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READY OR NOT? Hurricane preparedness, response, and recovery of farms, forests, and rural communities in the U.S. Caribbean

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ABSTRACT

Farmers, forest owners, and rural communities are among the groups most exposed to the effects and associated impacts of hurricanes and other extreme climate events in the Caribbean. Yet, little is known about their preparedness for or their capacity to respond to and recover from these disturbances. We conducted qualitative research involving focus group discussions and in-depth interviews with 152 farmers, forest owners, and agriculture and forest experts in Puerto Rico and the U.S Virgin Islands to understand the effects and associated impacts of hurricanes Irma and María at farm, forest, community, and sectoral levels and the internal and external factors that help to explain their capacities to anticipate, absorb, and adapt to hurricanes and other extreme climate events. Participants reported widespread crop and livestock losses; extensive damages to roads, facilities, and other private and public infrastructure; lengthy outages in electricity, telecommunications, and water supplies; and harmful impacts on human health and well-being that significantly affected their productive capacities and livelihoods. Most farmers and forest owners reported coping with the immediate effects and associated impacts of the hurricanes largely on their own, some also reported the emergence of informal or extemporized relief and recovery support, mostly from family members, neighbors, and others in their local community. Official relief and recovery resources for the agriculture and forest sectors were described by many as having been too rigid or onerous to access or navigate successfully, ultimately limiting their effectiveness in supporting farm and forest relief and recovery. Few participants or sectors reported having adequate hurricane preparations, mitigation, or adaptation practices in place prior to the storms. Low levels of risk reduction and adaptation mostly were associated with limited human, financial, and technological resources to design and implement related strategies and practices at individual and community levels. Many participants expressed a desire to incorporate more or specific hurricane and other disturbance plans and preparations into their production systems. Some participants also described plans to adapt, innovate, or transform their farm and forest systems, but few had implemented these types of changes at the time of data collection. Findings point to the need for improved understanding, adoption, and support of effective hurricane mitigation and adaptation measures in agriculture, forests, and rural communities; increased flexibility and adaptiveness of official response and recovery programs and processes to accommodate local contexts, capacities, and conditions; and practical planning, preparations, and other risk reduction measures for famers and forest owners at individual, community, organizational, and larger scales. Study results are important to the design and implementation of ongoing recovery

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efforts as well as broader conservation efforts within and across agriculture, forest, and rural communities in the U.S. Caribbean.

1. Introduction

Hurricanes shape social-ecological-technological systems across Puerto Rico and the U.S. Virgin Islands in multiple ways. Among the most recent major disturbances to affect these islands, hurricanes Irma and María made landfall within two weeks of each other in September 2017. Hurricane Irma was a Category 5 storm on the Saffir-Simpson scale when its center passed just north of St. Thomas and St. John on September 6, 2017 [1]. Thirteen days later, Hurricane María was a Category 4 storm when it passed slightly southeast of St. Croix and transected Puerto Rico in its entirety (Federal Emergency Management Agency [[2].

Agriculture, forests, and rural communities throughout the region were particularly hard hit by the back-to-back storms. In Puerto Rico, 80% of planted crops were reported to have been destroyed or significantly damaged (Puerto Rico Department of Agriculture, 2018) and an estimated 23% of aboveground forest biomass was lost to the storms' high winds and heavy rains [3]. Many smallholder farmers and forest owners who depend on their land for their livelihoods and whose ownerships together comprise a large part of the total land area experienced widespread losses and damages to their farm and forest systems, compromising food security, commodity production, and the provision and protection of ecosystem services [4–6].

The effects of hurricanes Irma and María and the associated impacts on social-ecological-technological systems have been linked to 2975 deaths (95% CI: 2658–3290) in Puerto Rico [7], five official deaths in the U.S Virgin Islands [8], and more than $20 billion in damages to infrastructure, telecommunications systems, electrical grids, and other assets across both jurisdictions [2,9]. High dependence on imports of food, fuel, and other basic necessities; shipping rules under the Jones Act that bar non-U.S. vessels from delivering goods to the islands; power and wealth disparities within the islands and with the mainland United States; protracted economic crises that constrained public services, resources, and investments; and limited mitigation and adaptation measures in place prior to the storms have been identified as key factors contributing to the islands' vulnerabilities to the storms' effects (see for example: [10–12].

Recent research has examined response and resilience of coffee farms in Puerto Rico following hurricane Maria [5], agricultural advisors' perspectives on hurricane preparedness and mitigation in the agriculture and forest sectors of Puerto Rico and U.S. Virgin Islands (Álvarez-Berríos et al., 2021; Weiner et al., 2020), and farmers' adaptive capacity in the aftermath of extreme weather events and in the context of climate change in Puerto Rico [6]. Other research has examined the effects and associated impacts of tropical cyclones on agriculture systems and farmer response and coping capacities in Zimbabwe [13], Madagascar [14], and Jamaica (Campbell and Beckford, 2009), as well as disaster management and emergent responses to cyclone impacts on agriculture and food systems in southern Africa [15,16]. Despite the expanding literature on the effects of hurricanes Irma and María in select communities, sectors, and systems (see for example: [3,7,11,12,17–20], there has been limited focus or integrated research on hurricane effects on agricultural and forested social-ecological-technological systems and their response and recovery, particularly at connected, cross-sectoral, and regional scales (for exceptions, see: [4,21]. To address these knowledge gaps, and to further expand the broader literature on disaster risk reduction in tropical agriculture and forest systems, we conducted multi-method qualitative research to understand the effects and associated impacts of hurricanes Irma and Maria on farms, forests, and rural communities, their response and recovery processes, and the internal and external factors that help to explain their capacity to anticipate, absorb, respond to, recover from, and adapt to hurricanes and other major disturbances.

Although there is some debate about the utility, parity, and even the intent of disaster risk reduction and resilience approaches (see for ex.: [22–24], reducing the risks associated with hurricanes and other hazards remains critical for farmers, forest owners, and rural communities throughout much of the Caribbean region, where climate models project hurricanes will occur with increasing intensity and frequency over the coming decades and where shifts in extreme weather events already are detected [25–30]. Planning, preparation, mitigation, and adaptation strategies and practices aimed at anticipating, responding to, and recovering from hurricanes and other disturbances are widely promoted to reduce the actual and potential risks to individuals, households, communities, organizations, assets, and systems at local to larger scales (see for example Intergovernmental Panel on Climate Change [[31–33]. These approaches also may contribute to enhanced absorptive, adaptive, and transformative capacities within and across systems, particularly when designed and implemented in concert and with a measurable degree of flexibility and adaptiveness to effectively address unexpected shocks and outcomes [31,34–47].

Accordingly, we explored the range in, use of, and perspectives on the advantages and constraints associated with preparedness, response, and recovery processes and practices on farms and forests and in rural communities throughout the region. We also explored how the social ties among people within and across agriculture, forest, and rural communities shaped their capacities to respond to and recover from the effects and associated impacts of the storms, given the influence that human relationships, connections, and other social factors can have on the trajectory, speed, and outcomes of disaster response and recovery [48]; Aldrich 2012; Cutter et al., 2008; [46,49]. Our goal is that these findings provide important information for the design and implementation of ongoing recovery work and broader conservation efforts within and across agriculture, forest, and rural communities in the U.S. Caribbean and can be shaped and shared with other communities, islands, and regions in hurricane prone areas and with similar social-ecological-technological conditions.

2. Methods and materials

2.1. Study setting

Puerto Rico and the U.S. Virgin Islands encompass six large islands and over 800 uninhabited smaller islands and cays in the Caribbean region (Fig. 1). The tropical climate and diversity of soils permit the production of a wide variety of agricultural products year-round. Forests and woodlands cover approximately 53% of Puerto Rico and 57% of the U.S. Virgin Islands according to the U.S. Forest Service Forest Inventory and Analysis. Farmlands occupy approximately 22% and 7% of the land areas in Puerto Rico and U.S. Virgin Islands, respectively. Most farmland area is classified as pasture, grazing, and rangeland (PR: 53.6%; USVI: 59.4%), followed by cropland (PR: 16.7%; USVI: 28.1%). Woodland occupies a smaller portion of total farmland area (PR: 6.5%; USVI: 7.4%) [50].

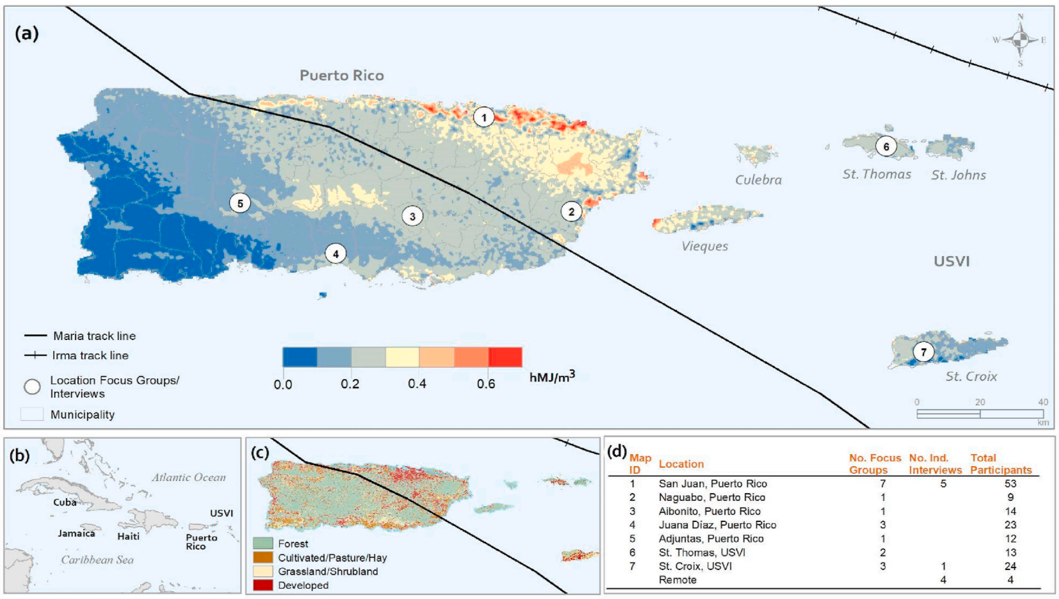
Agricultural and forestry land uses are prominent across the landscape in both jurisdictions but supply a relatively small proportion of the food and timber products consumed locally. Both jurisdictions are highly dependent on imported food products (e.g., USVI Dept of Agriculture reports about 95% of food consumed locally is imported; PR Dept of Agriculture reports approximately 85% of food consumed locally is imported and about five percent of total annual agricultural production in Puerto Rico is exported). Nevertheless, numerous locally consumed foods are primarily produced locally (e.g., in Puerto Rico: eggs (97%), plantains and bananas (97%), mangos (95%), milk (78%) [53]. And the region's forests provide and protect a broad range of highly valued goods and services, including water and soil, biodiversity, recreation opportunities, and nontimber forest products [54–57].

Dairy and livestock generate the most economic agricultural activity in the region (e.g., Puerto Rico: dairy sales = 35.5% ($172.2 million) of total agricultural sales; U.S. Virgin Islands: beef cattle, small ruminants, and other livestock sales = 19.5% ($649,300) of total agricultural sales [50]. Plantains and bananas (10.9% of total agricultural sales), vegetable crops (6.9%) and tree crops (3.8%) were the next highest grossing agricultural products in Puerto Rico in 2018 [50]. Coffee, a principal crop in Puerto Rico, had a significant drop in percent of total agricultural sales, from 5.35% ($29.3 million) in 2012 to 1% ($4.8 million) in 2018 [50,58], largely attributed to crop damages associated with the 2017 hurricanes. In the U.S. Virgin Islands, vegetable and nursery crops follow livestock as the next highest grossing agricultural product groups (33.9% and 21.7%; respectively).

2.2. Data collection

We designed focus groups and semi-structured interviews, together with site visits to farms and forests across Puerto Rico and the U.S. Virgin Islands to explore the effects and associated impacts of hurricanes Irma and Maria on agriculture, forests, and rural communities; their level of preparedness, mitigation, and adaptation to hurricanes and other hazards; and the factors affecting their response and recovery. These methods are useful for exploring and understanding complex systems and processes and are particularly effective in contexts and conditions in which there is limited information on the research population and related variables of interest [28,59,60].

From October 2018 to May 2019, we conducted 18 focus groups involving 142 research participants in Puerto Rico and the U.S. Virgin Islands (Fig.1; Fig. 2; Supplementary Material [Supp.] 1). Focus groups were designed to cover the range in agricultural and forest sectors, systems, and scales (e.g., coffee, bananas/plantains, row crops, poultry, livestock, dairy, small-scale farmers/forest owners), as well as major supporting services and organizations associated with agriculture and forests across the islands (e.g., fed-



Map ID	Location	No. Focus Groups	No. Ind. Interviews	Total Participants
1	San Juan, Puerto Rico	7	5	53
2	Naguabo, Puerto Rico	1		9
3	Aibonito, Puerto Rico	1		14
4	Juana Díaz, Puerto Rico	3		23
5	Adjuntas, Puerto Rico	1		12
6	St. Thomas, USVI	2		13
7	St. Croix, USVI	3	1	24
	Remote		4	4

Fig. 1. Composite figure of study area, Puerto Rico and US Virgin Islands, highlighting: a) hurricanes Irma and María tracks and their Gale Wind Kinetic Energy (hMJ/m^3) [51], location of focus groups and interviews; b) location of the study area within the Caribbean region; c) main land covers (National Oceanic and Atmospheric Administration [[52]; and d) the number of focus groups, interviews, and participants by location.

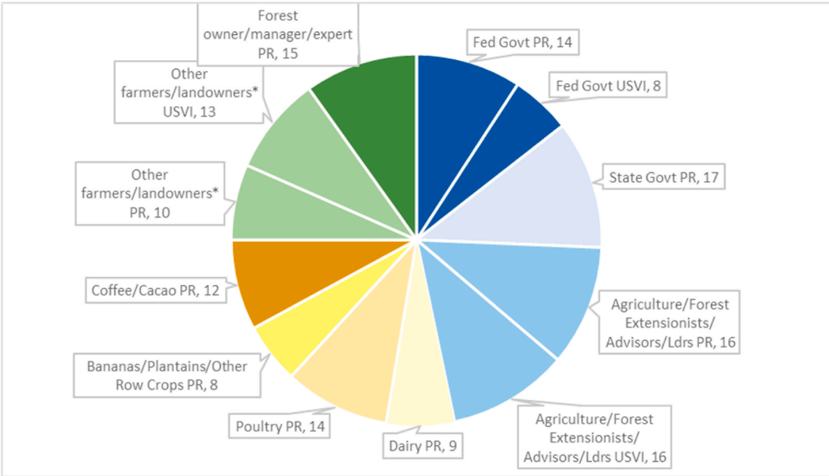


Fig. 2. Research Focus Group and Interview Participants by Type of Product(s) Produced/Employment/Expertise and Location (n = 152) (See Supp. 1 for additional details).

eral, commonwealth, territorial government agriculture and land management agencies). We utilized farm and forest owner databases from public agencies and programs (e.g., USDA, Puerto Rico Department of Agriculture, Puerto Rico Department of Natural and Environmental Resources, U.S. Virgin Islands Department of Agriculture) and our own contact lists to generate focus group invitation lists according to production system(s), land holding size, location, and other key variables, ensuring similarities across key factors within each focus group (e.g., primary crop(s)/product(s) produced; farm or landholding size, jurisdiction, location) and diversity of these elements representative of our populations of interest across focus groups. We aimed for six to 12 participants per focus group, seeking groups large enough to capture the range in experiences and perspectives, yet small enough to foster an environment in which participants were comfortable sharing their experiences, thoughts, and opinions [61,62].

*PR = Puerto Rico, USVI = U.S. Virgin Islands, Ldrs = Leaders, Other farmers/landowners includes multiple/mixed crop farmers and farm/forest landowners.

In addition to the focus groups, we conducted 10 in-depth semi-structured interviews with key informants in the agriculture and forest sectors in Puerto Rico and the U.S. Virgin Islands (Fig.1; Fig. 2; Supp. 1). These interviews were designed largely to supplement or expand on the data collected in the focus groups and to fill in gaps in data on specific topics or areas of inquiry (e.g., privately owned forests, small-scale farming, agroecological farmers). Focus group and interview participants were recruited following standard practices including initial contact and screening of participants by e-mail or phone; invitation to participate that included project background information and proposed focus group or interview date, time, and place; follow-up with confirmed participants; and reminders prior to the focus group or interview (e.g., Refs. [62–64]).

Focus group discussion and interview guides were developed in line with the study objectives and questions and were used to direct the discussion and collection of data on the key areas of inquiry: farming and forestry systems characteristics (e.g., size and number of landholdings; ownership type; products produced; management practices; program participation); hurricane effects and associated impacts on farms, forests, and communities; response, recovery, and risk reduction strategies and practices and their perceived effectiveness by participants; and sources and perceived effectiveness of related assistance and information. Focus group and interview guides were tested with agriculture and forest sector representative and experts who suggested minor changes to enhance the clarity and consistency of questions and discussion prompts. These guides included question elements that could be tailored to specific sectors, systems, scales, or locations for each focus group and interview. Research methods and tools were peer reviewed and reviewed and approved by the U.S. Office of Management and Budget (OMB Approval No. 0596-0246).

An experienced facilitator within the research team led the focus group or interview, using the guides as a ‘roadmap’ for focused discussion and standardized data collection. Focus groups and interviews were conducted in Spanish or English, accommodating the preferred language of the research participant(s) and were audio recorded with participant consent to capture the discussion and facilitate subsequent data analysis. A live transcript of each focus group and interview was captured by a designated member of the research team, which was subsequently augmented with the notes from other research team members and reviews of the audio recording when gaps or inconsistencies in the transcript and notes were detected. The augmented transcripts were imported into Dedoose, an online cloud-based software package useful for large datasets, multiple users, and multiple and mixed methods analysis [65].

2.3. Data analysis

Augmented transcripts were reviewed and analyzed in Dedoose through qualitative data analysis techniques, including coding and memoing to organize, label, sort, and learn from the data [66,67]. We developed and utilized a common coding guide, initially consisting primarily of predetermined codes based on the study objectives and questions and focus group and interview guides in a deductive approach to the data analysis. As coding and data analysis proceeded, we also developed new codes inductively based on emergent themes and variables discovered through the analytical process and revised and combined codes in a hybrid approach to the coding and theme development [68]; Supp. 2). The research team met regularly during the data analysis phase to discuss emergent themes and topics, refine coding measures, align coding strategies, and discuss significant findings and possible explanations, through a constant comparative method [62,69]. We continued to develop and refine codes and themes from the data until no new or revised codes occurred or emerged [70].

Coded data were further analyzed to explore the range and recurrence of themes and topics across sectors, scales, sites, and other factors, taking into consideration the frequency with which a practice, concept, idea, or experience was mentioned; the range in participants mentioning the same practice, experience, etc.; and the range in force or intensity associated with a particular practice, concept, etc. In this stage of analysis, we focused our attention on recurring ideas and broader themes that connected various codes. Through the analysis of patterns, themes, and variations in the data, we generated theories and explanations about the effects of the 2017 hurricanes on agriculture, forests, and rural communities in the U.S. Caribbean; their preparedness for, response to, and recovery from the storms; and the internal and external factors that help to explain their capacities to anticipate, absorb, and adapt to hurricanes Irma and Maria and potential future extreme weather events.

3. Results

Focus group and interview data related to hurricane effects and associated impacts on farms, forests, and rural communities are presented first, grouped by the biophysical, economic, and social aspects affected by the storms. Then, we present the results related to hurricane response and longer-term recovery, followed by hurricane risk reduction practices and strategies. Throughout the results section, terms like 'most', 'many', 'several', 'some', and 'few' are representative the relative frequency (from higher to lower, respectively) of responses or comments coded for a specific topic or theme. Quotes cited in the results section were selected for their representativeness of responses related to a specific topic or theme.

3.1. Hurricane effects and impacts

Research participants (n = 152) reported a broad range of impacts on farms, forests, and livelihoods associated with the direct and indirect effects of hurricanes Irma and María (Fig. 3). Three major themes emerge in the analysis of all responses related to the storms' effects, including those associated with biophysical aspects, including crops, trees, and water and soil resources; those associated with economic aspects, such as infrastructure, services, and markets; and those associated with social aspects, such as human well-being, families and households, and community structures and ties.

3.1.1. Biophysical

Crops, livestock, and other farm animals; water and soil resources; forests and trees outside forests; and weeds, grasses, and other unwanted plants and animals were among the biophysical factors reported to have been significantly affected by the storms. Altogether, 28% of all coded 'hurricane effects and impacts' were associated with biophysical factors (Fig. 3).

Crops – Banana and plantain growers and advisors reported some of the most widespread and significant crop losses and damages associated with the hurricanes' high winds, heavy rains, and other direct and indirect effects. As reported by an extensionist in Puerto Rico: "Except for a few very recently established plantations, nearly 100% of plantains in my area were lost" (AE-FG1). Coffee crops, exclusive to Puerto Rico, also were reported to have sustained significant damages and losses, including uprooting of plants and losses in landslides, particularly on steep slopes, where much of the island's coffee is grown (FF-FG4; AE-FG1; PS-II1; PS-FG5; FF-FG3). As described by one coffee grower: "my [coffee] farm was totally destroyed by hurricane María; the only thing that

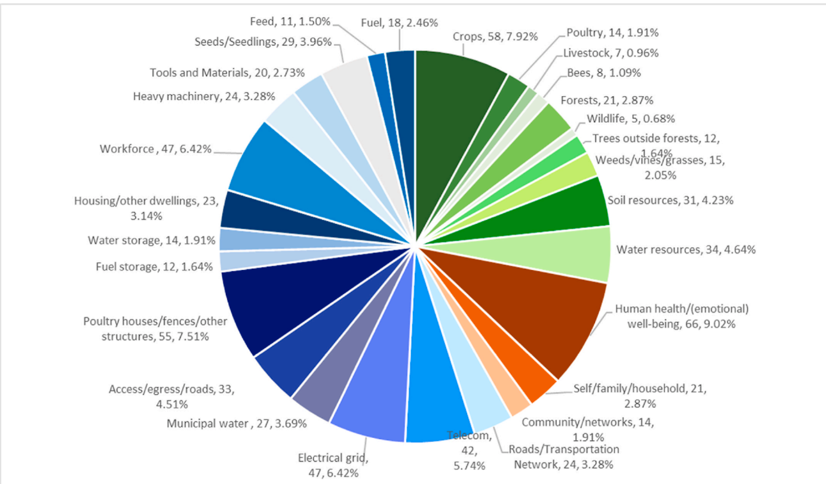


Fig. 3. Agricultural, forest, and rural community biophysical (green), economic (blue), and social (brown) aspects significantly affected by hurricanes Irma and María in Puerto Rico and the U.S. Virgin Islands as reported by 152 farmers, ranchers, forest owners, agricultural and forest advisors and extensionists, public-sector personnel, and other key stakeholders in Puerto Rico and the U.S. Virgin Islands. Number of mentions and percent of all effects mentioned are included for each aspect affected (e.g., crops: aspect affected; 58: number of mentions; 7.92% percent of all effects mentioned).

survived were the weeds" (FF-FG4). Several participants described major damages to and some losses of tree crops (e.g., avocado, mango, citrus, soursop) (AE-FG1; AE-FG2; FF-FG2; FF-FG9; FF-II2; FF-II3). Others reported major damages to vegetables and other ground crops (e.g., peppers, cucumbers, lettuces) from the heavy rains, flooding, and other hurricane effects (AE-FG1; FF-FG8; PS-II1; FF-II4).

Livestock and Other Farm Animals – Poultry farmers in Puerto Rico described extensive injuries and losses to their flocks, exceeding 50% mortality in most of the cases reported (FF-FG1; AE-FG1; PS-FG1; PS-FG2; PS-FG6; PS-II1). As recounted by one poultry farmer: "We lost 90% of our birds. They were crushed when the ranches came down or drowned in all the water from the rains" (FF-FG1). Several other poultry farmers reported similar impacts and losses. Beekeepers described significant losses to their honeybee colonies from damages associated with the storms' high winds and heavy rains (PS-II1; AE-FG1; FF-FG8; FF-FG9). A farmer in St. Thomas, U.S. Virgin Islands said: "I had 85 hives and lost all of them. My hives were destroyed, and the bees are gone" (FF-FG9). Similarly, an extensionist in Puerto Rico noted: "beekeepers lost everything … at least 90% of their bees are gone" (AE-FG1).

Reported livestock injury and death rates were significantly lower than those reported by poultry farmers and by beekeepers. Instances of livestock death or damage mostly were associated with flying and downed debris, drowning, displacement, or escape (FF-FG5; AE-FG1; FF-FG8; AE-FG2).

Water and Soil Resources – Significant storm effects on water and soil resources were described in all focus groups and interviews including increased rates or numbers of landslides, erosion, flooding, and sedimentation associated primarily with the heavy rains of the hurricanes were among the most noted soil and water resource-related impacts across all sectors and regions. Participants in both jurisdictions frequently reported blocked, clogged, or contaminated water ways, bodies, and reservoirs from sedimentation, downed debris, and runoff (FF-FG3, FF-FG2, PS-FG3, FF-FG8, FF-FG9, AE-FG2, AE-FG3).

Forests and trees outside forests – Many participants across agricultural and forest sectors described widespread defoliation, delimbing, uprooting, and other effects on forests and trees outside forests from the hurricanes' direct and indirect effects (PS-FG3, FF-FG2, AE-FG1, PS-FG1, FF-FG3, FF-FG1, AE-FG1, AE-II1, AE-II2, AE-II3, FF-FG5, FF-FG8, FF-FG4). Downed and damaged trees in agricultural, urban, and other settings, trees often were associated with subsequent damages to or obstruction of roads, bridges, buildings, waterways, and other features (FF-FG5, FF-FG8 FG, AE-FG1, FF-FG4). In the U.S. Virgin Islands, several participants noted damages to 100+ year old mahoganies lining major roadways that impacted roads, fences, and other structures and had subsequent social impacts on local communities where these trees are culturally significant (PS-FG4, FF-FG8, AE-FG2). A few participants also described significant storm effects on birds, including the endangered Puerto Rican parrot, and other wildlife, which sustained injuries and deaths during the storms and in the days and weeks following the hurricanes associated mostly with decreases in food sources and shelter (PS-FG1, PS-FG3, AE-II2).

Weeds vines and grasses – Some farmers, forest owners, and other participants reported an increase in weeds, vines, grasses, and other unwanted plants and animals post-hurricane (FF-FG3; PS-FG3; FF-FG4, AE-FG2). Coffee farmers, in particular, reported a notable rise in weeds, pests, and disease where farms had been subject to extensive uprooting, defoliation, and other storm damages and losses (FF-FG4).

3.1.2. Economic

Public and private infrastructure, supply chains, and workforces were among the factors of an economic nature reported to have been most affected by the storms. Economic factors accounted for 58.2% of all coded 'hurricane effects and impacts' (Fig. 3). The financial costs associated with the storms' direct and indirect effects on farms, forests, and livelihoods were significant for many participants and noted in all focus groups and interviews.

Public Infrastructure – All focus groups (n = 18) and interviews (n = 10) described widespread storm-related damages to public infrastructure, including roads and transportation networks, telecommunications systems, electrical grids, municipal water supply systems, and government facilities. These damages resulted in telecommunication and electrical power outages; limited to no access to potable water; and blocked and limited access to and egress from public and private lands, among other impacts, which constrained farmer, forest owner, and rural community capacities to cope with and recover from the storms effects.

Farm, Forest, Other Private Infrastructure – Extensive damages and losses to farm, forest, and other private infrastructure from the storms' direct and indirect effects were reported in all focus groups and interviews as well. Poultry farmers in Puerto Rico reported some of the most widespread damages to infrastructure, particularly to commercial-scale poultry houses (i.e., one and two-story structures for housing 15,000–30,000 birds), many of which were destroyed or extensively damaged (FF-FG1; AE-FG1). Hydroponic and ornamental growers and their advisors reported major structural damages, mostly to greenhouses (AE-FG1, FF-FG7, AE-FG2). Numerous participants reported storm-related damages to fencing; shelter and shade structures for livestock; irrigation systems; water and fuel storage facilities (e.g., milking, refrigeration, packing); and other structures (PS-FG4, FF-FG5, FF-FG8, FF-FG9, AE-FG1, FF-FG7, FF-FG1, PS-FG5, PS-FG6, FF-FG2, AE-II3, FF-FG6). Several participants also described significant storm-related damages to their homes (PRDA, PS-FG4, PS-FG2, PS-FG3, FF-II3, FF-FG6).

Supply Chains – Indirect storm effects on supply chains were noted in all focus groups and interviews. Supply chains were suspended or constricted for some time after the hurricanes due in part to closures and delays at cargo ports and airports throughout the region. Many farmers, land managers, and other participants recounted the lack or limited availability of and access to heavy machinery (e.g., bulldozers, excavators), tools (e.g., chainsaws), and other supplies and materials (e.g., fuel, generators, batteries, fencing supplies, seeds, feed) in the days, weeks, and months after the storms. As noted by a farmer in Puerto Rico: "No availability or access to machinery, seeds, and other materials was one of the most difficult challenges we faced after María …. And more so for small producers who don't have good connections or many resources to locate or acquire them" (FF-FG6).

Workforce – A number of participants also noted the indirect impacts of the storms on the availability of and access to manpower and workforces (FF-FG4, PS-FG4, FF-FG2, PS-FG3, FF-II2, PS-FG2, PS-FG5). As described by a tree crop grower: "many of our employees had major damages to deal with … some lost their homes … helping them became a priority for us because without them our business cannot run" (FF-II2). An agriculture agency staff also noted: "many employees lost their homes or had major damages to deal with … Even many without major damages couldn't get back to work quickly because roads were blocked, and power and cell towers were out" (PS-FG6).

Financial Costs– In a voluntary exit survey of research participants in Puerto Rico and the U.S. Virgin Islands (n = 35), farmers and forest owners reported losses in crops, livestock, and infrastructure ranging from $10,600 to $3.0 million per farmer or landowner (Table 1). Survey responses are not generalizable to the broader population or to specific sectors since it was not randomly assigned or administered. Nevertheless, the responses provide a snapshot of the range in financial impacts on farmers and forest owners across the region.

Banana and plantain growers reported the largest losses amongst the exit survey respondents. On average, 98% of their crops were damaged or decimated, representing nearly one million dollars in lost crops per farmer (i.e., $17,863 per hectare or $7229 per acre). Coffee, poultry, and other row crop (i.e., other than bananas and plantains) producers followed with 82, 75, and 68% of their crops lost or damaged on average, respectively. Poultry producers reported lower average financial losses from animal death or injury than dairy and beef cattle producers, however, poultry farmers' rate of animal losses was notably higher, with 60–100% of their flocks reported to have been lost or injured compared to eight to 30% of dairy and beef cattle. In addition to crop and livestock losses, infrastructure damages were significant for many survey respondents, with an average of more than $120,000 in losses per farmer. Poultry farmers reported the highest losses in infrastructure on average, mostly associated with total loss or significant damages to commercial scale poultry houses (Table 1).

* Respondents included 26 individuals from Puerto Rico and nine from the U.S. Virgin Islands; 62% of respondents owned their farmland, 38% rented their farmland; Farm area averaged 47.75ha and totaled 1,667ha reported, with a minimum of 0.1ha, a maximum of 324ha, and a median of 26ha reported; 60% of respondents (n = 21) had forest area on their farm, totaling 175ha, averaging 8.5ha per farm and an average farm forest cover of 35%.

3.1.3. Social

Human health and well-being, and family, household, and community structures and ties were among the social aspects reported to have been most affected by the storms. Altogether, social aspects accounted for 13.8% of all coded 'hurricane effects and impacts' (Fig. 3).

Health and Well-being – No participant reported direct injuries or losses of human life directly associated with the hurricanes and only a few described indirect impacts on their physical health, mostly associated with limited to no access to medical supplies or services for pre-existing conditions. Conversely, numerous participants across all sectors and scales described significant impacts on their emotional health and well-being, including bouts of depression, associated with the hurricanes and their direct and indirect effects on their farms, forests, and livelihoods but only a few of these participants reported seeking professional or medical help (AE-II1, PS-FG3, FF-FG1, FF-FG6, FF-FG2, PS-FG5, PS-FG6, AE-FG1, PS-FG4, PS-FG2, 19, PS-FG1). As described by a poultry farmer in Puerto Rico: "We had significant damages and many others had worse than us … to see entire lives destroyed overnight affected me emotionally, spiritually … it still affects me today" (FF-FG1).

Family/Household/Community Structures – Several participants described the storms' indirect effects on family, household, and community structures ties, mostly in terms of negative impacts on human relationships and networks since many were physically and virtually isolated as a result of the storms' effects on infrastructure and telecommunications but some positive effects as well as neighbors, friends, and colleagues came together to help each other in the initial response and longer term recovery (PS-FG5, PS-FG6, AE-FG1; AE-FG2; PS-FG2, PS-FG4, FF-FG4; FF-II4; FF-FG6). Some communities of place, practice, and interest also were impacted by the temporary or permanent departure of community members who left for the mainland or other off-island locations after the storms. As described by a coffee farmer in Puerto Rico: "there was so much damage and destruction, people's priorities changed almost overnight … some left for the States, some quit farming, and our sense of community [as coffee growers] was really affected" (FF-FG4).

Table 1
Reported damages and losses for major crops, livestock, and infrastructure (n = 35*).

Product	Average Percent (and Range) of Crop/ Livestock Damaged/Lost	Range in Loss per Farmer/ Landowner (US$)	Avg. Loss per hectare (crops, pasture) or per Farm (livestock, infrastructure) (US$)	Total Reported Loss (US$)
Banana/ Plantain	98% (90–100%)	$40,000-$2,500,000	$17,863	$5,850,000
Coffee	82% (25–100%)	$150,000-$2,500,000	$16,896	$2,850,000
Poultry	75% (60–100%)	$30,000- $40,000	$35,000	$105,000
Other Row Crops	68% (10–100%)	$1000- $32,000	$3034	$255,500
Pasture	48% (25–75%)	$25,000- $150,000	$677	$390,000
Dairy/Beef Cattle	10% (8–30%)	$12,000- $250,000	$75,125	$601,000
Infrastructure	N/A	$1500-$1,800,000	$120,514	$4,218,000

3.2. *Hurricane response*

Research participants described a broad range of actors, strategies, and practices involved in the immediate response to hurricanes Irma and María and their effects on farms and forests. Overall, limitations and constraints associated with the initial relief and response were reported more frequently than effective or advantageous strategies, practices, or resources (Fig. 4).

3.2.1. *Hurricane response constraints and limiting factors*

Numerous farmers, forest owners, and other stakeholders described having to fend for themselves, often with little preparation or resources, in the initial days, weeks, and months after the storms. Most farmers and forest owners reported having insufficient materials and supplies on hand, provided through emergency aid or relief efforts, or available in the marketplace to address their immediate needs and to prevent further or compounding damages (FF-FG1, FF-FG4, FF-FG8, FF-FG9, FF-FG2, PS-FG3, AE-II2, FF-II3, FF-II4, FF-FG6, AE-FG1, AE-FG2, AE-FG3, PS-FG3, PS-FG1). For instance, a farmer in St. Croix reported: "Our fences were seriously damaged, and we didn't have the materials or help to repair them for a long while after [hurricane] María. … We didn't lose many animals in the storm, but some escaped through downed fences … they may have survived the storm but when they got loose some were hurt in all the debris or could've been killed on the roads" (FF-FG8).

For most participants, widespread and persisting losses of electricity, telecommunications, and municipal water supply; blocked and damaged roadways and points of access and egress; and disrupted supply chains significantly constrained coping, relief, and response efforts and greatly limited their ability to connect with sources of related aid or assistance. As one forest sector expert described, "Basic necessities for farmers and forest owners, like gasoline, feed, fencing, and chainsaws weren't available anywhere right after the storms … and with no phone or internet, there was no way to know if and when any were coming" (AE-II2).

Multiple public policy and programmatic obstacles or constraints to the initial hurricane response on farms and private forestland were reported, including a lack of clarity among landowners and other local actors on response related authorities, roles, and responsibilities (FF-FG1, FF-FG4, FF-FG8, FF-FG9, FF-FG2, FF-FG7, AE-FG1). Some participants also described the initial response, particularly among government agencies, as fragmented or poorly coordinated (PS-FG1, PS-FG3, FF-FG1, PS-FG2, PS-FG4, AE-II1). Few farmers and landowners knew who to ask, where to go, and how to get help meeting basic needs and preventing further damages after the storms. For example, poultry farmers and other participants described high levels of uncertainty in the rules and responsibilities for handling the large numbers of dead and decaying birds after hurricane María (FF-FG1, PS-FG2, PS-FG5, PS-FG6). Government sponsored or supported relief programs targeting farms or forests also were described by many farmers, forest owners, and their advisors as overly burdensome in terms of the related requirements (e.g., farm documentation, detailed crop information) or largely inaccessible due to telecommunications and electricity outages.

3.2.2. *Effective response strategies and advantages*

Farm, Forest, and Community level– Most participants reported 'fending for themselves' in the initial days and weeks and, in some cases, months after the hurricanes passed, clearing debris and trying to secure water, fuel, and feed supplies (FF-FG2, PS-FG3, FF-FG1, AE-FG2, AE-II2, FF-FG4, PS-FG1, PS-FG2). These response efforts were described mostly as having been borne out of necessity as landowners recognized given the widespread and extensive damages to roads, telecommunications, and other critical

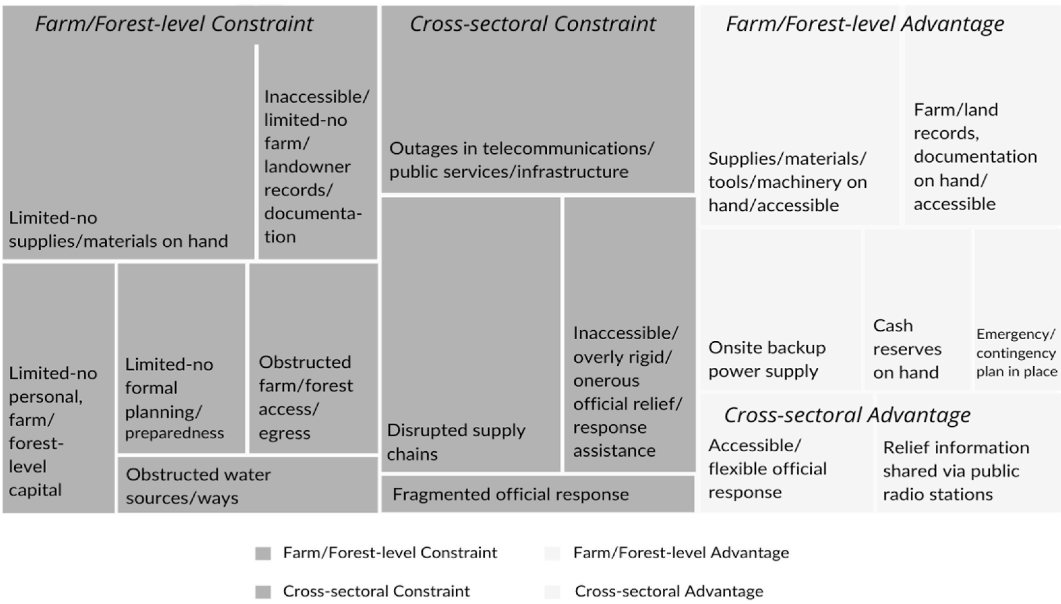


Fig. 4. Constraints and advantages associated with the initial response to hurricanes Irma and María in agriculture, forest, and rural communities in Puerto Rico and the U.S. Virgin Islands. Box size relates to number of coded segments of text, box color relates to constraints or limitations (light grey) and advantages or effective strategies and practices (dark grey) at farm/forest and cross-sectoral levels.

infrastructure and services region-wide, ‘help was not coming’, at least not in the initial days and weeks after the storms (FF-FG2, FF-FG1, FF-FG8, FF-FG6, FF-FG4). Some participants considered their individual-level response efforts to have been relatively effective in assessing and addressing damages and moving on to the work of recovery, particularly those who had supplies and materials on hand and secured prior to the storms and those who were able to connect with relief supplies and services (PS-FG1, AE-FG2, AE-II2, FF-FG2, FF-FG4, FF-FG8).

Several participants reported working with their neighbors, friends and local community members in the initial days, weeks, and months after the storms to clear debris, secure critical materials and supplies, meet other basic needs, and avoid additional damages or losses (AE-FG2, AE-FG3, FF-FG2, PS-FG3, FF-FG1, AE-II2, FF-FG4, PS-FG1, PS-FG2, PS-FG6, FF-II5, FF-FG5, FF-FG6, FF-II2). These broader, community-level responses occurred among communities of place, practice, and interest, mostly in an informal or ad hoc approach, and often in the absence of official or formal forms of assistance (PS-FG3, AE-II2, FF-FG2, FF-FG4, FF-II4, FF-II5). Relatively few communities were described as having been well-organized or prepared to carry out critical relief and response activities focused on farms and forests; the few that were described as such mostly were associated with established community level or sector specific association or other established social networks and ties (PS-FG3; PS-FG1).

Local/Territorial/Commonwealth Government – Overall, a relatively small number of focus groups and interviews identified actions and strategies at local and commonwealth/territorial levels of government that were considered to have been effective in the early response to storm-related impacts on farms and forests. A few farmers in Puerto Rico reported relief and response support provided by their municipal government, mostly in terms of clearing roads and points of access/egress (FF-FG7, AE-II1, AE-II2). A few participants also mentioned public meetings, communications, and other forms of information dissemination by local agriculture agencies as having been helpful in their efforts to cope with the storms' effects in the initial days, weeks, and months after the storms (FF-FG8; PS-FG4; FF-FG2; FF-FG5).

Federal Government – Participants reported federally sponsored programs or practices (e.g., NRCS Emergency Watershed Protection Program, Emergency EQIP practices) that were considered to have been effective in helping farmers and forest landowners clear debris and acquire feed and other critical supplies and materials (FF-FG5, FF-FG3, AE-FG1, FF-FG1, FF-FG7, FF-II5, FF-FG8). Most farmers and forest owners reporting experiences or examples of effective federal-level relief and response had been registered with federal programs prior to the storms. Conversely, many farmers, forest owners, and others not previously registered in federally sponsored programs described difficulties accessing most to all government relief programs.

Non-Government/Civil Society Organizations – Participants also identified numerous nongovernmental actors and initiatives as having been helpful in the initial relief and response stages, particularly in terms of helping to clear debris (e.g., AmeriCorps, Boy Scouts) and providing critical materials and supplies (e.g., Red Cross, PR Conservation Trust, American Society for the Prevention of Cruelty to Animals, Love City Strong) (FF-FG4, AE-FG2, AE-FG3, PS-FG4, PS-FG3, FF-FG2, AE-II2). Many described civil society relief efforts as having been relatively quick and unencumbered in providing relief and response to farmers and forest owners in need, particularly in comparison to government agencies. Additionally, participants described support from agriculture and forest extensionists, particularly in terms of providing critical information on relief and response. Extensionists' use of local radio stations to communicate with farmers, forest owners, and other rural residents was noted as having been particularly effective for sharing important information on hurricane relief and response (AE-FG1, AE-FG3, FF-FG5, FF-FG7, FF-FG8). As recounted by an extensionist in Puerto Rico: “The radio was the best way for us to connect with farmers … since there was no other way to communicate for some time in most places … especially in rural areas. … We were on the radio almost every day providing information about [relief] assistance and resources … and things like pest and disease outbreaks and what to do about them” (AE-FG1).

3.3. Hurricane recovery

Participant descriptions of the state of recovery 18–22 months after the hurricanes varied widely across sectors and subregions. A broad range of actors, strategies, and practices were involved in agriculture, forest, and rural community recovery efforts, including many involved or utilized in the initial relief and response. Participants described numerous limitations and obstacles to the recovery, some of which were identified in the initial response and continued to limit the effectiveness of recovery efforts, and others that delayed or further constrained the recovery of agriculture and forest systems across the islands. They also reported some strategies, practices, programs, and resources considered to have been effective in moving beyond the initial response to restore or improve farms, forests, and livelihoods (Fig. 5).

3.3.1. State of recovery 12–18 months post-hurricanes

Most (90% and more) of the major transportation networks, electrical grid, and public water supplies had been restored within five to six months of the hurricanes in the U.S. Virgin Islands and ten to twelve months in Puerto Rico (Federal Emergency Management Agency [[2,10]. However, many participants reported ongoing intermittent and longer-term outages, mostly in rural and remote areas of the islands for up to a year and in some cases longer after the storms (FF-FG3, PS-FG4, PS-FG1, FF-FG4, FF-FG2, PS-FG6, AE-FG1, FF-FG8).

In Puerto Rico, some crops including plantains, bananas, tomatoes, root crops, peppers, and other vegetables were reported to have recovered 75% or more of their pre-hurricane production levels within six to 12 months of the hurricanes (PS-II1; FF-FG3; AE-FG1). A few agriculture commodities reportedly had surpassed their pre-hurricane production levels within a year after the hurricanes, including pork and beef production in Puerto Rico (PS-II1). Conversely, coffee, cacao, other tree crops, and poultry production in Puerto Rico demonstrated relatively slower, lower levels of recovery 12–18 months post hurricanes, associated in part with more extensive damages and longer production cycles (FF-FG3, PS-II1, AE-FG1, FF-FG4, FF-FG1). In the U.S. Virgin Islands, agricultural

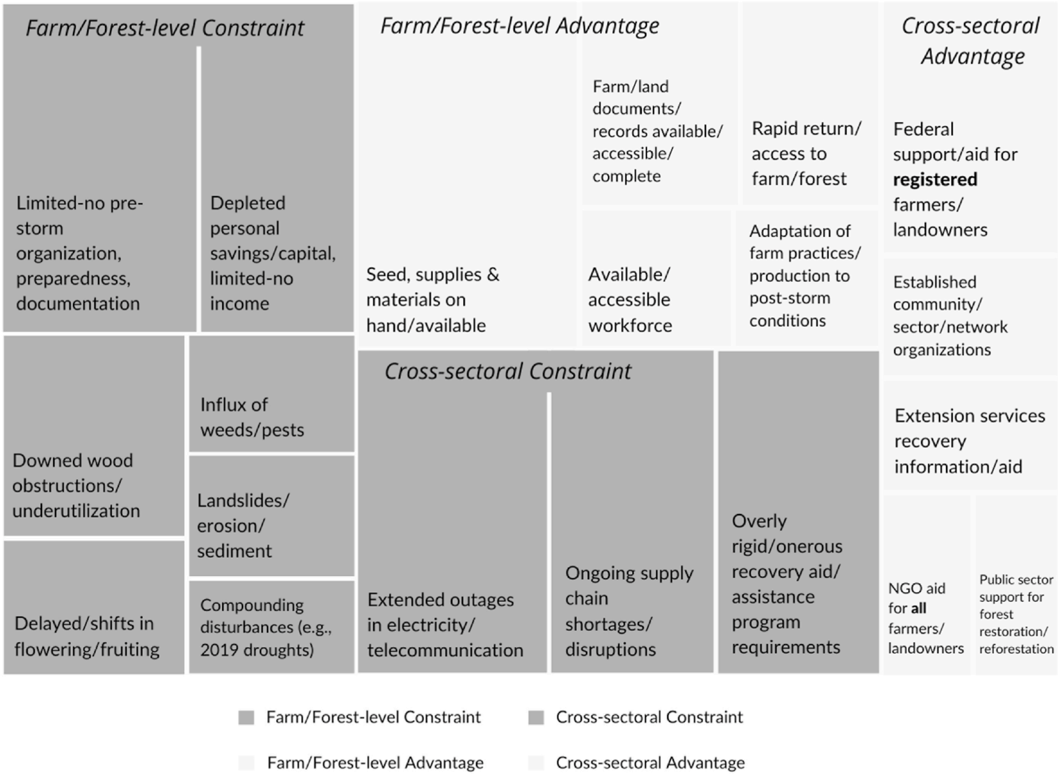


Fig. 5. Constraints and advantages associated with the recovery from hurricanes Irma and María in agriculture, forest, and rural communities in Puerto Rico and the U.S. Virgin Islands. Box size relates to number of coded segments of text, box color relates to constraints or limitations (light grey) and advantages or effective strategies and practices (dark grey) at farm/forest and cross-sectoral levels.

production levels generally were reported to be much lower than pre-hurricane levels 12–18 months after the storms (AE-FG3, AE-FG2, FF-FG9).

Forest recovery, including new foliage, flowering, and fruiting; downed trees starting to decompose on the forest floor; vines and grasses giving way to early successional species (e.g., *Spathodea campanulate, Cecropia* spp.); and increasing populations of forest birds and other wildlife within 12–18 months post-hurricanes were reported by several participants in Puerto Rico and the U.S. Virgin Islands (PS-FG1, PS-FG3, AE-II2, AE-FG2). Several participants reported public forests in varying states of recovery, some having re-opened to the public but with limited access and facilities due to ongoing repairs and unaddressed damages, but many remaining closed to visitors (PS-FG1, PS-FG3).

3.3.2. Hurricane recovery limitations and constraining factors

Materials, infrastructure, and other economic factors – Among the most frequently reported limitations to the recovery of agriculture and forest systems across the islands were extended outages in electricity, telecommunications, and transportation networks, which significantly slowed or limited recovery efforts. As noted by an agriculture agency staff member in Puerto Rico: "In some communities, it took six to nine months to get electricity restored. … some communities are still without power today. … it's hard to rebuild or recover without these basic services" (PS-FG6). These issues also limited the effectiveness of recovery assistance and aid, as noted by an agriculture agency staff member in St. Croix, U.S. Virgin Islands: "telecommunications and power outages and issues continue to be a big challenge for us … for getting work done and assisting farmers" (PS-FG4).

Many participants reported ongoing shortages in fuel, feed, seeds, machinery, and other materials and supplies that limited recovery efforts and progress. As recounted by a forest owner in Puerto Rico 14 months after the storms: "recovery has been nearly impossible – there haven't been enough materials, supplies, access to them, or cash to buy them" (FF-FG2). Similarly in the U.S. Virgin Islands, an extensionist noted: "seeds, supplies, and materials continue to be scarce here [20 month post-María] … some farmers are trying to source and import resources from off island but for most that just isn't feasible" (AE-FG3). Limited to no seed supplies were among the most frequently reported constraints to farm recovery, particularly among coffee farmers in Puerto Rico and banana and plantain farmers in the U.S. Virgin Islands (FF-FG4, AE-FG1, FF-FG9). Access to heavy machinery also posed challenges as described by a forest owner in Puerto Rico: "there are areas on my land that I still cannot access because of the debris, trees still coming down, and no tractor or skidder available to get in there to clean up or stabilize it" (FF-FG2). An agriculture agency staff member in Puerto Rico indicated heavy machinery was difficult for farmers and forest owners to access a year and longer after the storms due in part to "ongoing needs and priorities for their use in reopening and restoring roads" (PS-II1).

Lack of equipment and limited local technical capacity for selecting, hauling, and processing high-value hurricane downed wood and unclear or inexistent rules, roles, and responsibilities for such processes in both jurisdictions were noted by a number of participants to have limited recovery and resulted in lost opportunities for developing the islands' wood industries (PS-FG1, -FG3, FF-FG2, AE-FG1, PS-FG2, FF-FG8, AE-FG2). As described by a forest sector expert in Puerto Rico: "downed trees and woody debris remain untouched on most private land … some are of high value and many are already decomposing … landowners require heavy machinery, skilled labor, chainsaws, and other tools, which few landowners have on hand or accessible to them. … Even those with the tools, don't know how to process the wood, how to market it, or even who to sell it to …" (AE-II1). Some participants also reported issues with hurricane-downed woody debris that impeded farm and forest recovery work 12–18 months after the storms (FF-FG2, PS-FG3, FF-FG9, AE-II1, AE-II2, AE-II3, FF-FG4, FF-FG6, AE-FG1).

Relatively low levels of farm and forest hurricane preparedness in many sectors and areas were described as having constrained not only the initial response but also progress in hurricane recovery since there were few existing or familiarized plans or resources in place to help guide and carry out the restoration, improvement, or adaptation of pre-storm social-ecological-technological conditions and production systems (FF-FG4, FF-FG1, PS-FG1, PS-FG3, AE-II2, FF-FG2, FF-FG6, AE-FG1, AE-FG2, AE-FG3, PS-FG4, PS-FG2). Many farmers and forest owners reported financial constraints to the recovery as well, including having depleted their personal savings in early efforts to cope with the hurricanes' effects and related impacts and having limited access to or success with government sponsored recovery initiatives (FF-FG6, FF-FG4, FF-FG9, AE-FG1, AE-FG2, FF-FG1, FF-FG3). Some participants also reported that crop and farm insurance payouts for storm damages, recovery assistance payments, and reimbursements for approved recovery work were insufficient to offset their associated costs, were slow to reach them, and in most cases, had yet to arrive (FF-FG8, PS-FG4, FF-FG3, FF-FG1, FF-FG4, FF-II2, FF-II3).

Governmental programs and policies – Major obstacles to government supported recovery initiatives for farmers and forest owners without documentation or records of farm ownership, title, production, and damages were noted by many participants (AE-FG1, PS-FG4, PS-FG2, AE-FG3). As recounted by an agriculture extensionist in the U.S. Virgin Islands: "when disaster assistance and recovery programs opened up for farmers… I realized that many of our farmers would have trouble … the government was asking for documentation on their land and their production, inputs, and investments that very few have or are willing to share with the Feds" (AE-FG3). Even for landowners with this type of documentation on hand, there were barriers to relief and response programs associated with 'extensive paperwork', lengthy processing times, lack of materials in Spanish (for Spanish speakers in Puerto Rico) and mostly reimbursement-based assistance (FF-FG8, FF-FG9, FF-FG3, FF-II4, PS-FG4, FF-FG6, PS-FG2, FF-FG2). Several participants also reported that policies and programmatic rules for recovery assistance did not align with or were not adaptive to local contexts and conditions (e.g., electronic files or registration requirements while telecommunications outages persisted) (FF-FG1, FF-FG4, FF-FG9, FF-FG6, PS-FG2, PS-FG4, PS-FG6, PS-FG1, PS-FG3).

Biophysical factors and compounding effects – Participants described a range of biophysical responses to the storms and their cascading effects that constrained farm and forest recovery, including increased pests, weeds, and unwanted vegetative growth a year or more after the storms (PS-FG3, FF-FG2, FF-FG4, FF-FG3, PS-FG4, AE-II2). Some farmers and extensionists also described delays or shifts in flowering and fruiting cycles of key crops, like avocados and mangoes, associated with "higher than normal precipitation totals from the storms" and "declines in bee and other pollinator populations" (AE-FG1). Several farmers, land managers, and other participants also described ongoing issues with landslides, erosion, and sedimentation that constrained recovery efforts, particularly in higher elevations and on steep slopes (FF-FG4, FF-II2, FF-II3, FF-FG7, FF-FG9, FF-FG3, PS-FG3). Additionally, some farmers and extensionists noted the compounding challenges of extended drought conditions occurring in 2018, while still trying to recover from the 2017 hurricanes (FF-FG9, FF-FG8, AE-FG1).

3.3.3. Hurricane recovery advantages and effective strategies

Farm- and forest-level – Participants identified numerous strategies and practices at the farm or forest level considered to have been effective in the recovery phase, including having basic necessities, supplies, materials and essential documentation (e.g., title, proof of tenure, production records, damages, etc.), on hand or readily available for repairing, rebuilding, replanting and enrolling in aid and assistance programs (AE-FG1, AE-FG2, FF-FG8, FF-FG5, FF-FG1, PS-FG2, FF-FG2, FF-FG6, AE-II2). For many farmers, seed reserves were listed among the most important resources to have on hand for rapid recovery where crops had been damaged or destroyed.

A number of participants noted that farmers and forest owners who were able to return to work on their farms or forest relatively quickly (i.e., within days to weeks) to start the process of repairing, replanting, or rebuilding, recovered more quickly than those who could not reach or tend to their land quickly after the storms (AE-FG1; AE-FG2; FF-FG8; FF-FG5; FF-FG7). Farmers and forest owners with access to and availability of manual labor or workforces also were reported to have recovered more quickly than those without these resources. Farmers who were able to adjust or adapt to post-storm conditions and available resources were described by a number of participants as having been quite effective in restoring and, in some cases, improving farm conditions and productivity (AE-FG1, FF-II5, FF-FG7). For example, as noted by an extensionist, "after María, some farmers started using new farming methods, like permaculture, or planted new crops, like peppers and other fast-growing commodities … They adjusted to seed availability, soil conditions, and resources … or temporarily scaled back production and were able to start the recovery process faster than others" (AE-FG1).

Community- and Network-level – Farm and forest communities with established social networks or a history of coordination and collaboration prior to the storms were frequently described as having been able to successfully navigate recovery aid and resources and were reported to have demonstrated more measurable progress in their recovery than communities or networks with limited or less developed social ties, networks, or organizational capacity (AE-II2, PS-FG3, AE-FG2). Several participants noted that farmers, forest owners, land managers, and others involved in formal (e.g., sector-specific associations; national groups) and informal (e.g., groups of farmers in a specific region) networks utilized these institutions to connect with recovery resources and assistance (FF-FG4, AE-FG1, AE-FG3). Some participants, in the coffee sector in particular, also described their 'sense of community' and their commitment to each other and to their sector as an important factor facilitating their recovery trajectory (FF-FG4).

Local/Commonwealth/Territorial Government – A few participants noted examples of local and commonwealth/territorial government support for agriculture and forest recovery, mostly involving information on, connections to, and direct provision of seed sources, tree seedlings for reforestation, feed, materials and supplies (FF-FG4, AE-FG1, PS-FG5, FF-FG7). Local- government- led recovery initiatives focused on forests and agriculture included a large-scale forest recovery and reforestation initiative – *Sembrando Futuro*, established by Puerto Rico Department of Natural and Environmental Resources, with support from USDA FS, and a municipal-government sponsored initiative to establish a coffee seedling nursery, with support from a private coffee company (PS-FG3, AE-II1, AE-II3, FF-FG4).

Federal Government – Numerous farmers and forest owners described varying levels of recovery assistance through federal programs (e.g., USDA WHIP, EQIP, EWP) for aspects including fencing and other infrastructure repairs, debris removal, and streambank stabilization (FF-FG3, FF-FG4, FF-FG5, FF-FG1, FF-FG7, FF-FG8, FF-FG2). Participants noted that most approved practices under these programs had yet to be reimbursed at the time of data collection, but many expected that they eventually would be beneficial to farm and forest recovery. Some participants also noted that Federal support for forest restoration and tree nursery reconstruction and improvement had a significant boost on forest restoration and recovery efforts across the islands (PS-FG2; PS-FG3, FF-FG2, AE-II1, AE-II3, AE-FG2, AE-FG3). A few participants also mentioned the effectiveness of the USFWS Puerto Rican parrot recovery program, noted for its high success rate in protecting its captive bird population in its entirety during both storms and in its captive breeding program post-storms (PS-FG3) (Approximately 70 chicks were born in captivity within a year of hurricane María [71].

Civil Society – Most nongovernmental and civil society organizations and initiatives identified as having been important in the initial relief for farms, forests, and livelihoods, also were noted as being important to their recovery. In addition to many of the organizations identified as being effective in the early storm response, several participants noted the positive impact of recovery assistance from Seed Relief, Hispanic Federation, and Para La Naturaleza, among others. Agriculture and forest extensionists and advisors also were described by numerous participants as an important conduit of information, technologies, and practices critical to farm and forest recovery. Many extensionists and advisors themselves recounted tapping into extensive existing relationships with farmers and forest owners to facilitate recovery work across the islands and increasing connections and cooperation with other nongovernmental and governmental actors to channel recovery aid to their clients (AE-FG1, AE-FG2, FF-FG5, FF-FG7, FF-FG8).

3.4. Risk reduction strategies and practices - preparedness, mitigation, and adaptation

Overall, research participants reported relatively low levels of hurricane risk reduction strategies and practices having been in place prior to the storms. As noted by a farmer and forest owner in Puerto Rico: "disaster planning or prevention is not something many people do here … I don't know anyone who had a clear plan or preparations for what to do before or after the storms … we didn't and I wish now we did …" (FF-FG2). Low levels of farm- and forest- level preparedness were attributed mostly to limited resources (e.g., financial, human, technological) and lack of knowledge of what exactly to do for a given production system or sector, but also to some degree of skepticism regarding hurricane and storm forecasts and a sense of 'false' security that a major hurricane would not affect the area (FF-FG1, FF-FG6, FF-FG8, FF-FG3, PS-FG6, AE-FG3). Although comprehensive preparedness planning was uncommon, a number of practices were reported to have been effective in preparing for and coping with immediate and longer-term storm effects (Table 2).

A few participants, mostly associated with relatively large farming operations in Puerto Rico, reported having an emergency, contingency, or continuing operations plan in place prior to the hurricanes, which they described as having been useful in anticipating, responding to, and recovering from at least some hurricane effects and associated impacts and for being better prepared to access sources of aid and assistance after the storms had passed (FF-FG5, FF-FG1, FF-FG7, FF-FG3). Yet, even the best-laid plans were strained by the extensiveness of storm-related effects and impacts. For instance, as recounted by a farm operator in Puerto Rico: "We have an emergency plan. And everyone knew their part and what to do before the hurricanes … but the damages on our farm and

Table 2
Preparedness practices reported to be effective in addressing hurricane effects on farms and forests in U.S. Caribbean.

- Seed reserves and other supplies and materials (e.g., posts, wire for fencing, animal feed and medications, etc.) on hand and safely stored
- Tools (e.g., chainsaws) and heavy machinery (e.g., tractor, bulldozer) on hand and secured or prepositioned in secure and accessible areas across the landscape
- Backup power sources tested and secured (including removal, safe storage of solar panels)
- Fuel and water tanks filled and strapped down or otherwise secured
- Heavy equipment secured and raised up in flood prone areas
- Ranch/barn roofs strapped downed or otherwise secured
- Removal and safe storage of greenhouse coverings or plastics
- Access/egress points cleared of potential obstruction
- Cash reserves on hand
- Copies of critical documentation (e.g., land title, registration, farm inputs and outputs) stored both as hardcopy in waterproof container and as electronic copy in cloud-based system
- Drones on hand and charged for pre- and post-storm reconnaissance and monitoring)

across the island were so extreme … it took months for us to clear all the debris before we could even see what we had left and what it would take to start up again …" (FF-FG7).

Hurricane mitigation and adaptation practices also were reported to have been relatively rare across most farms and forests throughout the region. A number of farmers and forest owners indicated that they had received at least some support for risk reduction from public sector agencies over the years, mostly through consultations, information campaigns, and trainings, as well as some financial and technological assistance for mitigation and adaptation practices or resources (e.g., for backup solar power systems, drainage measures, contour planting, water reservoirs, and roadside tree maintenance through programs like NRCS Environmental Quality Incentives Program, Conservation Stewardship Program, Rural Energy for America Program; USFS Forest Stewardship Program) (FF-FG8, FF-FG1, FF-FG2, FF-FG3, FF-II4, FF-II5, FF-FG7). Specific practices and strategies reported to have been effective in mitigating or adapting to high winds, heavy rains, and other hurricane effects are noted in Table 3.

A number of farmers and forest owners expressed regret or frustration at not having been better prepared for the storms and not having reduced risks on their farms and in their forests, which they associated most frequently with lack of resources or information (PS-FG1 PS-FG2, PS-FG4, PS-FG6, AE-FG3, AE-FG1). Some participants, mostly in the U.S. Virgin Islands, also mentioned a lack of trust in government programs and services among some agriculture and forest communities, which was attributed in part to their resistance or aversion to program participation and adoption of recommended practices (PS-FG4, FF-FG8, PS-FG2).

4. Discussion

4.1. Hurricane effects and associated impacts on agriculture, forests, and rural communities

High winds, heavy rains, and other direct and indirect effects associated with hurricanes Irma and María affected a broad range of social, economic, and technological factors on farms, forests, and in rural communities across Puerto Rico and the U.S. Virgin Islands resulting in widespread crop and livestock losses; extensive damages to roads, facilities, and other private and public infrastructure; lengthy outages in electricity, telecommunications, and water supplies; and harmful impacts on human health and well-being. The storms revealed deep-rooted social, economic, and environmental vulnerabilities to major disturbances among and beyond much of the region's agriculture, forest, and rural communities. Many of these vulnerabilities were associated with limited resources (i.e., financial, technological, human) to reduce risks at local and larger scales and were shaped by prolonged economic crises, particularly in Puerto Rico, a high dependence on food and fuel imports, complex sociopolitical relations and histories with the U.S. government and other socio-economic and environmental dynamics.

4.2. Response and recovery

Much of the initial relief and response efforts in the islands' agriculture and forest sectors occurred at individual farmer and forest owner levels and among groups of individuals who mostly came together extemporaneously and in some cases as an extension or adaptation to existing groups or networks to help each other cope with and begin to recover from the storms' effects. Such initiatives were particularly prevalent where access to and communication with farms, forests, or entire communities was obstructed or limited for some time after the storms had passed and where immediate needs were not met by existing organizations and structures. These types of emergent behavior and action often arise in the context of disasters and have been shown to be an important and effective but frequently unanticipated or overlooked factor in risk reduction and resilience strategies and approaches [15,16,39,40,42,45,46,72–77].

Nearly all relief and response efforts in the agriculture and forest sectors were beleaguered by the extensive and compounding effects and associated impacts of the back-to-back storms, particularly in rural areas which were harder to reach by land or via telecommunications for many months after the storms. Few individual farm or forest level responses were reported to have been guided by formal plans or preparations. Some individual and local level strategies and practices were considered to have been effective in responding to and starting to recover from the storms' effects on farms and forests, including the limited number of cases described as having been well- planned, resourced, communicated, and connected ahead of the storms, the few who were able to successfully access official relief and recovery resources, and where groups and resources were able to come together quickly after the storms had passed often multiplying individual efforts, assets, and ties (e.g., $1 + 1 > 2$ (see for ex.: [75].

Official hurricane response and recovery resources for the agriculture and forest sectors reportedly went largely underutilized, as many farmers and forest owners described them as having been too difficult, rigid, or onerous to access or navigate successfully, ulti-

Table 3
Mitigation and adaptation practices and strategies reported to be effective in addressing hurricane effects on farms and forests in the U.S. Caribbean.

- Crop and species diversification
- Contour farming in sloped areas
- Erosion controls (e.g., cover crops, *Vetiveria zizanioides* L.), particularly on steep slopes
- Windbreaks/windrows with multipurpose species (e.g., *Casuarina* spp., *Erythrina* spp.)
- Forest protection/restoration on steep slopes and in riparian areas with native species
- Pruning/maintenance of roadside trees and those at points of access/egress
- Shade coffee (versus coffee planted in full sun)
- Single story poultry houses (versus two story poultry houses)
- Drainage measures along access and egress roads (e.g., culverts, ditches, water bars)
- Installation/maintenance of back-up water supply (e.g., reservoirs, retention ponds, cistern)
- Off-grid/back-up power source and supplies (e.g., generator, solar)

mately limiting their effectiveness in supporting farm and forest relief and recovery across the region. Additionally, there was a perceived lack of clarity among many farmers and forest owners regarding the rules, roles, and responsibilities associated with official response efforts that, for many, continued into the early stages of the recovery process. Consequently, many participants reported dealing with the storms' effects largely on their own and having sought relief mostly through ad hoc, local, and nongovernmental resources. Although most considered these sources of relief and early recovery support to have been helpful in addressing some of the storms' effects and associated impacts on their farms and forests, many also expressed strong desires to have been better prepared and connected to other farmers, forest owners, and response and recovery resources in their local communities. These results point to the need for enhanced hurricane preparedness in the agriculture and forest sectors at individual, local, and larger scales in Puerto Rico and U.S. Virgin Islands. The results also underscore the need for increased operational and strategic flexibility and adaptiveness in formal disaster relief and response approaches and programs, specifically in terms of access, requirements, and delivery mechanisms targeting agriculture, forests, and rural communities, and with regard to emergent actions and groups that could be more effectively incorporated or supported in response and recovery strategies. These results echo similar findings by Ref. [78] on drought risk reduction in the agriculture sector in southern Africa (see also [16,37,42,46,79].

Most recovery efforts in the agriculture and forest sectors were in their earliest phases at the time of data collection and reported recovery of resources and productivity varied widely across sectors, operational scales, and sites. Farmers and forest owners who reported the most progress in recovering from the storms' effects and associated impacts tended to be larger in scale, insured, registered in agriculture or forest related government programs, and having had an emergency or continuing operations plan in place prior to the storms. The majority of farmers and forest owners who participated in this study were still working to repair and rebuild their operations 18–24 months after the storms, some were uncertain if they would still be in business within a few years without significant additional support and resources, some were planning for a return to pre-hurricane conditions and productions levels, and some were putting into place changes or adaptations in light of the storms' effects and associated impacts and future projected disturbances.

Several farmers and forest owners described adjustments, adaptations, and enhancements to farm and forest systems that they had implemented or were planning to implement in the context of post-hurricane conditions and future climate projections (e.g., replacing damaged and destroyed two story chicken ranches with more resistant single-story ranches; incorporating new or more agroecological practices; acquiring back up power and water supplies; diversification of crops/species). Some official support was available to support farm and forest mitigation, adaptations, or more extensive transformations (e.g., targeted practices/investments supported by USDA WHIP, EQIP, etc.), but relatively few participants had accessed or were aware of these programs. Increasing awareness of existing resources as well as the development of additional mechanisms that support farm and forest adaptation and innovation will be important to enhancing food security, local livelihoods, ecosystem services, and other benefits from the agriculture and forest sectors in the context of projected increasing occurrence and intensity of hurricanes and other extreme weather events in the Caribbean.

Most recovery efforts at the time of data collection were described as focusing primarily on restoring farms and forests to pre-hurricane conditions notwithstanding a local focus to 'build back better' and increasing calls for disaster response and recovery to include efforts to enhance resistance and absorptive capacities through adaptations and innovativeness (see for ex.: Collof et al., 2017 [38]; Kates et al., 2012; [33]. Adaptation, innovation, and transformation of individual and interconnected systems certainly can conflict with immediate needs for the restoration of services and goods in terms of time, money, and vested interests and require reliable and transparent information, deliberative, participatory decision processes, and significant resources (O'Brien 2012). Nevertheless, with tens of billions of US$ in recovery funding obligated to be dispersed over the next decade or more in Puerto Rico and the U.S. Virgin Islands, related programs and resources certainly could be more directly tailored or harnessed to rebuild or transform farms, forests, and rural communities to be more resistant and resilient to future shocks and disturbances beyond their pre-storm conditions, particularly if decisions and actions are open, transparent, and participatory.

4.3. Risk reduction strategies and practices

Overall, participants reported relatively low rates of hurricane preparedness at the farm, forest, and local community or network levels. Many participants noted that hurricane preparations and broader scale hazard planning at the farm and forest level largely were precluded by limited capital and other assets to invest in preparations and plans, low levels of risk perception associated with hurricanes, and insufficient information or understanding of associated practices and strategies to adequately prepare for hurricanes or other major disturbances. The limited number of farmers and forest owners who reported having a plan or preparations in place prior to the storms generally associated these withpost-storm actions and behaviors that enhanced their ability to absorb and cope with the storms' effects and to connect more quickly with others in their community and with sources of support and assistance. Many participants also expressed a desire for hurricane preparations that include the identification and coordination of machinery, materials, supplies, strategies, and services that may not be available or feasible at the individual farm or forest level, but which might be acquired by local community groups, networks, or governments to maintain and manage for relief and recovery, particularly when disturbances are severe and outside assistance is impeded or otherwise delayed.

Emergency or disaster preparedness plans that assess and identify best practices for reducing risks and preparing for hurricanes and other major disturbances are relatively low-cost investments that can help to inform and equip farmers and forest owners, their staff, and their households with knowledge and best practices for preparing for, coping with, and recovering from disturbances and disasters [4]; Weiner et al., 2020). Individual farm and forest level plans also can incorporate mechanisms for communicating and coordinating preparations and practices with other farmers, forest owners, and community members (horizontally) and with higher level plans (vertically, e.g., municipality, commonwealth/territorial government, federal government, civil society organizations) to further prepare for and reduce the risks associated with hurricanes and other hazards [80,45,46,81–83].

Across agriculture, forests, and rural communities, hurricane and other extreme climate mitigation and adaptation strategies or practices were quite limited prior to the storms. Sector- and site-specific mitigation and adaptation practices and strategies considered to have been effective for resisting and coping with the storms' effects and associated impacts included backup power supplies (solar power systems, generators) and communications systems (radios, satellite phones); dry and secure storage of seeds and seedlings as well as important documentation; maintenance of drainage ditches, irrigation channels, and water reservoirs to minimize flooding or obstructions; protection, restoration, and reforestation of riparian areas along streams and rivers and on steep slopes to minimize erosion and sedimentation; and diversification of crops or crop species (see also Tables 2 and 3). Similar to other risk reducing approaches discussed above, the low rates of hurricane mitigation and adaptation across farms and forests were associated with limited levels of capital and resources to develop and implement associated practices, as well as limited information on and awareness of effective measures. A fairly broad range of public and private sector programs that offer financial and technical support for mitigation and adaptation practices on private farms and forests are available throughout the region, but enrollment, participation, and uptake rates were reportedly low, attributed in part to administrative and technical hurdles (e.g., extensive paperwork requirements, proof of (clear) title/tenure, etc.), and to farmer and landowner distrust of government sponsored programs.

Ultimately, there was a measurable gap between participants' recommendations and expressed desire for increased risk reduction on farms, forests, and in rural communities and existing and available resources to support hurricane and other hazard mitigation and adaption on private lands. Examining other programs with high participation or success rates in the region or in similar contexts and sectors will be important for finding more effective ways to promote and increase program participation by farmers and forest owners in mitigation and adaptation practices, particularly since investments in hazard mitigation and adaptation have been shown to be cost-effective compared to the costs of disaster response and recovery [30,36,84–87]. Moreover, mitigation and adaptation practices may generate co-benefits that contribute not only to reduced risks, but also to economic gains through increased efficiency and innovation, and additional environmental and social benefits when designed and delivered in a transparent and equitable approach and accounting for potential trade-offs between system processes and components [35]; Locatelli et al., 2015; [88].

5. Conclusions

Our study of agriculture, forest, and rural communities in Puerto Rico and the U.S. Virgin Islands and their response to and recovery from the effects and associated impacts of hurricanes Irma and María brings to light not only a range of environmental, economic, and social vulnerabilities across sectors and scales, but also various examples of and opportunities for reducing risks among farmers, forest owners, and rural communities. With extreme climate events projected to increase and intensify in the Caribbean, and the importance of the agriculture and forest sectors to local livelihoods, food security, and ecosystem services, reducing the risks of future shocks and disturbances to farmers, forest owners, and rural communities and enhancing their capacities to resist, absorb, and adapt to them remains vital.

The findings point to demonstrated and potential pathways to reduce the risks posed by hurricanes and other major disturbances, including enhanced understanding, adoption, and support for effective mitigation and adaptation measures in agriculture, forest, and rural communities; increased flexibility and adaptiveness of official response and recovery policies and programs to accommodate local contexts, capacities, and conditions; and increased and interconnected planning, preparations, and other risk reduction measures at individual, community, organizational, and larger scales. Reducing hurricane and other hazard risks in the agriculture and forest sectors in Puerto Rico and the U.S. Virgin Islands will require open, transparent, participatory, and equitable processes, as well as focused and sustained support at multiple scales.

Notably, sociopolitical will and windows of opportunity in the region seem to be open for this type of paradigm shift, and major fiscal resources already have been designated for post-hurricane recovery in Puerto Rico and U.S. Virgin Islands. Harnessing these resources to advance mitigation, adaptation, and innovation on farms and forests and in rural communities surely will require some reenvisioning or redesign to better fit local contexts, needs, and current capacities. But if well spent and implemented to support hurricane and other hazard risk reduction in the agriculture and forest sectors across the region, they might also contribute to additional social, economic, and environmental benefits, and broader, locally defined goals of poverty alleviation, sustainable development, and climate equity, particularly where integrated with local development decisions, policy agendas, and legal frameworks.

Through in-depth qualitative inquiry and analysis, we derived important information for the design and implementation of ongoing recovery and future risk reduction and resilience efforts within and across agriculture and forestry sectors, rural communities, and island jurisdictions. Information and insights from this study are expected to be useful to other islands and communities in hurricane prone areas with similar social-ecological conditions. Systematic collection of quantitative and longitudinal data on the long term and compounding effects of hurricanes and other hazards and related planning and management cycles in agriculture, forests, and rural communities would be useful for landowners, policy makers, and practitioners focused on risk reduction and resistance, absorptive, and adaptive capacity building. We also recommend future research focused on the uptake and outcomes of mitigation and adaptation strategies and practices to improve understanding of their effectiveness and related tradeoffs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2022.103346.

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