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Hurricane Fiona in Puerto Rico: assessing effects and adaptive responses in agriculture and forestry

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Hurricanes pose risks for agriculture and forestry in regions where successive storms contribute to cumulative effects that hinder recovery and reduce adaptive capacity. Hurricanes also provide learning opportunities, and successive hurricanes provide opportunity to evaluate whether lessons have been applied and if they reduce the negative effects or improve recovery times. In Puerto Rico, hurricane Fiona made landfall on September 18, 2022, while many communities and landscapes were still facing the longstanding impacts of hurricanes Irma and María, major hurricanes of 2017. This study examines the challenges hurricane Fiona posed to the agriculture and forestry sectors in Puerto Rico, drawing on the perspectives of advisors and professionals who support landowners in disaster preparedness and recovery. Through a multi-methods survey (n = 54), we examine: (1) hurricane effects and associated impacts across sectors, (2) barriers to response and recovery, (3) lessons applied from past events, (4) changes in response strategies over time, and (5) differences in perceived institutional capacity by organizational affiliation. Results indicate that many agricultural producers and advisors implemented adaptations based on prior experiences, with notable success. However, preparedness and recovery actions specific to forestry were rarely adopted, revealing a critical gap in disaster readiness and response. While the majority of the respondents viewed the hurricane Fiona response as adequate, some expressed concerns, citing persistent challenges in coordination across government levels. Improvements were noted in communication and non-governmental organization (NGO) engagement since 2017, and many advisors felt their agencies were increasingly equipped to support climate adaptation, with inter-agency collaboration and internal coordination emerging as essential elements. These findings underscore both progress and persistent vulnerabilities in disaster response systems and offer insights for strengthening hurricane resilience in Puerto Rico and other hurricane-prone regions.

KEYWORDS

cyclones, farmers, forest, landowners, preparedness, risk reduction

1 Introduction

Farmers, ranchers, and forest owners in the Caribbean face challenges in maintaining production amid more frequent and severe climate-related disturbances such as hurricanes, drought, extreme heat, and flooding. Hurricanes pose the most significant economic threat to agricultural and forestry systems in this region, causing widespread damage, delaying recovery efforts, and straining institutional resources (Mohan, 2017; Wiener et al., 2020a). In Puerto Rico, the combined effects of hurricanes Irma and María, which hit just two weeks apart in September 2017, left little time for preparation or recovery. Their cumulative effects triggered cascading disruptions that compromised food security, hindered commodity production, restricted access to essential resources, and exposed vulnerabilities that remained unresolved years later (McGinley et al., 2022). When hurricane Fiona struck in September 2022, many agricultural and forest producers were still dealing with the long-term consequences of the 2017 hurricanes, including damaged infrastructure, unreliable electrical grids, and financial hardship (Marcos, 2022). Research on hurricane and other natural hazard impacts and recovery processes in Puerto Rico often does not examine the same populations or subjects longitudinally (Belligoni et al., 2026). This study draws from the experience of agricultural advisors and professionals to assess the effects of hurricane Fiona and adaptive strategies undertaken by producers. By doing so, this study contributes to understanding recovery and risk management processes in the context of cumulative shocks.

The cumulative and recurrent nature of hurricane disturbances underscores the importance of adaptive capacity, defined as the ability of individuals, institutions, and systems to anticipate, prepare for, cope with, and respond to external stressors while maintaining essential functions [Armitage, 2005; Intergovernmental Panel on Climate Change (IPCC), 2023]. It encompasses different social-ecological capacities that together aim to reduce vulnerability to natural hazards' impacts (Adger, 2006; Brooks and Adger, 2005; López-Marrero and Wisner, 2012). In agricultural and forestry systems, adaptive capacity often depends on access to financial and technical resources, effective governance, and robust social and institutional networks (Masud et al., 2017; Rodriguez-Cruz et al., 2021; Silici et al., 2021). At the landowner level, adaptation can take many forms ranging from small-scale changes such as implementing contour farming to control stormwater runoff and erosion, or reinforcing infrastructure such as integrating solar panels, and irrigation systems (Marrero et al., 2022. Rodríguez-Cruz and Niles, 2021). More transformative adaptation examples include shifting from monocultures to diversified cropping systems that are more resilient to wind and flooding, adopting integrated pest and disease management to address post-hurricane outbreaks, and relocating production from highly exposed areas altogether (Rodríguez-Cruz and Niles, 2021). At the institutional and system level, enhancing adaptive capacity typically benefits from coordinated governance, improved disaster preparedness, and policies that support resource access and risk reduction across scales (Silici et al., 2021). Building adaptive capacity among smallholders requires not only technical interventions but also strengthening knowledge sharing, institutional support, and scaling up successful adaptation practices through partnerships and local engagement that reduce vulnerability (Silici et al., 2021; McGinley et al., 2022).

Adaptive capacity may be constrained by a range of internal and external factors. These include limited risk awareness, poor institutional coordination, low trust, insufficient funding and technical capacity, and fragmented decision-making processes, and broader structural conditions that shape the enabling environment for adaptation (Biesbroek et al., 2013; Rodriguez-Cruz et al., 2021; Kidane et al., 2023). Such challenges are well documented in climate-vulnerable contexts and were evident in Puerto Rico after hurricanes Irma and María, where gaps in preparedness and uneven response capacity exposed persistent weaknesses in coordination, information flow, and institutional support, especially for smallholder farmers and forest owners navigating post-disaster recovery with limited resources (Rodríguez-Cruz and Niles, 2021; Marrero et al., 2022; Wiener et al., 2020b; Alvarez-Berrios et al., 2021; McGinley et al., 2022).

In this context, public-sector advisors can play a crucial role as intermediaries facilitating climate adaptation across scales and fortifying collaboration networks among boundary organizations—entities that operate at the interface of science, policy, and practice to facilitate knowledge exchange and decision-making, including local, federal, and university institutions. Positioned at the nexus of research, policy, and on-the-ground practice, advisors provide technical expertise, promote adaptive management approaches, and assist farmers and forest owners in making complex decisions before, during, and after disturbances (Prokopy et al., 2015; Wiener et al., 2020a). More than just information providers, advisors often act as translators, turning complex scientific knowledge into practical, locally relevant strategies that support producer decision-making and resilience (Guston, 2001; Kirchhoff et al., 2015). By bridging gaps between government agencies, universities, and local stakeholders, advisors can strengthen the connection between science and policy, improving knowledge accessibility and fostering trust in adaptation efforts (Feldman and Ingram, 2009; Schattman et al., 2024). Advisors often serve in immediate response and recovery and long-term resilience of productive lands, particularly in regions of high disturbance. They also can play key roles in building networks that support continuous learning, feedback, and innovation across different sectors and scales, helping communities mitigate and adapt in the face of evolving climate challenges (Davis et al., 2014). Understanding gaps between advisor capacity and producer needs is therefore essential for designing effective professional development and outreach programs (Schattman et al., 2024).

In this study, we assessed the challenges hurricane Fiona posed to Puerto Rico's agriculture and forestry sectors from the experience and perspective of agricultural and forestry advisors and documented changes in preparedness and response capacity since the 2017 hurricanes. This allows us to examine recovery and adaptation processes over time under cumulative hazards. Furthermore, it can provide more understanding on the extent to which these cumulative hazards compound and shape adaptive strategies. To do so, we conducted a web-based, nonprobability survey of 54 advisors from seven boundary organizations, to gather information from their perspective and experience on hurricane effects and associated impacts, as well as the adoption and effectiveness of preparedness and recovery strategies by the farmers, ranchers, and forest owners they serve. We also collected information on institutional response and recovery processes, identifying improvements and persisting gaps, and assessed the ability of advisors to support producers in managing hurricane-related risks. Using an exploratory approach, we examined whether perceptions of institutional capacity to adapt to climate events varied by organizational affiliation. The findings from this study advance understanding of adaptive capacity across Puerto Rico's agriculture and forestry sectors across time and highlight the importance of learning from experience, sharing knowledge, and applying lessons learned to enhance long-term resilience to climate-related risks. They also provide insight into the delivery of adaptation support across sectors, including strengths and limitations in support systems and coordination processes.

1.1 Hurricane Fiona context

Hurricane Fiona made landfall in the southwestern region of Puerto Rico on September 18, 2022, as a Category 1 hurricane, according to the Saffir-Simpson Hurricane Wind Scale (Pasch et al., 2023) (Figure 1). The recorded peak sustained winds were approximately 85 mph (75 knots, 140 km/h), with a pressure of 986 MB, although gusts of up to 104 mph (90 knots; 167 km/h) were reported in southern Puerto Rico. The hurricane produced storm surge inundation between 1 and 3 feet above ground level along the southern coast.

While hurricane Fiona caused extensive wind damage, most of the effects from this tropical cyclone were related to rainfall. Its slow translational speed (around 13 km/h or 8 mph) and the abundance of moisture in the atmosphere resulted in significant rainfall across various parts of the island (National Hurricane Center and Central Pacific Hurricane Center, 2022). Rainfall during the event was recorded between 8 to 16 inches (203–406 mm), with higher totals reported in the southern and eastern regions (Pasch et al., 2023). One weather station measured a maximum rainfall accumulation of 824 mm (32.4 inches) between September 17 and 19, exceeding the previous peak recorded during hurricane María in 2017 by 10% (Hernández Ayala and Méndez-Tejeda, 2021; Ramos Scharrón et al., 2023).

Two weeks prior to hurricane Fiona, hurricane Earl passed just north of Puerto Rico, producing heavy rainfall that left soils near saturation across much of the island, with impacts that were primarily environmental rather than infrastructural or economical (Pasch et al., 2023). When Fiona arrived, rivers were running near normal or above-normal levels, further contributing to the flooding risk. The combination of these preexisting conditions and the prolonged heavy rainfall brought by Fiona led to widespread flooding, flash floods, and landslides across Puerto Rico.

Numerous landslides and rockfalls were reported across the island's interior and southern regions. The impacts of Fiona-related landslides continued for weeks after the storm, as tropical rains continued throughout the following month. The excess rainfall on already saturated hillslopes triggered frequent new landslides across various areas of the island (Morales, 2022). These events rendered dozens of structures uninhabitable and affected multiple communities. Infrastructure damage included buildings and other structures

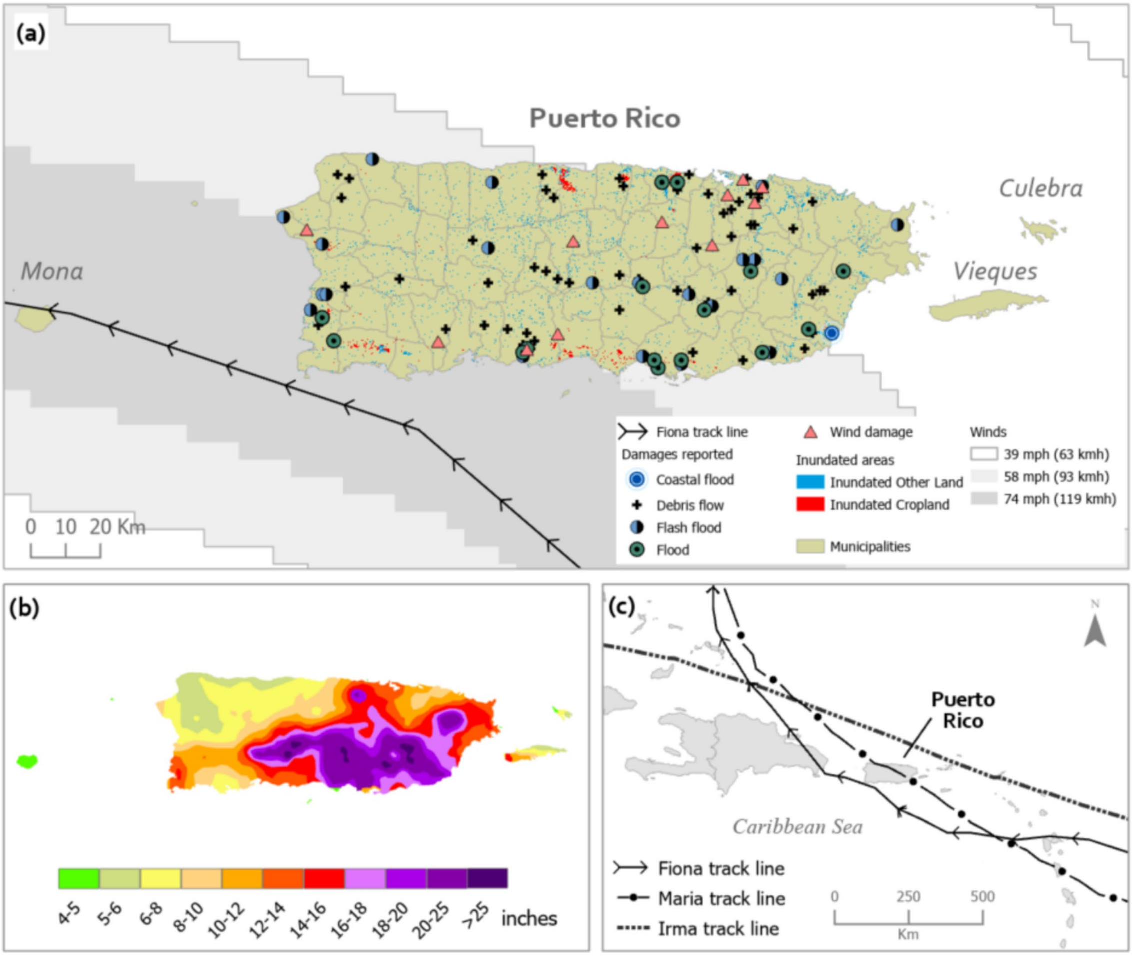

FIGURE 1
Composite figure of study area, Puerto Rico, highlighting: **(a)** hurricane Fiona track, wind swath (National Hurricane Center, 2025), damage reports issued by local the NWS forecast office (09/16/2022 to 9/20/2022) [Iowa Environmental Mesonet (IEM), 2022], and cultivated areas inundated during the event (USDA NASS Disaster Monitoring Team, 2022); **(b)** preliminary rainfall totals, 72 h rainfall accumulation associated with hurricane Fiona (in inches) (9/16/2022 to 09/20/2022) (National Weather Service, 2022); and **(c)** location of the study area within the Caribbean region.

affected by landslides, bridges that were washed away and roads that became impassable due to flooding or debris (Pasch et al., 2023).

Torrential rains and floods, coupled with strong winds, resulted in widespread power outages due to damage sustained by the island's distribution and transmission systems. When Fiona struck, the electric grid infrastructure and generation facilities were still fragile from the damage caused by hurricanes Irma and María in 2017, as well as a 6.4-magnitude earthquake and its aftershocks in 2020. Approximately 1.4 million households (93% of Puerto Rico's electrical users) lost power, and 760,000 experienced interruptions in water service. Twelve days after hurricane Fiona, 17% of households were still without power (U.S. Department of Energy, 2022). The certified death toll attributed to hurricane Fiona in Puerto Rico was at least 33 people (Santos-Lozada and Rivera-Reyes, 2024).

Hurricane Fiona destroyed approximately 90% of crops across Puerto Rico, with total crop losses estimated at $150 million. Roughly 83% of these losses were attributed to farinaceous crops, such as plantains and bananas, and coffee (Puerto Rico Department of Agriculture, 2018). The majority of the damage was concentrated in the west-central (23%) and southern (22%) regions of the island. Losses in the livestock sector, including cattle, milk production, and feed, were estimated at approximately $2.23 million, with 92% of these losses occurring in the southwestern region (Puerto Rico Department of Agriculture, 2018). Although economic damages were primarily attributed to hurricane Fiona, these losses may reflect cumulative environmental, economic and infrastructure impacts from prior events. Hurricane Fiona caused an estimated $2.7 billion (USD) in total damages in Puerto Rico, making it the third costliest hurricane on record for the island since 1980, following Irma and María in 2017 and Georges in 1998 [NOAA National Centers for Environmental Information (NCEI), 2025].

2 Materials and methods

2.1 Study setting, agriculture, and forestry

2.1.1 Agriculture

Puerto Rico is the smallest archipelago of the Greater Antilles (Figure 1), encompassing approximately 9,238 km^2. It is an unincorporated territory of the United States with a population of 3.2 million. The islands' tropical climate, complex topography, and diverse, fertile soils support a wide array of agricultural activities and forest ecosystems. Farmland occupies about 21% of the three populated islands, consisting of croplands (74%), pastures (15%), and a small portion of woodlands (7%). Livestock and poultry products represent the highest gross revenue agricultural products, while major commercial crops include grains and field crops, plantains, fruits, ornamentals, and vegetables [USDA National Agricultural Statistics Service (NASS), 2022].

Despite the diversity of agricultural production, the sector remains relatively small within the overall economy. Agriculture, including forestry and fishing, contributed to 0.7% of Puerto Rico's gross domestic product (GDP) in 2023 (World Bank, 2023). Although locally produced foods such as eggs, plantains and bananas, mangos, and milk play an essential role in the Puerto Rican diet and agricultural commerce (Hernández et al., 2021); as of 2017, total domestic agricultural production accounted for approximately 15% of the island's food demand, with the remaining 85% met through imports, mainly from the United States (Kenner et al., 2023). Though agricultural self-reliance varies across sectors, there is potential to increase local production to decrease dependence on imports (Bezares et al., 2025).

The agricultural sector faces significant challenges due to its vulnerability to hurricanes, which frequently lead to severe crop losses, livestock fatalities, infrastructure destruction, and disruptions in supply chains (Méndez-Lazaro et al., 2023; Gould et al., 2018). The effects of hurricanes Irma and María were particularly devastating, resulting in a decline of over 80% in agricultural production, highlighting the sector's sensitivity to extreme weather events and its limited ability to adapt.

2.1.2 Forestry

Forests cover approximately 53% of Puerto Rico's land area and include subtropical moist, dry, and cloud forests (Marcano-Vega, 2023). These forests are primarily secondary, with stands ranging from young regrowth (~25 years) to older forests exceeding 80 years in age (Martinuzzi et al., 2022). The majority of forests (85.2%) are privately owned, with 11.1% managed by the local government and 3.7% by the federal government (Brandeis and Turner, 2013). Forest inventories suggest there are approximately 40 million cubic meters of commercially viable wood across the island's forests, with higher-quality, large-diameter timber concentrated in the interior moist and lower montane zones (Marcano-Vega, 2017). Despite this potential, Puerto Rico lacks industrial-scale forest product processing infrastructure, and most timber, including that generated by hurricane events, is either left unused, disposed of in landfills, or minimally processed. Exceptions include small cottage or home-based enterprises, led by artisans or sawyers, who harvest and process wood and non-wood forest products for traditional crafts, furniture, musical instruments, and handicrafts (Forero-Montaña et al., 2025).

The lack of wood processing infrastructure and active forest management for commercial purposes became evident after hurricanes Irma and María in 2017 (Forero-Montaña et al., 2025). More than 4.4 million cubic yards of plant material (approximately 70% of it wood) were left unused, and much of it ended up in landfills. This included valuable species such as mahogany (*Swietenia* spp.), teak (*Tectona grandis*), white acacia (*Albizia procera*), yellow acacia (*Albizia lebbeck*), mahoe (*Talipariti elatum*), black olive (*Bucida buceras*), pterocarpus (*Pterocarpus* spp.), white cedar (*Tabebuia heterophylla*), and Spanish cedar (*Cedrela odorata*) (Brinton et al., 2022).

2.2 Survey design and administration

We developed a nonprobability web-based survey to gather information and insights from public-sector agriculture and forestry advisors about the effects and challenges posed by hurricane Fiona in Puerto Rico and associated preparedness, response, and recovery efforts (Supplementary Informations 1). Design of the survey questionnaire was informed by prior research on hurricane impacts and adaptation conducted with agricultural advisors and professionals (e.g., Wiener et al., 2020a; Alvarez-Berrios et al., 2021; Rodriguez-Cruz et al., 2021; McGinley et al., 2022), relevant NRCS and Cooperative Extension publications, and expert consultations. Seven agricultural and forestry experts from boundary organizations including the Natural Resources Conservation Service (NRCS), the

U.S. Forest Service, the University of Puerto Rico Cooperative Extension Service, and the Federal Emergency Management Agency (FEMA) pretested the questionnaire. Their feedback was used to refine question wording, skip logic, and sector-specific response options. The study, associated survey instrument, and related materials were reviewed and approved by University of Puerto Rico, Mayagüez Campus Institutional Review Board (IRB) under protocol #2023020018.

The questionnaire included 20 questions comprising Likert-scale, multiple-choice, and open-ended questions. Several questions were tailored to the producer group(s) served by each advisor (farmers, ranchers, forest owners, all sectors). Skip logic between questions and within response options ensured that respondents only viewed strategies relevant to the producer group(s) they served. For instance, livestock-related preparedness strategies (e.g., 'move livestock from low-lying areas') were shown only to advisors who indicated they served ranchers, while forestry-specific strategies (e.g., 'increase age diversity of trees') were shown only to advisors serving forest owners. Respondents serving multiple producer groups received questions and response options relevant to the groups they served.

The survey questionnaire addressed the following key topics:

1. Effects and associated impacts of hurricane Fiona on agricultural, ranching, and forested lands, as well as on farmers, ranchers, and forest owners.
2. Short-term and long-term hurricane preparedness and recovery strategies, including their perceived effectiveness.
3. Comparisons of preparedness levels and recovery resources for hurricane Fiona relative to hurricanes Irma and María in 2017.
4. Advisors' capacity to provide services following hurricane Fiona.
5. Differences in perceptions of institutional capacity to adapt to climate events across organizational affiliations.
6. Additional resources needed to improve support for farmers, ranchers, and forest owners in future hurricane events.

Because staff lists and contact information were not publicly available for all boundary organizations of interest for this study and in an effort to maximize the likelihood of response, we contacted agency directors, deans, and associate deans and requested their support in distributing the survey to staff involved in hurricane preparedness and recovery efforts. The survey was disseminated by these directors and deans to relevant staff three times between June and October 2023, following the principles of Dillman's Tailored Design Method (Dillman et al., 2014). The survey remained open until January 31, 2024. Participation in the survey was voluntary, and responses were anonymous to maintain confidentiality.

2.3 Quantitative and qualitative data analyses

Quantitative survey data were analyzed using descriptive statistics and non-parametric tests appropriate for ordinal data in Qualtrics and JASP software packages (Qualtrics, 2005; JASP Team, 2025). To assess significant differences in perceived institutional capacity, preparedness, and recovery effectiveness across the different organizational affiliations with which the respondents were affiliated (federal government, local government, university), we employed the Kruskal-Wallis test. This particular test is useful for nonparametric and ordinal data, which was the case for the Likert-scale ordinal responses to these questions from our nonprobability (i.e., nonparametric) sample. When the Kruskal-Wallis test indicated significant differences between organizational groups, we also conducted Dunn's post-hoc tests with Bonferroni correction to improve assessment of the differences between groups. Missing responses in the returned surveys were managed by listwise deletion for each analysis.

Results are displayed in tabular and figure form below. Some quantitative data (e.g., distribution of hurricane effects and associated impacts) are displayed in a descriptive manner, particularly when we sought to characterize patterns across the complete dataset rather than compare or test differences across groups or where the size of subgroups was too small to derive nonparametric statistical inference.

Responses to open-ended survey questions were analyzed using an inductive thematic analysis approach in which themes were derived directly from the data rather than based on predefined categories. One member of the research team reviewed the responses to open-ended questions, identifying recurring themes, concepts, and patterns, which were developed into an initial list of codes. A second member of the research team, reviewed the codes and coded responses and together they refined the coding list through constant comparison and grouping themes into parent and sub codes [e.g., Material resources (parent code), equipment (subcode), basic supplies (subcode)] (Supplementary Informations 2, 6, 7). Subsequently, a member of the research team reread and coded the open-ended question responses, which were reviewed by a second member of the research team. Any discrepancies in coding were resolved by discussion and team consensus. Representative quotes were selected from the open responses to illustrate key themes as presented in the results and discussion.

3 Results

3.1 Description of survey respondents

Fifty-four advisors from six public agencies responded to the survey: federal 43%; local 41%; university 15%; other 2% (Supplementary Information 1; Álvarez-Berríos et al., 2025). The majority were affiliated with the USDA Natural Resources Conservation Service (NRCS) (39%, 21 respondents), followed by the Puerto Rico Department of Agriculture (DAPR) (30%, 16 respondents), University of Puerto Rico Cooperative Extension (15%, 8 respondents), and Puerto Rico Soil and Water Conservation Districts (11%, 6 respondents). Additionally, two respondents were from the USDA Forest Service State, Private and Tribal Forestry (SPTF), and one respondent selected "other" affiliation. Most respondents primarily worked with farmers (43%) and ranchers (41%), followed by private forest owners (20%). Nearly all respondents (94%) were in Puerto Rico during hurricane Fiona's passage.

3.2 Perceived hurricane Fiona's effects and associated impacts

We asked advisors to rank the primary and secondary effects, as well as the associated impacts, of hurricane Fiona on the agricultural, livestock, and forestry lands they work with, or on the farmers, ranchers, and forest owners they serve. These categories were defined to distinguish between direct or primary hurricane effects (e.g., wind, rainfall), secondary effects (e.g., flooding, landslides), and associated impacts, which refer to resulting damages such as fallen trees, damage to infrastructure, and disruptions to transportation, energy, and other public services. Advisors reported that flooding – particularly river swelling and rainfall-driven flooding – was the most severe impact of hurricane Fiona. Eighty-nine percent of respondents rated river flooding as 'devastating' or 'high' effect and 85% indicated the same for rainfall-driven flooding. Strong winds and landslides also were highly reported as causing 'devastating' or 'high' effects (60–66% of respondents) (Table 1). This was followed by flooding due to rain (84.8%), strong winds (65.9%), and landslides (63.8%).

Similarly, advisors identified a wide range of secondary or associated impacts (Figure 2). Electric power outages or failures were

TABLE 1 Hurricane Fiona main effects and associated impacts (scale: no impact/effect, low impact/effect, moderate impact/effect, high impact/effect, and devastating impact/effect; not sure).

Question	Effect/impact	*N*	No (%)	Low (%)	Moderate (%)	High (%)	Devastating (%)	Not sure (%)
Flooding due to river swelling	Secondary effect	47	0.0	2.1	8.5	36.2	53.2	0.0
Flooding due to rain	Secondary effect	46	0.0	2.2	13.0	52.2	32.6	0.0
Power outages or power failures	Associated impact	47	2.1	4.3	21.3	44.7	25.5	2.1
Blocked entrances or exits to farms and wooded lands	Associated impact	46	4.4	8.7	15.2	52.2	17.4	2.2
Fallen trees	Associated impact	47	2.1	8.5	23.4	42.6	23.4	0.0
Strong winds	Primary effect	47	0.0	8.5	23.4	34.0	31.9	2.1
Landslides	Secondary effect	47	6.4	8.5	17.0	40.4	23.4	4.3
Impassable or closed roads	Associated impact	47	2.1	17.0	21.3	40.4	19.2	0.0
Lack of time to work on the farm/field	Associated impact	46	0.0	19.6	21.7	39.1	15.2	4.4
Coastal flooding/ storm surge flooding	Secondary effect	47	10.6	14.9	10.6	42.6	8.5	12.8
Lack of potable water	Associated impact	46	8.7	32.6	21.7	26.1	8.7	2.2
Impacts on the health and well-being of the people served	Associated impact	47	10.6	23.4	31.9	29.8	4.3	0.0
Impacts to technology and tools (e.g., irrigation systems, automatic feeders)	Associated impact	47	10.6	23.4	25.5	31.9	2.1	6.4
Difficulty in accessing or purchasing food after the event	Associated impact	47	14.9	23.4	31.9	23.4	4.3	2.1
Fuel shortages (gasoline, diesel)	Associated impact	47	17.0	27.7	25.5	19.2	8.5	2.1
Communication problems (no phone or internet service)	Associated impact	47	12.8	36.2	23.4	17.0	10.6	0.0
Lack of access to health services	Associated impact	47	17.0	29.8	29.8	14.9	2.1	6.4

Sorted by devastating + high. Effect/impact categories include direct effects (e.g., wind, rainfall), secondary effects (e.g., flooding, landslides), and associated impacts (e.g., fallen trees, infrastructure damage, service disruptions).

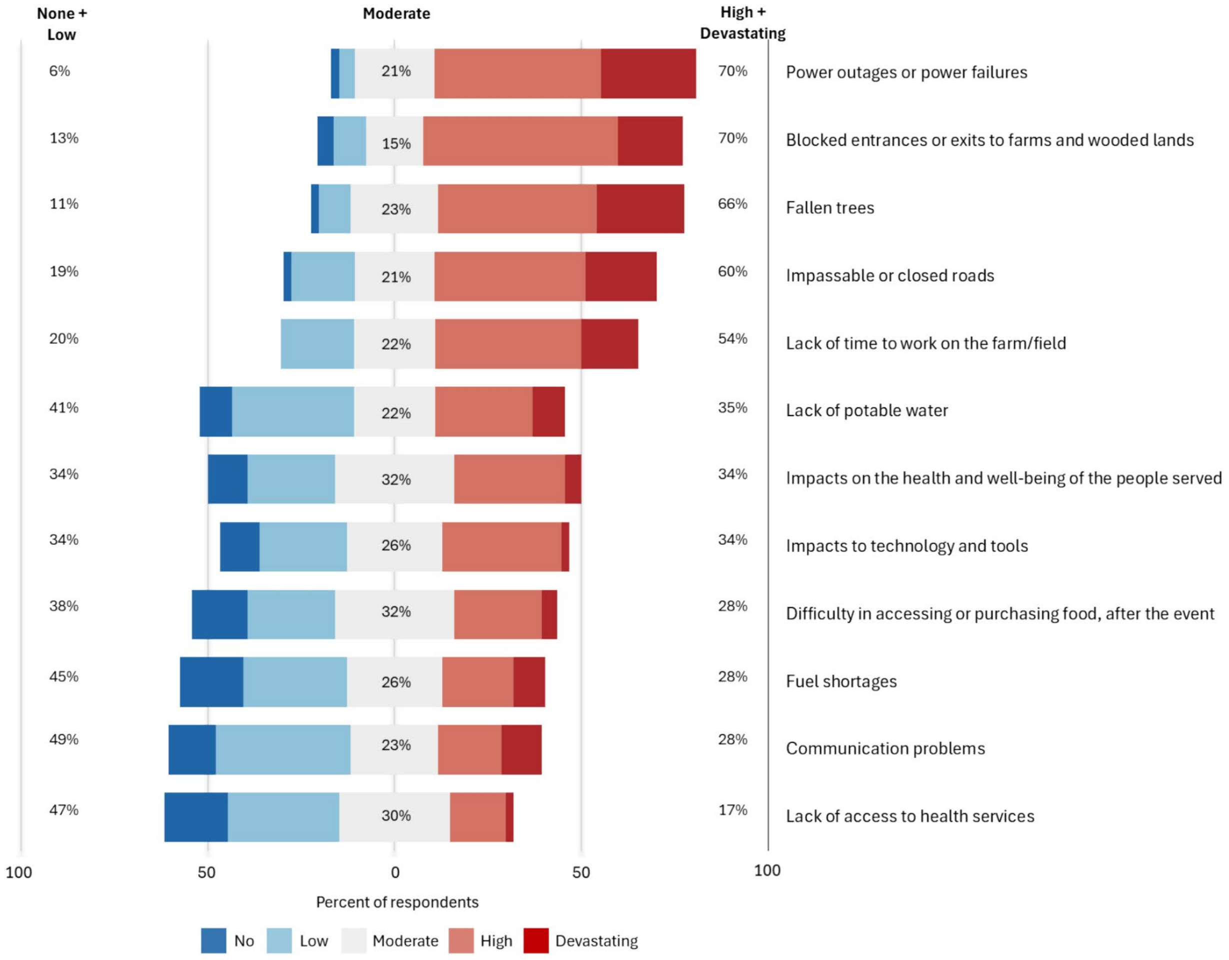

FIGURE 2
Perceived associated impacts reported by advisors on agricultural and forest landscapes, as well as on the land managers they serve. Percentages on the left side of the graph indicate *no or low impact*, those in the center indicate *moderate impact*, and those on the right indicate *high or devastating impact*.

considered to have had a "devastating" or "high" impact by 70.2% of respondents, followed by blocked access to farms and forest lands (69.6%), fallen trees (66.0%), and impassable or closed roads (59.6%). In contrast, communication disruptions (e.g., loss of phone or internet service), fuel shortages (gasoline, diesel), and lack of access to health services were reported as having had "no" or "low" impact by 49.0, 46.8, and 44.7% of respondents, respectively.

Twelve respondents provided additional qualitative descriptions of hurricane effects and associated impacts (Supplementary Information 2). More than half referenced impacts on plants and animals, including animal deaths and heat stress, as well as crop damage. For example, qualitative responses mentioned "elevated post-hurricane temperatures resulted in heat stress in livestock" and "coffee harvest losses were reported; strong winds damaged plantain and banana plantations." Land and soil degradation, including erosion and loss of arable land (e.g., "loss of arable land due to significant erosion"), were also noted. Infrastructure damage, particularly fencing failures (e.g., "fence damage led to livestock movement and subsequent land degradation"), and challenges with damage assessment and recovery processes (e.g., "no formal assessment of crop losses was conducted") were also mentioned.

3.3 Hurricane preparedness

3.3.1 Short-term hurricane preparedness and changes since hurricanes Irma and María

We asked advisors to estimate the percentage of farmers, ranchers, or forest owners who used short-term preparedness strategies (actions taken to prepare for a hurricane that is expected to make landfall in the next week or sooner) prior to Fiona's landfall. We also asked about their perception of whether these strategies worked to mitigate or alleviate the effects and associated impacts of the hurricane and whether the practices were adopted following hurricanes Irma and María.

Seventy-five percent (75%) of advisors reported that a majority (categories *more than 50%* plus *all*) of the farmers, ranchers, and forest owners they serve clients (hereafter clients) stocked up on fuel for generators, and 59% reported a majority of their clients stocked up on potable water in preparation for hurricanes. Other commonly reported practices included removing livestock from enclosures or allowing them to free range (reported by 46% of advisors for the majority of their clients), inventorying livestock (43%), and relocating livestock from low-lying areas (37%). In contrast, most advisors reported that few (i.e., less than half to none) of their clients removed cut wood from forests (reported by 94% of respondents), pruned crops to reduce wind damage (91% of respondents), or pruned trees for the same purpose (81% of respondents) (Figure 3a).

Preparedness varied widely across management categories (Supplementary Information 3). Administrative and planning measures, such as stocking up on fuel or potable water, were reported to

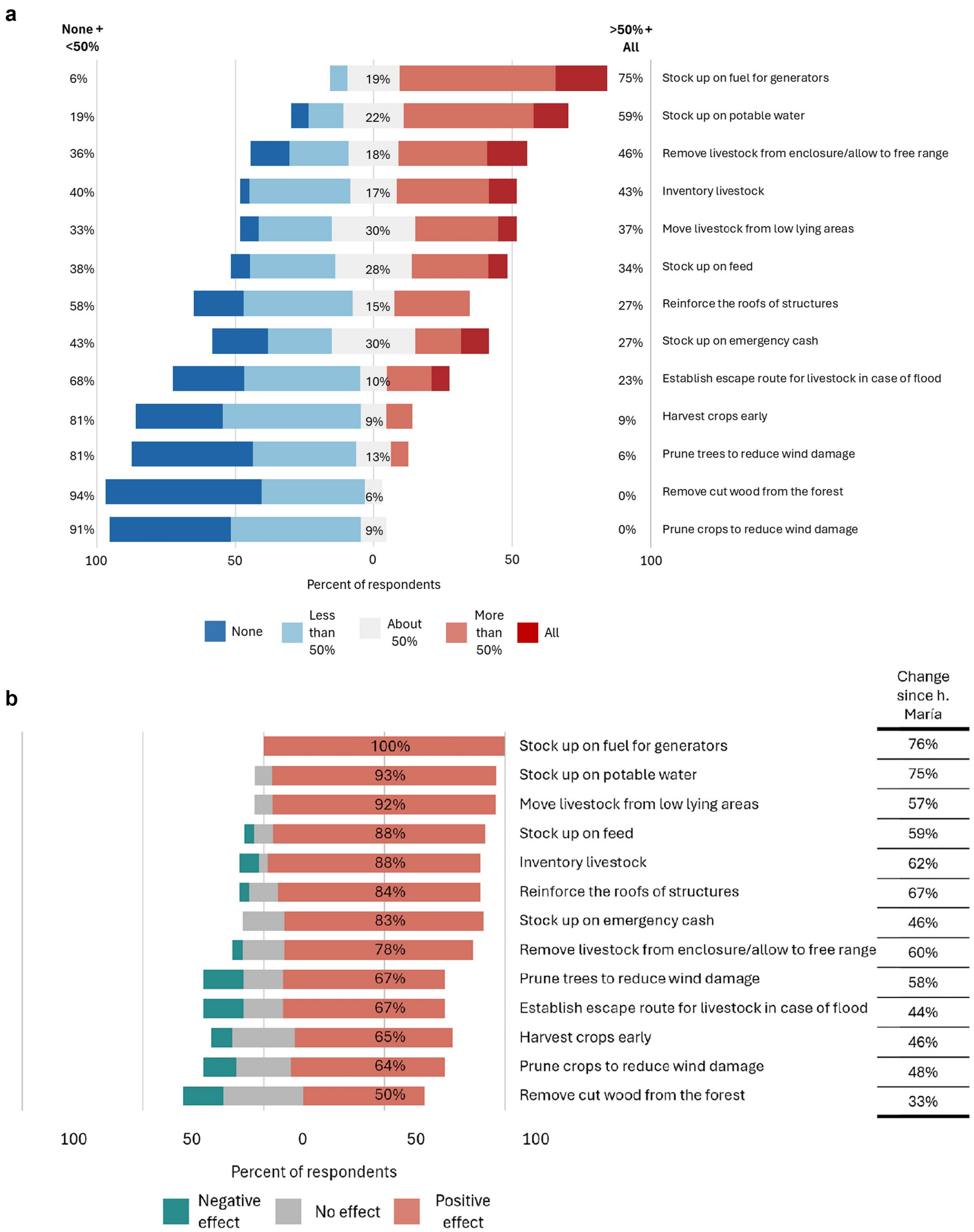

FIGURE 3
(a) Advisors' perceptions of the percentage of land managers utilizing short-term preparedness strategies. Percentages on the left side of the graph indicate *none or less than 50%* participation, those in the center indicate *about 50%*, and those on the right indicate *more than 50% or all*. Response options also included "I do not know." **(b)** Perceived effectiveness of short-term preparedness strategies, sorted by positive effect (bars). Response options also included "No" and "I do not know." The table at the right indicates the percentage of advisors who indicated "Yes" regarding the adoption of short-term preparedness strategies following hurricanes Irma and María.

have been the most commonly adopted short-term strategies, with half of the respondents (50%) indicating that more than 50% or all land managers utilize these strategies. In contrast, crop management and forestry or planted tree strategies were considered to have much lower adoption rates, with more than 85% of respondents reporting that implementation of these strategies occurs in less than 50% or none (Supplementary Information 3).

Advisors shared their perceptions on whether the short-term strategies listed were effective in mitigating the effects of hurricane Fiona (Figure 3b). For all 13 strategies listed, a higher proportion of advisors viewed them as being effective than as having no effect or a negative effect. There was consensus among respondents that *stocking up on fuel for generators* had an overall positive effect (100% of respondents), followed by *stocking up on potable water* (93%), *moving livestock from low-lying areas* (92%), *stocking up feed* (88%), *inventory livestock* (88%), *reinforcing the roofs of structures* (84%), and *stocking up on emergency cash* (83%). There was less agreement on the effect of strategies involving *removing cut wood from the forest* (33% no effect, 17% negative effect), *harvesting crops early* (26% no effect, 9% negative effect), and *pruning crops to reduce wind damage* (23% no effect, 14% negative effect).

A majority of respondents indicated that producers–particularly farmers and ranchers–had improved their preparedness since the 2017 hurricanes, reporting that the following strategies were likely to have been adopted after hurricanes Irma and María: *stocking up on fuel for generators* (76% of respondents), *stocking up on potable water* (75%), *reinforcing the roofs of structures* (67%), *inventorying livestock* (62%), *removing livestock from enclosure or allowing them to free range* (60%), *pruning trees to reduce wind damage* (58%), and *moving livestock from low lying areas* (57%) (Figure 3b). Fewer respondents indicated that other key preparedness strategies had been adopted post Irma and María, *including pruning crops to reduce wind damage* (48% of respondents), *harvesting crops early* (46%), *stocking up on emergency cash* (46%), *establishing escape route for livestock in case of flood* (44%), and *removing cut wood from the forest* (33%).

Open-ended responses describing additional short-term preparedness strategies indicated that some producers implemented alternative measures prior to hurricane Fiona, such as using solar technology to support basic operations ("solar technology for light activities") and inspecting and restoring facilities for managing animal mortality ("inspect and restore facilities for animal mortality management").

3.3.2 Long-term hurricane preparedness and changes since hurricanes Irma and María

We asked advisors to estimate the percentage of farmers, ranchers, or forest owners who used long-term hurricane preparedness strategies (actions taken to protect land from hurricanes that may arrive in the coming months or years), the perception of whether these strategies effectively mitigated or alleviated the effects and associated impacts of hurricane Fiona, and whether such practices were adopted following hurricanes Irma and María.

Among the long term strategies presented, 63 % (63%) of advisors reported that a majority of their clients (i.e., *more than 50%* including *all*) enrolled in crop insurance and 58% believed that more than half had purchased generators (Figure 4a). In contrast, most advisors indicated that only a minority (i.e., l*ess than half* including *none*) of their clients adopted the following strategies: developing better access routes for timber salvage (94%), harvesting trees at economic maturity (90%), constructing emergency shelters for laborers, family members, or animals (90%), adjusting forest species composition to include more wind-resistant trees (86%), and developing additional milk storage capacity (85%).

The highest percentages of long-term practice adoption ("More than 50%" 22% and "All" 7%) were associated with administrative and planning strategies, such as hurricane preparedness plans, crop insurance, and seed banks. In contrast, forestry-related practices, such as adjusting species composition or increasing age diversity, had the highest proportion of non-adoption ("None" 50%), indicating limited implementation across land managers (Supplementary Information 3).

Advisors also shared their perceptions on the effectiveness of the long-term strategies listed for hurricane preparedness (Figure 4b). Nineteen of the 21 strategies evaluated had a higher percentage of advisors perceiving an overall positive effect compared to adverse effects or no effect. All respondents agreed that purchasing generators had a significantly positive effect (100%). This was followed by the *renovation of farm/field buildings for increased wind resistance* (96%), *development of a hurricane preparedness plan* (88%), *establishment of solar energy systems or alternative energy sources* (84%), *contour planting* (83%), *implementation of erosion control and/or landslide prevention practices* (81%), and *crop diversification* (80%). Conversely, certain strategies were deemed to have a negligible or no significant effect. For instance, *increasing the age diversity of trees* was viewed as ineffective by 56% of advisors, while 44% perceived a positive effect. Additionally, *constructing emergency shelters for laborers, family, or animals* had mixed responses, with 48% indicating no effect, 48% indicating a positive effect, and 5% citing a negative effect.

We asked advisors whether the listed strategies were likely to have been adopted after hurricanes Irma and María (Figure 4b). For fifteen of the 21 strategies, more than 50% of respondents reported they were incorporated following these hurricanes. In contrast, six strategies were perceived as unlikely to have been adopted after hurricanes Irma and María, including *planting windbreak tree species* (46%), *developing additional milk storage capacity* (45%), *harvesting trees at economic maturity* (40%), *constructing emergency shelters for laborers, family, or animals* (38%), *adjusting forest species composition to favor wind-resistant trees* (30%), and *increasing age diversity of trees* (25%). For many of these strategies, advisors were unsure whether they represented a change after hurricanes Irma and María.

3.3.3 How do you consider the preparedness of farmers, ranchers, and forest owners for hurricane Fiona compared to hurricanes Irma and María?

Advisors indicated that ranchers and farmers improved their level of hurricane preparedness before hurricane Fiona compared to their level of preparedness for hurricanes Irma and María (Figure 5). Specifically, 79 and 76% of advisors reported that the ranchers and farmers they serve had enhanced their preparedness efforts. In contrast, fewer advisors (39%) indicated that forest owners had improved their preparations since hurricanes Irma and María and prior to Fiona. Twenty-seven percent of advisors (27%) felt preparedness efforts remained the same, while 33% were unsure. Notably, no advisor indicated that preparedness had worsened. A Kruskal–Wallis test indicated a statistically significant difference in perceived

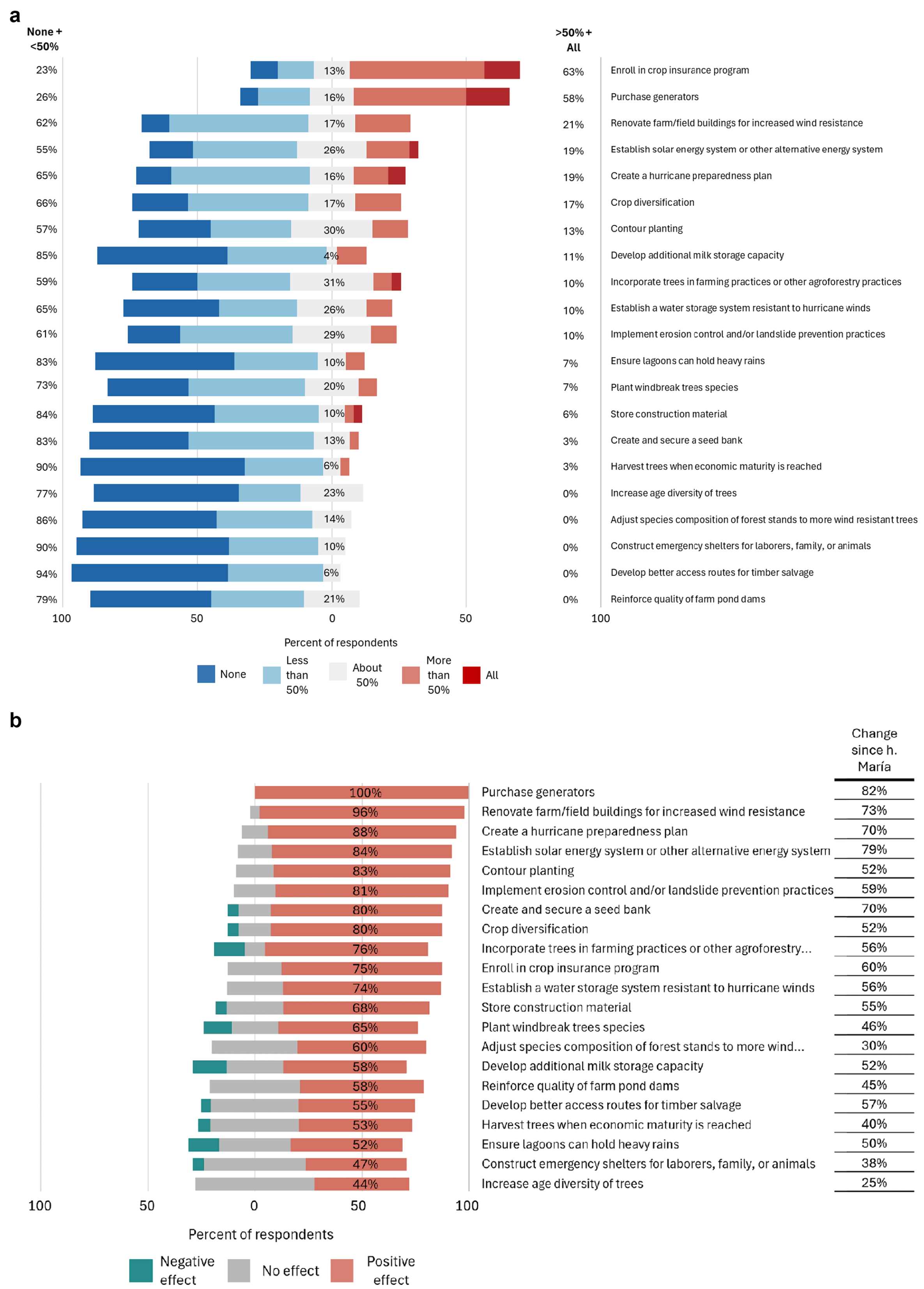

FIGURE 4
(a) Advisors' perceptions of the percentage of land managers utilizing long-term preparedness strategies. Percentages on the left side of the graph indicate *none or less than 50%* participation, those in the center indicate *about 50%*, and those on the right indicate *more than 50% or all*. Response options also included "I do not know." **(b)** Perceived effectiveness of long-term preparedness strategies, sorted by positive effect (bars). Response options also included "No" and "I do not know." The right-hand column provides the percentage of advisors who indicated "Yes" regarding the adoption of long-term preparedness strategies following hurricanes Irma and María.

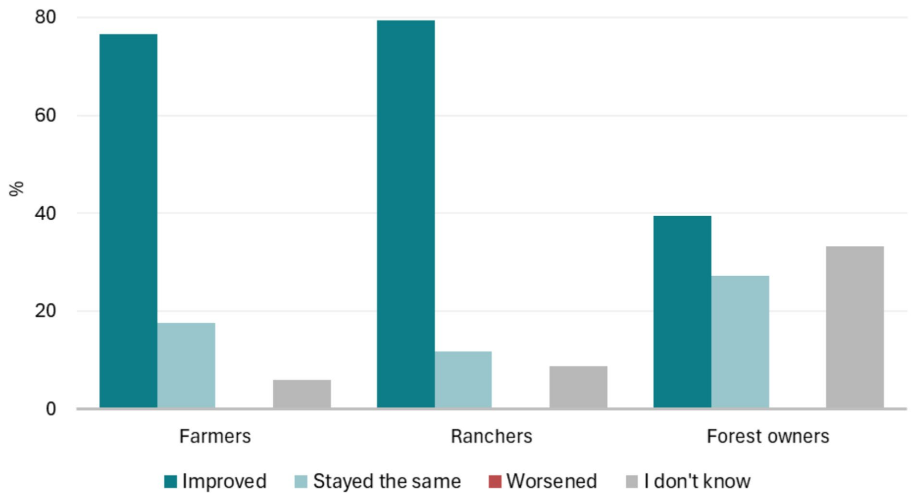

FIGURE 5
Preparedness of farmers, ranchers, and forest owners for hurricane Fiona compared to hurricanes Irma and María. Preparedness differences across groups were significant (Kruskal–Wallis: H(4) = 16.81, p = 0.002).

preparedness across respondent groups, H(4) = 16.81, p = 0.002, suggesting that perceptions varied by group.

3.4 Hurricane recovery

3.4.1 Hurricane recovery strategies: prevalence, effectiveness, and incorporation after hurricanes Irma and María

We asked advisors about the recovery strategies used by farmers, ranchers, and forest owners following hurricane Fiona (actions taken for recovery in the days following a hurricane), their perception of whether these strategies effectively mitigated or alleviated the effects and associated impacts of hurricane Fiona, and whether such practices were adopted following hurricanes Irma and María.

Respondents indicated that farmers, ranchers, and forest owners incorporated a range of recovery strategies following hurricane Fiona. Eighty-three percent of advisors reported that a majority (i.e., more than 50% including all) of their clients made crop insurance claims. Similarly, 83% indicated that a majority applied for official disaster assistance. In contrast, most advisors perceived that only a minority (i.e., less than 50% including none) of their clients adopted the following strategies: consulting a professional forester (86%), salvaging downed trees for timber (79%), reforesting with more hurricane-resistant species (72%), and accessing various markets to sell products (52%) (Figure 6a).

Advisors shared their perceptions on whether the listed recovery strategies helped alleviate the effects of hurricane Fiona (Figure 6b). All eight strategies were viewed more positively than negatively, with more than 65% of advisors agreeing that each had an overall positive effect. Notably, 100% of advisors indicated that applying for official disaster assistance had a positive outcome, and 93% reported the same for making crop insurance claims. Overall, advisors perceived that all recovery strategies represent a change in adoption after hurricanes Irma and María (Figure 6b). For instance, seven of the eight strategies had more than 50% of the respondents perceiving that these were likely incorporated after hurricanes Irma and María.

3.4.2 Level of agreement with statements about recovery resources. How has this changed since hurricanes Irma and María?

We asked advisors about their agreement on various aspects of the post-Fiona response, including communication of recovery assistance, access to recovery resources, coordination of response and recovery efforts, inclusivity of response efforts, preparedness of first responders, and adaptation to local conditions (Figure 7; Supplementary Information 4).

More than half of the advisors agreed or strongly agreed that information on recovery assistance and resources was widely communicated and that the official response and recovery processes engaged nongovernmental and local organizations. Additionally, more than 50% indicated that these aspects have improved since hurricanes Irma and María (Figure 8; Supplementary Information 4). Conversely, more than 50% of advisors disagreed or strongly disagreed that response and recovery processes were well coordinated between local, state, and federal governments and were divided on whether these processes had improved (40%) or stayed the same (40%) since hurricanes Irma and María. For the remaining statements associated with farmer and forest owner utilization of recovery resources, first responder capacity, and adaptation of recovery processes to local conditions and capabilities, advisors expressed more varied opinions without a strong consensus. Likewise, most respondents indicated that these aspects had stayed the same, rather than having improved or worsened since hurricanes Irma and María.

A Kruskal-Wallis test showed a statistically significant difference in perceptions across federal, local, and university groups regarding whether "immediate official response and recovery programs and processes adapted to local conditions and capabilities" had "improved," "worsened" or "stayed the same" after hurricanes Irma and María

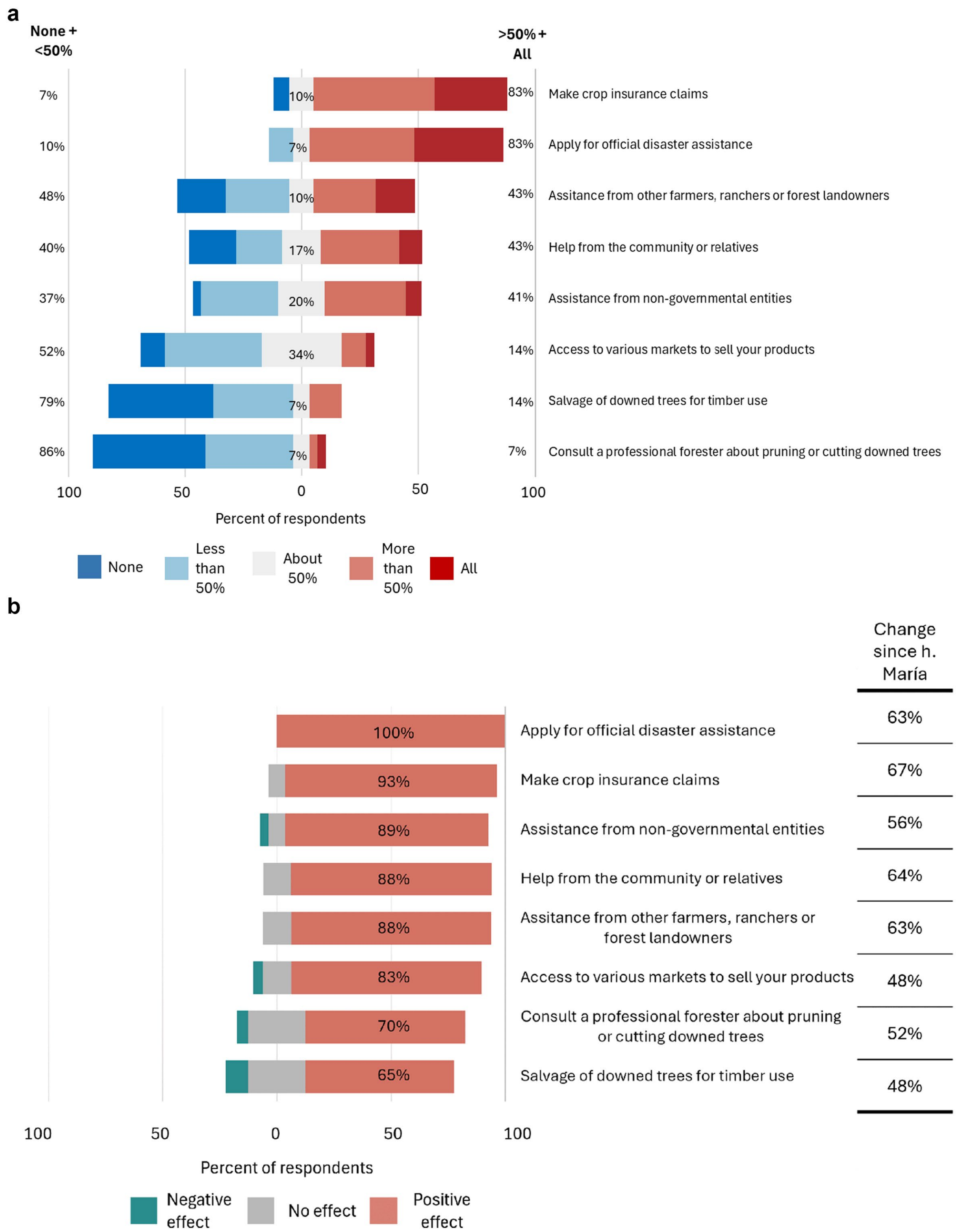

FIGURE 6
(a) Advisors' perceptions of the percentage of land managers utilizing recovery preparedness strategies. Percentages on the left side of the graph indicate *none or less than 50%* participation, those in the center indicate *about 50%*, and those on the right indicate *more than 50% or all*. Response options also included "I do not know". **(b)** Perceived effectiveness of recovery strategies, sorted by positive effect (bars). Response options also included "No" and "I do not know." The table at the right indicates the percentage of advisors who indicated "Yes" regarding the adoption of recovery strategies in following hurricanes Irma and María.

(H(2) = 8.53, $p = 0.014$) (Figure 8). Federal respondents most frequently reported improvements, while university-affiliated advisors were more likely to express uncertainty or indicate that no change occurred.

For the other statements about recovery resources the Kruskal-Wallis test ($p > 0.05$) indicated no statistically significant differences in responses among the three organizational affiliations (Local Agency, Federal Agency, and University). This finding suggests that the three groups generally share similar perceptions or attitudes regarding the topics addressed in these questions (Figures 7, 8).

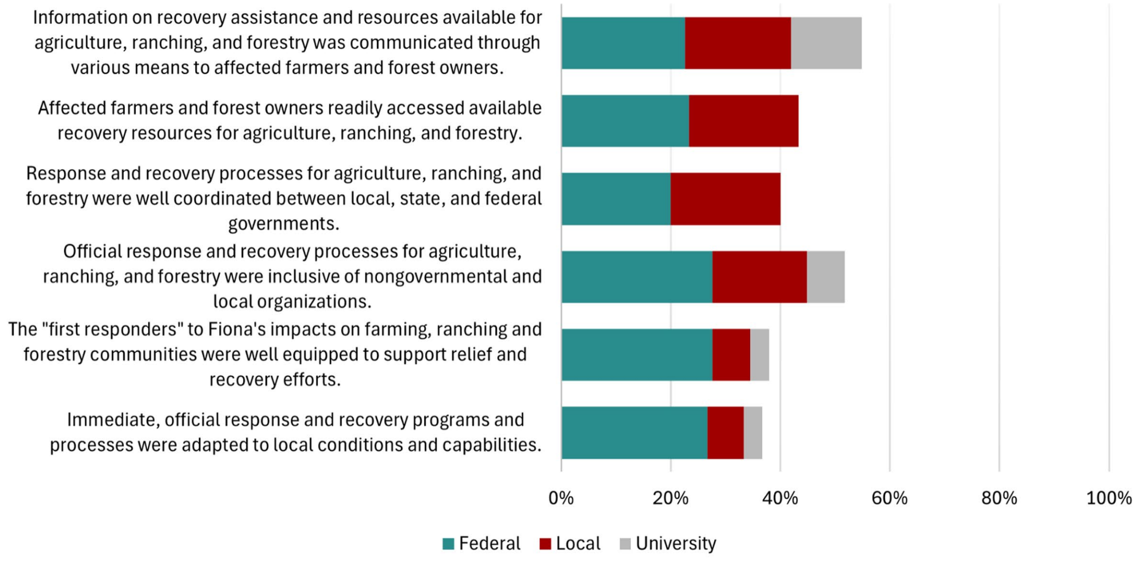

FIGURE 7
Percentage of advisors who "Somewhat agreed" or "Strongly agreed" with each statement regarding post-Fiona recovery and relief resources for the agriculture and forestry sectors. Response options also included "Neither agree nor disagree," "Somewhat disagree," and "Strongly disagree." Bars are segmented by organizational affiliation: Local Agency, Federal Agency, and University.

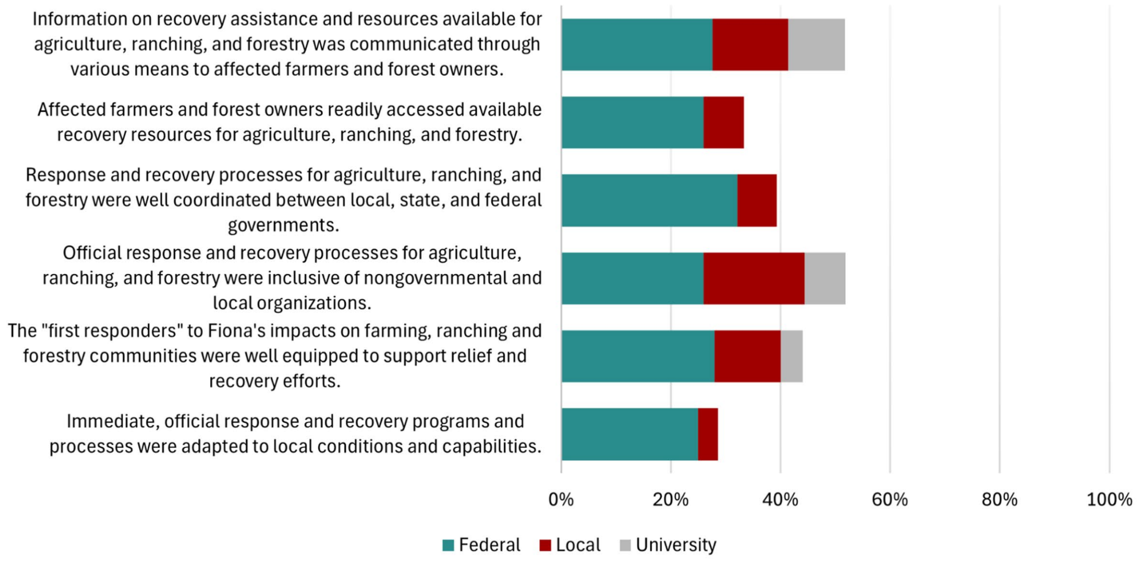

FIGURE 8
Percentage of advisors who reported that each aspect of recovery resources had "Improved" since hurricanes Irma and María. Response options also included "Stayed the same," "Worsened," and "I am not sure." Bars are segmented by organizational affiliation: Local Agency, Federal Agency, and University. Perceptions differed significantly across federal, local, and university groups (Kruskal–Wallis: $H(2) = 8.53$, $p = 0.014$) regarding whether "immediate official response and recovery programs and processes adapted to local conditions and capabilities" had "improved," "worsened," or "stayed the same" since Hurricanes Irma and María.

3.5 Capacity

3.5.1 Agency's ability to provide services that assist farmers, ranchers, and forest owners in preparing for, mitigating, adapting, and recovering from a climate event

Advisors shared their opinions on how well their agencies support farmers, ranchers, and forest owners in preparing for, mitigating, adapting to, and recovering from climate events (Figure 9; Supplementary Information 5). Most respondents (48%) disagreed (*somewhat or strongly*) that hurricane Fiona affected their ability to perform their jobs. Similarly, 68% agreed (*somewhat or strongly*) that their agencies or institutions provided the necessary tools to carry out their tasks during weather-related events. Additionally, 80% of respondents agreed that they have the capacity to help farmers, ranchers, and land managers adapt to climate change. Advisors also agreed that collaboration with other agencies enhances their ability to deliver services effectively (80%), while 87% acknowledged that teamwork within their agency or institution positively impacts their service

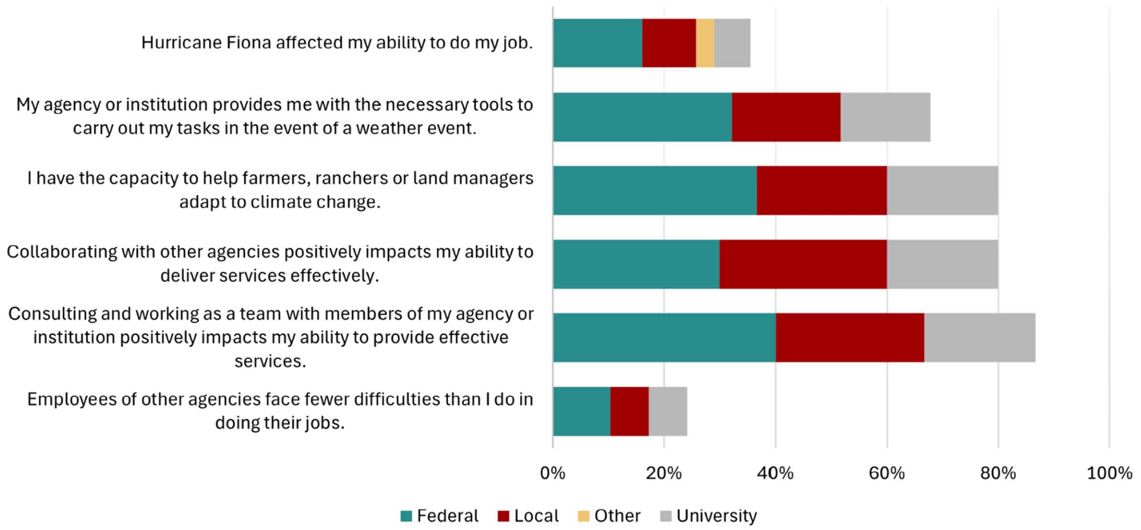

FIGURE 9
Percentage of advisors who "Somewhat agreed" or "Strongly agreed" with statements about their agency's ability to assist farmers, ranchers, and forest owners in preparing for, mitigating, adapting to, and recovering from climate events. Response options also included "Neither agree nor disagree," "Somewhat disagree," "Strongly disagree," and "I do not know." Bars are segmented by organizational affiliation: Local Agency, Federal Agency, and University. One respondent did not report organizational affiliation and is categorized as "Other." This respondent selected "Strongly agree" for only one item; therefore, their response appears only once in this figure.

delivery. However, advisors remained neutral (37.93%) on whether employees of other agencies face fewer challenges in their roles. A Kruskal-Wallis test ($p > 0.05$) indicated no statistically significant differences in responses among the three organizational affiliations (Local Agency, Federal Agency, and University).

3.5.2 What was the biggest challenge you faced in carrying out your work before and after hurricane Fiona?

Qualitative response to the open-ended question: "What was the biggest challenge you faced in carrying out your work before and after hurricane Fiona?", revealed four major categories of challenges faced by respondents related to: infrastructure (31%), institutional (28%), operational (22%), and environmental (11%) challenges (Supplementary Information 6). Infrastructure challenges included limited access to farms and offices due to blocked roads from landslides and fallen trees, as well as widespread utility disruptions. As one respondent noted, "getting to the office and to farms (roads blocked by landslides and fallen trees)" was a major constraint, while others highlighted that "lack of internet, water, and electricity" further hindered their ability to work. These disruptions involved the loss of electricity, potable water, internet service, fuel shortages, and food scarcity.

Institutional challenges primarily involved limitations in emergency funding, bureaucratic delays, and land tenure issues. One advisor remarked: "We attended a large group of requests from people without agricultural activity who registered to participate in programs aimed at mitigating the impact on agricultural activity. And for those who do have agricultural activity, the bureaucracy is eternal; the paperwork is unstoppable since the evaluation of farms at the beginning." Operational challenges involved difficulties in damage assessment and data collection, a lack of established emergency protocols, and a high volume of requests from individuals not directly involved in agriculture. Advisors also noted response and recovery challenges ($n = 2$), including a lack of crop losses censuses (Table 1). Finally, environmental challenges were associated with disruptions caused by flooding, landslides, and wind damage.

3.5.3 What additional resources do you need to better assist farmers/ranchers/forest owners with hurricane preparedness and recovery?

Advisors identified various resources needed to better support farmers, ranchers, and forest owners in preparing for and recovering from hurricanes. These needs fall into five main categories: personnel ($n = 8$), knowledge ($n = 8$), administrative ($n = 8$), material ($n = 5$), and financial resources ($n = 5$) (Supplementary Information 7).

Many advisors emphasized the need for additional field staff and improved staffing across agencies, with one noting that "more trained personnel are needed to visit affected farms". Gaps in knowledge were also identified, including the need for simulation exercises and improved access to information across agencies, as reflected in the comment that "knowing the processes of other government agencies and the required documentation would help us refer the farmer to the appropriate agencies." Material needs included communication devices, appropriate field gear, and weather-resistant technologies to facilitate effective response in adverse conditions. Finally, financial resources were deemed essential, particularly increased funding for assistance programs and coverage for response-related expenses with one advisor noting the need for "pay for expenses such as gasoline and overtime [and] better benefits and labor pay."

4 Discussion

4.1 Hurricane Fiona impacts on agriculture, ranching, and forests in Puerto Rico

Hurricane Fiona brought unprecedented rainfall to Puerto Rico, triggering widespread flooding due to overflowing rivers and prolonged periods of heavy rainfall. Its trajectory over the southwestern region of Puerto Rico, an area with extensive agricultural and ranching activity, resulted in substantial damage to the agricultural sector. Geospatial assessments suggest that nearly 10% of the island's agricultural land may have experienced inundation (USDA NASS Disaster Monitoring Team, 2022).

Agricultural and forestry advisors described widespread direct and indirect effects from hurricane Fiona on agricultural operations. Advisors reported extensive crop losses, particularly in farinaceous crops, including "extensive wind damage to plantain and banana plantations," as well as significant damage to agricultural infrastructure and adverse impacts on livestock systems. Survey responses highlighted multiple challenges including heat stress in animals, livestock fatalities, compromised grazing lands, and damage to perimeter fencing, while qualitative responses to open-ended questions noted that "elevated post-hurricane temperatures resulted in heat stress in livestock" and that fence damage led to livestock movement and further land degradation. These effects were further exacerbated by "numerous landslides blocking roads" that reduced accessibility to farms and the "displacement of arable land due to severe erosion" which in some cases reportedly resulted in loss of productive land.

Fallen trees were among the top five reported impacts of hurricane Fiona. Several respondents indicated that fallen trees obstructed access to farms, offices, or residences. The direct and indirect impacts of fallen trees on agriculture, forestry and rural communities have been increasingly reported across multiple recent hurricanes and flooding events (e.g., Alvarez-Berrios et al., 2021; McGinley et al., 2022), yet few landowners implement forest management actions to reduce the impacts of fallen trees (Brinton et al., 2022). Downed trees along roadways and energy corridors also have been reported as a significant issue post-hurricane but these trees are typically managed by state agencies. As a result, indirect impacts of fallen trees on energy, transportation, and communications may be out of the scope of the agricultural and forestry sectors to mitigate. Post-hurricane management of vegetative debris also represents challenges as current mechanisms and capacity limit utilization or salvage of wood resources that comprise the vegetative debris stream (Brinton et al., 2022).

Other forestry considerations involve post-hurricane reforestation efforts, which may be suboptimum or inefficient where inadequately coordinated or planned. More strategic approaches to post-hurricane reforestation, such as targeted planting in priority areas (e.g., steep slopes, riparian zones, roadside forests, and agroforestry systems) are likely to improve risk reduction but will require enhanced inter-institutional and collaborative strategies that identify shared priorities, align planting with intended ecological and protective functions, and ensure spatially targeted interventions (Gould et al., 2022).

4.2 Effectiveness of preparedness and recovery strategies and comparison between hurricanes Irma and María

4.2.1 Preparedness strategies

Considering the reported impacts from hurricane Fiona, short-term strategies such as stocking up on generator fuel, potable water, and animal feed were regarded as having been effective in mitigating some of the storm's impacts, particularly for ranchers. In contrast to hurricane María, stocked supplies of gasoline, diesel, and fuel in Puerto Rico prior to Fiona were considered sufficient in the immediate response and all ports reopened just three days after the storm without restrictions (U.S. Department of Energy, 2022), making access to critical resources more efficient than after María. In the livestock sector, relocating livestock from flood-prone areas and the inventory of animals were reported to have been both widely used and effective among ranchers. Reinforcing the roofs of agricultural structures prior to the hurricane's landfall was also frequently mentioned as a successful short-term strategy.

Adoption of forest management strategies by forest owners as part of hurricane preparedness was considered to be rare. For example, removing damaged and downed trees from forests, a practice that can help prevent debris-related damage during storms and improve emergency access (Worthley et al., 2024), was perceived to be almost nonexistent and generally viewed as having little relevance to short-term storm preparedness. Limited forest-based mitigation and adaptation strategies reported by advisors in this study likely reflects the island's limited infrastructure and institutional capacity in the forestry sector. Past experiences with timber harvesting in Puerto Rico highlight these limitations, as government agencies often lack the physical and organizational infrastructure needed to recover usable wood (Santiago et al., 2022). Compared to other agriculture and ranching preparedness actions, forest-related strategies may be perceived as more challenging or less cost effective to implement by forest owners and thus may be deprioritized in the face of an approaching hurricane.

Advisors generally agreed that hurricane Fiona prompted an increase in the adoption of most long-term preparedness strategies, although uncertainty remained regarding forestry and infrastructure measures, which were reportedly less likely to have been adopted or recognized as new strategies following María. Forestry preparedness was perceived to be notably low, with approximately half of respondents indicating that few to none of the producers they work with had implemented long-term forest management strategies (e.g., planting wind-resistant species, adjusting species composition, or improving access for post-hurricane wood salvage). This limited adoption of forestry-related preparedness measures likely reflects broader structural and capacity constraints within Puerto Rico's forestry sector, including limited technical assistance, weak market incentives, and a lack of coordinated forest management and wood-processing infrastructure, as documented in previous studies (Brinton et al., 2022; Forero-Montaña et al., 2025).

Enrolling in crop insurance is widely regarded as an essential long-term preparedness and recovery strategy for land managers (Walthall et al., 2013). In Puerto Rico, most farmers rely on the Farm Insurance Corporation of Puerto Rico, a public–private partnership with the USDA Risk Management Agency responsible for assisting farmers in acquiring insurance, assessing hurricane-related damages, and processing crop insurance claims. Qualitative data from open-ended questions indicate that there is widespread frustration among respondents due to significant delays in receiving crop insurance indemnities after hurricanes. These delays could be attributed in part at least to the noted absence of crop censuses necessary for damage verification and insufficient records of farm production and losses. Farmer data from hurricane Maria shows that crop insurance was the most common reported adaptation strategy to be undertaken for future extreme weather events. In that time, accessing insurance funds was among the most common obstacles mentioned by farmers in their recovery processes (Rodriguez-Cruz et al., 2021). Findings from the present study suggest that this support mechanism's operation still requires it to be fine-tuned to clients' needs. Understaffing within agencies and difficulties accessing farms after hurricanes further complicate the claims process. Strengthening collaboration between local and federal agencies could improve efficiency, as current communication and coordination gaps may hinder effective support for farmers.

Backup generators and solar or alternative energy systems have become key components of long-term preparedness strategies for many land managers in Puerto Rico. A 2024 report by the Puerto Rico Association of Farmers indicated that 88% of surveyed farmers have invested in backup power solutions to mitigate the impact of frequent power outages on agricultural operations (Núñez, 2024). That surpasses data from 2018, where around 58% of farmers reported intending to acquire solar panels to adapt to future extreme weather events (Rodriguez-Cruz et al., 2021). Despite these investments, many producers still suffer significant losses due to the unreliable electrical grid, including spoiled crops and milk, damaged equipment, and livestock deaths. The financial burden of these energy systems is particularly challenging for small-scale farmers, leading some to consider abandoning their land. The situation highlights the urgent need expressed by many respondents for more resilient energy infrastructure and accessible support mechanisms to sustain Puerto Rico's agricultural sector.

Overall, advisors noted significant improvements in hurricane preparedness among farmers and ranchers since hurricane María, though forest owners lagged behind. Qualitative data indicate that preparedness strategies were quickly activated, reflecting greater responsiveness. However, it is unclear if this translated into meaningful resilience gains. Key barriers remain, including limited guidance, financial constraints, and reliance on external aid. As one advisor stated: "The preparation of the farmers has improved, but I feel it was not enough. This may be due to a lack of guidance, limited resources, or reliance on provided funds."

4.2.2 Recovery strategies

Advisors identified several key recovery strategies being implemented on productive lands after hurricane Fiona. The most prevalent strategy was applying for official disaster assistance, which was also perceived as highly effective (100% of advisors reported a positive impact following the hurricane). Other support mechanisms, including aid from NGOs, community groups, and fellow producers, were reportedly commonly utilized. Yet, qualitative responses highlighted challenges that landowners faced when navigating official disaster assistance programs after Fiona. Advisors reported that landowners expressed a need for direct recovery support, such as reestablishing access routes, clearing fallen trees, and removing debris. Advisors further underscored the need for a coordinated, multi-agency action plan that could be activated immediately following a disaster to streamline first-response efforts, including "a plan that can be implemented in a structured way and practiced (simulated)." The effectiveness of this type of planning is likely to be enhanced when embedded within sustained, long-term inter-agency coordination that supports both preparedness and response. Respondents also noted that multi-agency recovery planning would benefit from established procedures or protocol for post-hurricane wood salvage, which at the time of this study was neither prioritized nor clearly defined in recovery plans and was not a prevalent strategy. Additionally, respondents highlighted gaps in communication and coordination, calling for "more communication with agencies that provide financial assistance" and the establishment of communication networks between first responders and rural and agricultural communities. Advisors also recommended the development of a centralized information hub for disaster assistance resources, as current information is scattered across multiple platforms. As an alternative, advisors suggested the creation of a comprehensive toolkit that consolidates available resources, enabling landowners to easily identify applicable forms of assistance. Emerging digital tools, including systems that prefill forms or integrate existing data, may further streamline access to disaster assistance by reducing administrative burdens and improving efficiency.

Previous research highlighted the critical role of non-governmental organizations (NGOs) and civil society in the immediate response following hurricanes. After hurricanes Irma and María, these groups proved essential in delivering rapid and flexible relief, facilitating debris removal, and providing vital materials and supplies without the constraints typically faced by government agencies (McGinley et al., 2022). Additionally, farm and forest communities with established collaborative networks prior to the storms demonstrated greater resilience and were more successful in accessing recovery aid and advancing their recovery efforts (Álvarez-Febles and Félix, 2020; Marrero et al., 2022; McGinley et al., 2022). In contrast, communities with limited organizational capacity struggled to navigate assistance programs effectively. The experience of navigating recovery after Irma and María underscored the importance of preparedness and strong local networks. Communities recognized the need to be better connected with fellow farmers, forest owners, and local response and recovery resources to improve resilience in future disasters.

Overall, advisors expressed mixed views on the response to hurricane Fiona. A majority of respondents agreed that information on recovery assistance and resources was widely communicated, and that nongovernmental and local organizations were engaged in response and recovery efforts, both areas seen as having improved since hurricanes Irma and María. However, coordination between local, state, and federal governments emerged as a persistent concern, with over half of advisors expressing disagreement and only about 40% perceiving any improvement since María. Views on other aspects, such as the preparedness of first responders and adaptation of response and recovery processes to local conditions, were more varied. Still, around half of the respondents felt that the accessibility of recovery resources and the availability of equipment remained largely unchanged. These findings suggest progress in communication and stakeholder engagement but highlight ongoing challenges in intergovernmental coordination and resource availability.

The survey results reveal a mix of perceptions regarding changes in response and recovery efforts for agriculture, ranching, and forestry following hurricane Fiona compared to those efforts for hurricanes Irma and María. Most respondents noted improvements in the communication of recovery assistance and the inclusion of nongovernmental and local organizations. However, access to recovery resources and the adaptation of recovery programs to local conditions were largely seen as unchanged. Perceptions of coordination among local, state, and federal governments were divided; some participants recognized improvements, while others felt the situation had not changed. Responses about first responders were also mixed; while many viewed them as well-equipped, opinions were equally split between those who noted improvements and those who observed no change.

4.3 Institutional capacity, challenges, and resource needs

Advisors, regardless of their organizational affiliation, Local Agency, Federal Agency, and University, generally expressed high confidence in their agencies' capacity to assist producers in mitigating, adapting to, and recovering from climate-related disasters. Most respondents agreed that their institutions provided the necessary tools for these efforts. A strong majority emphasized the value of internal teamwork and reported that collaboration with other institutions enhanced service delivery. Notably, nearly half of the advisors indicated that hurricane Fiona did not significantly affect their ability to perform their roles, a marked contrast to experiences during hurricanes Irma and María. In 2017, widespread infrastructure failures, limited access to resources, and personal challenges hindered advisors' ability to respond (Alvarez-Berrios et al., 2021). This enhanced capacity during Fiona points to institutional learning and adaptation since the challenges experienced during María. It may also reflect the comparatively lower severity of Fiona's effects. Additionally, the convergence of perceptions across organizational affiliations suggests potential leverage points and areas of synergy to strengthen institutional cooperation and cohesion. Future research could examine the extent to which this cross-institutional alignment is realized and sustained over time.

Despite reported improvements in disaster response, recovery, and adaptive capacity, several persistent challenges affected service delivery following Fiona, many of which echoed issues reported during previous hurricanes. Accessibility was a major one, with advisors citing blocked roads, transportation difficulties, and delays in reaching producers, similar to the logistical barriers reported by advisors during the 2017 hurricanes, including impassable roads, landslides, lack of 4×4 vehicles, and delayed communication (Alvarez-Berrios et al., 2021; McGinley et al., 2022). In addition, institutional factors further complicated or hindered response efforts. These included delays in the disbursement of emergency funds, bureaucratic inefficiencies, and complications related to land tenure documentation, all of which hindered aid delivery. These challenges mirror previous findings where advisors highlighted "bureaucratic red tape," excessive paperwork, and unresolved land tenure issues as major impediments to effective and efficient post-disaster support (Alvarez-Berrios et al., 2021).

Operational limitations also emerged as a critical constraint. Advisors noted the absence of formal damage assessments, an overwhelming volume of aid requests, including from non-agricultural actors, and the lack of established emergency protocols. As in 2017, there were repeated calls for more field staff, targeted training, and improved inter-agency communication. Advisors emphasized the need for hurricane-specific response manuals, simulation exercises, and standardized assessment tools to improve institutional readiness. Finally, material and financial needs were also prominent. Respondents identified a need for weather-resistant equipment, reliable field communication tools, and additional financial support to cover overtime, fuel costs, and direct farm-level interventions. Enhancing administrative procedures, such as accelerating evaluations and streamlining communication systems, was seen as essential to improving future disaster response capacity.

4.4 Limitations

First, the findings are based on advisors' perceptions, which may not fully capture the experiences of farmers, ranchers, and forest owners. Nonetheless, the advisors surveyed have extensive experience working with farmers, ranchers, and forest owners in Puerto Rico (Supplementary Information 1; Alvarez-Berrios et al., 2021). Second, the sample size is modest, with fewer advisors working in forest landscapes than in agricultural sectors, potentially underrepresenting forestry perspectives. Third, the study relied on a nonprobability sample distributed internally by agency leadership, meaning respondents may not be representative of the broader target population and may over-represent agencies or individuals with stronger internal communication or greater engagement in hurricane preparedness and response.

In addition, qualitative responses were unevenly distributed across organizational types, with a higher concentration from local agencies and fewer responses from federal and other organizations, which may indicate differences in the likelihood of providing qualitative input across groups. The analysis also relied on descriptive statistics (frequencies and percentages) and an inductive thematic approach, both of which involve some degree of interpretation. Furthermore, the survey design was based on previous research (e.g., Wiener et al., 2020a; Alvarez-Berrios et al., 2021) and replicates key questions from these prior surveys to maintain continuity and track changes over time. While this approach supports needed longitudinal analysis, it may limit the diversity of response options. For example, drawing on lessons from prior research, the survey included more long-term than short-term preparedness strategies, which may have influenced how respondents assessed feasibility and effectiveness across different time horizons and sectors. Because the responses represent advisor perspectives, the reported adoption levels may reflect a combination of advisors' professional opinions and their clients' views and practices on the ground.

Finally, the predefined list of impacts focused on those commonly associated with hurricanes in this context and may not capture the full range of possible effects across different production systems (Supplementary Informations 8). Although open-ended responses allowed participants to report additional impacts, expanding the predefined list to include other crop, livestock, and forest-specific effects would strengthen future surveys and support more comprehensive assessments. The study is also context-specific, which may limit its generalizability to other regions or settings. In addition, the study does not explicitly examine broader structural factors, such as policy frameworks, financial constraints, and the organization of the economy and agricultural sector, that may influence investment in adaptation measures. Nonetheless, insights from this paper can inform future work in that regard. Despite these limitations, the study offers valuable insights into advisor perspectives across sectors, particularly in understanding these responses across time. Furthermore, this study's findings can inform the development of training programs for advisors or for general outreach activities that aid their work.

5 Conclusion

Findings from this study demonstrate both progress and persisting constraints in the adaptive capacity of Puerto Rico's agriculture and forestry sectors following hurricane Fiona. Advisors reported that, compared to the 2017 hurricanes, producers were more proactive in preparing for the storm, with increased adoption of practical measures for both short-term and long-term preparedness. These advancements reflect institutional learning and improved readiness at both the producer and agency levels. Across organizational affiliations, advisors expressed confidence in their institutions' capacity to support producers in disaster risk reduction and recovery and noted that inter-institutional collaboration enhanced service delivery, pointing to shared priorities and complementary strengths that could further strengthen coordination. However, persistent gaps in intergovernmental coordination, delays in resource disbursement, bureaucratic inefficiencies, and land tenure complications continue to challenge how producers and institutions allocate limited time and resources across preparedness and recovery needs. Future research could examine the extent to which cross-institutional alignment is realized and sustained, and incorporate direct input from farmers, ranchers, and forest owners through interviews or other participatory approaches to complement advisor-based perspectives.

Despite overall gains, preparedness and recovery efforts remain uneven across sectors. Forest owners, in particular, adopted few sector-specific strategies and recovery actions in forest systems were limited. This likely reflects broader structural challenges in Puerto Rico, including limited technical support for forestry, an underdeveloped wood industry and market, and narrow focus on forests in disaster planning. Another notable challenge is the preference for administrative or planning-based hurricane preparedness strategies over land and resource management and risk reduction practices. These planning-oriented measures may be viewed as more accessible, cost-effective, or incentivized, which likely contributes to their broader implementation across agricultural and forested landscapes. At the same time, this trend suggests that such strategies could be viewed as preliminary steps that precede the implementation of on-the-ground management actions, rather than as endpoints in themselves. This highlights an important opportunity to better support the transition from planning to implementation through targeted technical assistance, resources, and incentives. Collectively, these findings illustrate that how adaptive capacity isas a multi-level condition, dependent on interconnected individual and collective elements.

While many advisors expressed confidence in their agency's ability to support producers, persistent barriers, including complex processes, delayed resource delivery, and limited field accessibility, continue to impede timely and effective response. Although interagency communication and NGO engagement have improved since 2017, coordination between local and federal agencies remains inconsistent and continues to hinder recovery efforts. Findings underscore the need for sustained investment in institutional capacity, locally tailored planning, and cross-sector collaboration. Enhancing adaptive capacity in Puerto Rico's working lands among Puerto Rico's producer groups will depend not only on resource accessibility but also on the ability to translate lessons from past events into coordinated, actionable procedures that support producers before, during, and after hurricanes.

Data availability statement

The data supporting the conclusions of this article are available in the USDA Forest Service Research Data Archive at: https://www.fs.usda.gov/rds/archive/catalog/RDS-2025-0058.

Ethics statement

The studies involving humans were approved by University of Puerto Rico, Mayagüez Campus Institutional Review Board (IRB) and associated survey instrument under protocol #2023020018. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

NÁ-B: Conceptualization, Investigation, Writing – original draft, Visualization, Writing – review & editing, Data curation, Project administration, Formal analysis, Methodology. KM: Visualization, Writing – review & editing, Resources, Validation, Formal analysis, Methodology, Conceptualization, Project administration, Data curation, Supervision. PR-S: Writing – review & editing, Validation, Data curation, Visualization, Methodology, Formal analysis. LR-C: Writing – review & editing, Conceptualization. WG: Project administration, Conceptualization, Supervision, Resources, Writing – review & editing, Funding acquisition.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer HM-V declared a past co-authorship with the XX to the handling editor at the time of review.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1682446/full#supplementary-material

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