (31.0%)	91 (39.7%)		
Education				—	0.644
Some college or more	84 (31.1%)	85 (31.5%)	100 (37.0%)		
High school diploma or less	40 (30.0%)	36 (27.5%)	54 (41.2%)		
Farm production	3.4 ± 2.5	2.8 ± 2.2	3.3 ± 2.7	0.227	—
Farm size ^a	75.6 ± 118.5	58.0 ± 95	45.1 ± 81.6	0.029	—
Food assistance				—	0.139
Participant of PAN	15 (23.1%)	22 (33.8%)	28 (43.1%)		
Not participant	105 (35.7%)	86 (29.3%)	102 (34.5%)		
Sex				—	0.846
Female	17 (30.9%)	18 (32.7%)	19 (34.5%)		
Male	105 (31.0%)	102 (30.0%)	132 (38.8%)		
Metropolitan ^a				—	0.016
Metropolitan municipality	72 (31.4%)	40 (17.5%)	76 (33.2%)		
Not metropolitan	52 (30.8%)	81 (47.9%)	75 (44.4%)		
Network	2.6 ± 2.6	2.5 ± 2.0	2.0 ± 1.8	0.140	—
Biophysical variables					
Distance from eye ^a	25.3 ± 15.1	21.5 ± 14.2	18.9 ± 12.3	0.001	—
Landslides	9.1 ± 11.6	7.7 ± 10.3	12.2 ± 16.4	0.208	—

Note: Percentage of categorical variables is based on the total n of each variable.

^a Significant variable ($p < 0.05$).

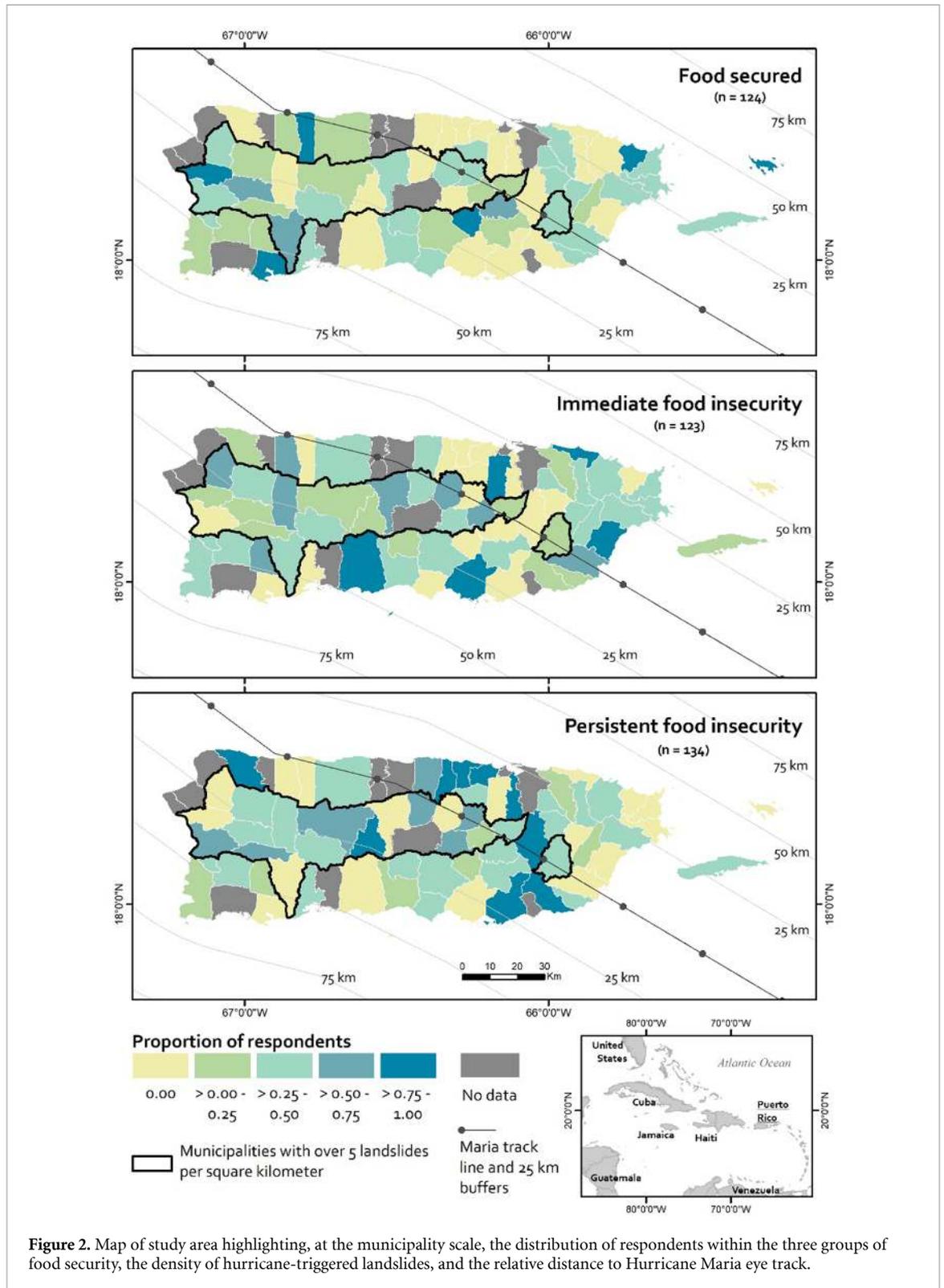


Figure 2. Map of study area highlighting, at the municipality scale, the distribution of respondents within the three groups of food security, the density of hurricane-triggered landslides, and the relative distance to Hurricane Maria eye track.

(Programa de Asistencia Nutricional or NAP) were significantly more likely to be immediately food insecure, as compared to food secure ($\beta = 0.09330$, $p = 0.040$).

Multiple variables predicted persistent food insecurity, as compared to the food secure reference group,

including older respondents ($\beta = 0.0224$, $p = 0.030$), *bona fide* farmers were less likely to be food insecure ($\beta = -0.0570$, $p = 0.034$), and further distance from the eye of Maria ($\beta = -0.0341$, $p = 0.017$). Having a larger network was weakly associated ($p < 0.10$) with less likelihood of being persistently food insecure.

Table 4. Multinomial regression model results predicting food insecurity. Results for immediate food insecurity and persistent food insecurity categories are presented in comparison to the food secure category (reference group). Coefficients (β), robust clustered standard errors (SE), and significance (p) are reported.

Variable	Categories	β	SE	p
Age	Immediate food insecurity	−0.0017	0.0110	0.877
	Persistent food insecurity ^a	0.0224	0.0103	0.030
Bona fide Being <i>bona fide</i>	Immediate food insecurity	0.1360	0.3702	0.325
	Persistent food insecurity ^a	−0.0579	0.3752	0.034
Damages Total loss	Immediate food insecurity	0.0761	0.2639	0.773
	Persistent food insecurity	0.0834	0.3579	0.816
Education Some college or more	Immediate food insecurity	0.1360	0.3223	0.673
	Persistent food insecurity	−0.0579	0.3522	0.869
Farm production	Immediate food insecurity	−0.0444	0.0665	0.504
	Persistent food insecurity	0.0751	0.0701	0.284
Farm size	Immediate food insecurity	−0.0003	0.0019	0.890
	Persistent food insecurity	−0.0030	0.0018	0.109
Food assistance Participant of PAN	Immediate food insecurity ^a	0.9330	0.4533	0.040
	Persistent food insecurity	0.4729	0.4970	0.341
Sex Female	Immediate food insecurity	0.0764	0.4983	0.878
	Persistent food insecurity	0.1919	0.3882	0.621
Metropolitan Farm in a metropolitan municipality	Immediate food insecurity	0.1670	0.5657	0.768
	Persistent food insecurity	−0.1964	0.5568	0.724
Network	Immediate food insecurity	−0.0366	0.0689	0.596
	Persistent food insecurity	−0.1308	0.0768	0.089
Distance to eye	Immediate food insecurity	−0.0139	0.0119	0.243
	Persistent food insecurity ^a	−0.0341	0.0144	0.017
Landslides	Immediate food insecurity	−0.0139	0.0180	0.427
	Persistent food insecurity	0.0182	0.0175	0.300

^a Statistically significant ($p < 0.05$).

4. Discussion

4.1. Farmer households, island food security, and disaster

The results of this study validate claims that extreme weather events can trigger transitory food insecurity, and that its length is dependent on both the biophysical impacts from an extreme weather event, but more prominently on other social and infrastructure factors. While less than 1% of farmers in this study reported low food security prior to Hurricane Maria's landfall, 69% of Puerto Rican farmer households reported at least one month of not having enough food to consume or having struggled to acquire food in the aftermath of Maria, with 31% experiencing immediate (1–2 months) and 38% persistent (three months or more) food insecurity. Findings suggest that household food security outcomes, in light of disaster, is compounded on individual risk factors and access to sources of support, which aligns with previous research [3, 54, 56]. Furthermore, given islands local food systems' importance in buffering impacts from extreme weather events [16, 44, 55],

farmers adaptive capacity must be strengthened in order to safeguard local food security [29].

Results showed that farmers who were farther from Hurricane Maria's track were less likely to report persistent food insecurity. Though landslides were not significant in predicting food security outcomes, those in the persistent food insecurity category resided in municipalities with higher number of landslides, which were the causes of road blockages and slowing farm operations in Puerto Rico [29, 75, 83, 84]. The eye of the hurricane is characterized by sustaining the strongest winds, coupled with sustained rains, which in turn cause more infrastructure damages [74, 89]. Infrastructure damages in Puerto Rico due to Hurricane Maria surpassed the billions of dollars, and many food retailers throughout Puerto Rico were permanently closed or had disrupted operations due to damages [21, 80, 90, 91]. Furthermore, lack of electricity and water catalyzed longer recovery periods [29, 75].

Social and natural circumstances of each place, such as urban and economic levels, as well as topography, for example, play an important role in gen-

erating obstacles and buffers to natural hazards and to have a sustainable food system [76, 92]. Results suggest that farming in a metropolitan municipality was associated with food security outcomes. Coastal municipalities in Puerto Rico and those near high urban sectors were more likely to have utilities restored quickly due to higher adaptive capacity. Spatial distribution of food sources and critical infrastructure is key in providing food access, availability, and stability. Disruption in critical components within a network, combined with a place's levels of vulnerability, play a key role in food security after an extreme weather event [42].

Within a set of disruptions, those prone to risk factors and lower adaptive capacity—access to individual assets or structural support—face more obstacles in buffering the impacts of extreme weather events [21, 42, 80, 91, 93]. Evidence from this study suggests that older farmers, and those already with low food security, were more likely to report more months of food insecurity. Puerto Rican farmers average age is 61, and reflects a broader Puerto Rican population that is aging, which points to diverse risk factors that may play a role in food security outcomes [69, 94, 95]. Results also align with others that have found that those food insecure before an extreme weather event or other sudden shock, such as in the current COVID-19 pandemic [96], are likely to experience food insecurity afterwards [9, 39]. Being participant of the Puerto Rico Nutrition Assistant Program (PAN in Spanish) also increased the risk of reporting immediate food insecurity. PAN participants can use their funds through an electronic benefit transfer card. Given that Puerto Rico faced the longest black-out in United States history [73], and communications were down for several months, it is likely that PAN participants struggled to access those funds.

Results also showed that higher levels of adaptive capacity provide a buffering effect. Farm size was associated with food security groups in this study, and farmers that were part of the *bona fide* program were less likely to report persistent food insecurity. *Bona fide* farmers in Puerto Rico are recognized by the local Department of Agriculture and have access to financial and agricultural services, as well as to governmental tax exemptions and incentives. This variable was positively and highly correlated with income, and those who were *bona fide* reported a higher average of network institutions and organizations. This result aligns with other studies that suggest that, in the context of disaster, external sources of support, whether institutional or financial, can support farmers' adaptive capacity to navigate recovery [29, 54, 97]. These variables also point out to how these individual attributes in 'normal times' may build the resistance and resilience of farming systems [49, 98, 99], in light of compounding shocks in the ongoing climate crisis.

Future studies focusing on transitory or episodic food insecurity should develop new instruments or consider approaches that capture people's lived experience in acquiring food, beyond nutritional or quantity values [47, 80, 100, 101]. While food security is traditionally considered through an economic lens (e.g. enough money) [46, 101, 102], disasters create new circumstances or impacts that are not always safeguarded by economic access [40, 80]. Such circumstances may be especially pronounced in island communities where the biophysical impacts of an event may be widespread, and the safety nets available may be physically and economically distant [16, 44, 45]. This study shows that Puerto Rican farmers, who in general are mainly commercial and focus on domestic markets, may have faced similar struggles as the broader population to support their household food security. Understanding the hurdles that people face in acquiring the foods they need to prepare an adequate meal that fits their physiological and emotional needs could provide a more complete picture of how social-ecological dynamics shape food security during and after an extreme weather event.

Hurricane Maria made visible that in a catastrophic event, food transportation to and from one main source generates difficulty in maintaining food security [25]. In Puerto Rico, like other SIDS, food is frequently imported into a single port, increasing vulnerability. Thus, a robust local island food system contributes to buffering such disruption by providing island food sources [44, 76, 103]. SIDS diverse topographic, infrastructure, and climatic gradients' shape how impacts from extreme weather events are experienced. This study's findings, considering Puerto Rico's narrow resource base and high dependence on imports, similar to many other SIDS, underlines the critical role of local food systems in disaster response and recovery. Understanding the drivers and barriers to strengthening farmers' adaptive capacity is key in safeguarding local food systems, which are reliant on farmers and farm workers' work, as well as on other key agents of the food system. Nonetheless, the role of broader structures of support, coupled with individual adaptive capacity must be further considered.

4.2. Moving beyond the household level

The full survey report used in this study found that less than 14% of farmers think that Puerto Rico has the necessary policies to protect and support local agriculture [104]. Moreover, more than 85% disagreed with the statement that imports are not an obstacle to increase the access of local products in the Puerto Rican markets [104]. Future studies could further inquire about the relationship of structural components to individual food security outcomes. Given how critical imports are to island food

security, SIDS's embeddedness in a globalized world and their food systems' susceptibility to volatile markets must be considered when examining island food security [26, 44, 45, 92, 105]. In the case of Puerto Rico as a US territory, future studies could assess the extent to which structural elements within US policy frameworks influence island food security outcomes. For example, a comprehensive study of the Merchant Marine Act of 1920 (commonly known as the Jones Act, which control shipping between US ports) could inform how to incorporate structural variables (e.g. related to imports) to food security assessment instruments [25, 106]. That law received attention after Hurricane Maria, and other extreme weather events, such as 2017's Hurricane Harvey, because it is waived to permit more flexible maritime supply chains. Less than 11% of Puerto Rican farmers support the Jones Act or think it does not affect local food security [104].

Extreme weather events can create local impacts, as Hurricane Maria did, but they also can trigger disruptions from afar. Thus, future research should explore the extent to which local island food systems' dependence on external forces shape their adaptive capacity, and the factors beyond farmers' individual adaptive capacity that contribute to the local food system's ability to feed its people. Put succinctly, what are the limits of adaptive capacity in island food systems? Of the 58 recognized islands nations and territories by the United Nations, 27 are in the Caribbean [107]. Almost half of those are not United Nation members, such as Puerto Rico, which is an Unincorporated Territory of the US. Hence, island food security assessment must incorporate that reality into their approaches.

4.3. Looking forward

Future studies should build upon this study's approach of combining social and biophysical data to better understand how people navigate disaster, and the degree to which reinforcing the adaptive capacity of vulnerable populations can be supported, so that recovery efforts can be effective. Given our limited data on variables related to structural components, such as import rates, access to important utilities related to storing and preparing food (e.g., electricity, water, gas, etc.), infrastructure descriptors, and other political aspects, future studies could develop multi-dimensional frameworks (e.g. combination of ethnographic and modeling approaches) that assess food security in varying levels within a social-ecological system (e.g. from the household to the national level).

This study is limited in the way that it assesses food insecurity since it only asked the months farmers struggled to have enough food rather than asking a series of food insecurity questions (see the Food Insecurity Experience Scale), and highlights the need for better instruments that consider the drivers and

barriers for people to access food while navigating disaster. Future studies could generate a more contextualized approach based on Household Hunger Scales [108] and the Food Insecurity Experience Scale [109, 110], among other tools, that take into account the subjective or lived experience of people in acquiring and preparing foods. Furthermore, given that disruptions are lived differently, and recovery periods vary, promptly approaches that consider these early obstacles and experiences may provide a more nuanced understanding of how people navigate such states.

5. Conclusion

This study found that Hurricane Maria triggered a period of transitory food insecurity among Puerto Rican farmer households, and that its length depended on individuals' risk factors, suffered biophysical impacts, and levels of adaptive capacity. Results suggest that navigating disruptions in the natural and built environment can be constrained or alleviated by a combination of broader structures of support and adaptive capacity. As island food systems play a key role in providing local food; therefore, safeguarding farmers from extreme weather events and their impacts—as reflected here by the number of months of food insecurity—must be effectively addressed to safeguard local food security. However, island food security does not depend solely on farmer productivity and therefore, cannot be assessed only through a supply or production approach. Thus, future studies should better consider islands' embeddedness in globalized systems, and the extent to which volatile markets and power imbalances influence local food security. This goal could be achieved by developing new mixed-methods approaches that better assess how different social-ecological components interact and connect in relation to food security at varying levels (from the household to the national and regional levels) in the context of disasters. Variables that better reflect or represent disruptions lived, as well as incorporating qualitative approaches that grasp lived experiences in relation to acquiring, storing, producing, and preparing food after extreme weather events, could present more nuanced solutions and understanding to safeguarding island food security. Moreover, future research can better explore the limits of local island food systems' adaptive capacity, and the degree to which local food systems can meet local food demands, while balancing SIDS's limitations.

Data availability statement

The data that support the findings of this study are available upon request from the authors.

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