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# Tradeoffs and Synergies Across Global Climate Change Adaptations in the Food-Energy-Water Nexus

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**Key Points:**

- This study performed the first large-n assessment of evidence-based adaptations that target food-energy-water (FEW) vulnerabilities
- FEW vulnerabilities share tradeoffs and synergies across adaptation characteristics
- Documented responses to FEW vulnerabilities do not take a nexus approach in planning, implementation, and evaluation

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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## Abstract

Food-energy-water (FEW) systems are increasingly vulnerable to natural hazards and climate change risks, yet humans depend on these systems for their daily needs, wellbeing, and survival. We investigated how adaptations related to FEW vulnerabilities are occurring and what the global community can learn about the interactions across these adaptations. We conducted a global analysis of a data set derived from scientific literature to present the first large scale assessment ($n = 1,204$) of evidence-based FEW-related climate adaptations. We found that the most frequently reported adaptations to FEW vulnerabilities by continent occurred in Africa ($n = 495$) and Asia ($n = 492$). Adaptations targeting food security were more robustly documented than those relevant to water and energy security, suggesting a greater global demand to address food security. Determining statistically significant associations, we found a network of connections between variables characterizing FEW-related adaptations and showed interconnectedness between a variety of natural hazards, exposures, sectors, actors, cross-cutting topics and geographic locations. Connectivity was found between the vulnerabilities food security, water, community sustainability, and response to sea level rise across cities, settlements, and key infrastructure sectors. Additionally, generalized linear regression models revealed potential synergies and tradeoffs among FEW adaptations, such as a necessity to synergistically adapt systems to protect food and water security and tradeoffs when simultaneously addressing exposures of consumption and production vs. poverty. Results from qualitative thematic coding showcased that adaptations documented as targeting multiple exposures are still limited in considering interconnectivity of systems and applying a nexus approach in their responses. These results suggest that adopting a nexus approach to future FEW-related adaptations can have profound benefits in the management of scarce resources and with financial constraints.

## Plain Language Summary

The food-energy-water (FEW) nexus is an emerging field that studies the connections between systems involving agriculture and food, energy and electricity, and water as well as the vulnerabilities of access to and availability of these resources. Understanding the interdependencies between these systems is crucial for decision making to ensure the long-term sustainability of resources considering the impacts of climate change. This study analyzes a data set of documented climate change adaptations that are relevant to the social and environmental vulnerabilities of the FEW nexus. One of our outcomes found that adaptations targeting food security are more robustly documented than adaptations relevant to water and energy security. Additionally, these adaptations share common characteristics such as their associations to cities and

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infrastructure, sea level rise, and deserts. Several of these relationships show potential for mutually beneficial adaptations, while others may negatively impact another system with tradeoffs in their implementation.

## 1. Introduction

Sustainable management of food, energy, and water (FEW) systems is crucial for human development and for meeting the needs of an increasing world population under a changing climate (Albrecht et al., 2018; Conway et al., 2015; Leck et al., 2015; Mpandeli et al., 2018; Rasul & Sharma, 2016). Evidence suggests climate change impacts the FEW nexus, thus putting at risk the viability and sustainability of these systems and introducing vulnerabilities such as food, water, and energy insecurity (Djehdian et al., 2019; Mpandeli et al., 2018; Nhamo et al., 2018; Phetheet et al., 2021; Wang et al., 2021; Zhang et al., 2018). For example, most climate models show that certain regions are already and will continue to experience water scarcity and crop yield loss while others will be hard hit by frequent extreme events, affecting global resilience in the coming decades (IPCC, 2018). Such climate futures require adaptive systems and the development of effective adaptation strategies. As individuals, households, communities, and nations continue to deploy adaptation strategies, it remains crucial to systematically assess adaptation behavior to contribute knowledge to future climate planning decisions using evidence-based and holistic data.

The Paris Agreement and Katowice Climate package rulebook highlighted the importance of documenting global progress on climate adaptation in a systematic and transparent manner (Berrang-Ford et al., 2019; Conway et al., 2015; Tompkins et al., 2018). Numerous studies have showcased adaptation progress (Araos et al., 2016; Canosa et al., 2020; Gagnon-Lebrun & Agrawala, 2007; Robinson, 2018), policy insights (Biesbroek & Delaney, 2020; England et al., 2018; Ulibarri et al., 2022), and best practices for climate adaptation within various regions or sectors. To strengthen this progress, the Global Adaptation Mapping Initiative (GAMI) brought together a network of 126 experts in adaptation research to build the first-ever global stocktake of adaptation responses (Berrang-Ford et al., 2021). These scholars applied machine learning and human screening techniques to systematically screen over 48,000 articles between 2013 and 2019 in Web of Science, Scopus, and MEDLINE for documented evidence of adaptation responses by humans published in scientific literature. They manually extracted information from 1,682 articles to answer questions such as: what climate hazards are driving responses, who is responding, what types of responses are documented, what is the extent of the responses, and is there evidence that responses are reducing risk (Berrang-Ford et al., 2021)? This effort identified the need for systematic analyses at regional and sectoral levels, enhanced understanding of limits to adaptation, and dynamics of adaptation responses to understand synergies and tradeoffs between climate adaptation responses over time (Berrang-Ford et al., 2021). The FEW nexus presents an opportunity for exploring these issues due to the complexity of interactions among and between FEW vulnerabilities (Al-Saidi & Elagib, 2017; Bazilian et al., 2011; D'Odorico et al., 2018; Irwin et al., 2016).

Tradeoffs as a result of adaptation responses appear in the form of maladaptation and limitations, which potentially increase risks in the adaptation of another sector or exacerbate vulnerabilities. In Africa, Asia, and Latin America, maladaptation associated with the FEW nexus has been reported in response to climate-induced droughts resulting in intensive cultivation of marginal lands for food (Afriyie et al., 2018; Hummel et al., 2018; Olivares et al., 2017; Singh et al., 2018), decreased yields from rainfed-dependent agriculture (Murray-Tortarolo et al., 2018; Singh et al., 2018), poor irrigation schemes (Ticehurst & Curtis, 2018), and risks to the loss of livelihoods (Bele et al., 2014; Kronik & Verner, 2010; Villamayor-Tomas & García-López, 2017). On the other hand, adaptation synergies include co-benefits or opportunities that aid risk reduction in other areas or even address multiple vulnerabilities at once. For example, co-benefits have been reported to occur from FEW-related adaptations such as implementing water-use efficiency measures to reduce overall water withdrawals and energy needed for water distribution (Rasul & Sharma, 2016), planting indigenous crops to expand agricultural production areas without increasing water demand (Mpandeli et al., 2018), and renewable energy sources to reduce water demands for electricity generation (Mpandeli et al., 2018). Building upon these case studies, a systematic assessment of FEW-related adaptation responses has the potential to provide a broader understanding of these opportunities by identifying synergetic co-benefits, potential maladaptation, and new insights for future decision making in response to future climatic hazards and vulnerabilities.

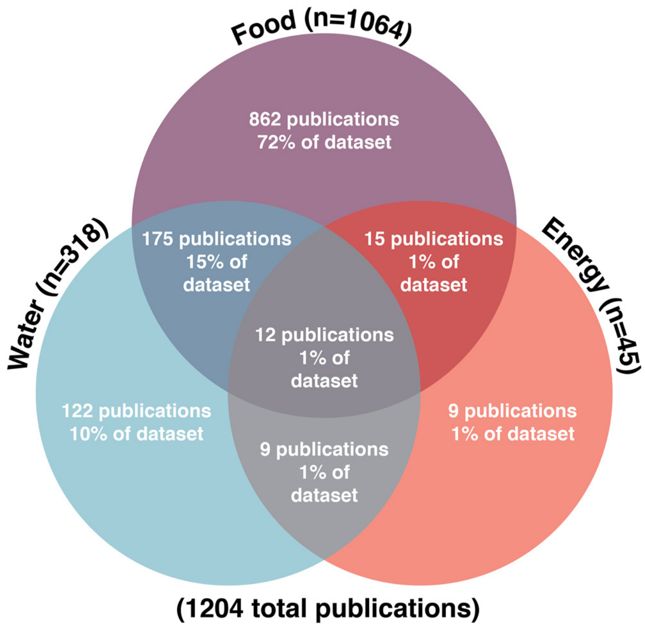


**Figure 1.** An overview of the food, energy, and water (FEW) Global Adaptation Mapping Initiative (GAMI) data set. The overlapping parts of the Venn diagram indicate publications coded as pertaining to two or more vulnerabilities of the FEW nexus.

Climate hazards such as droughts, increased precipitation, sea level rise, rising temperatures, and ocean acidification influence the provisioning of water, food, and energy services to humans and ecosystems worldwide (Conijn et al., 2018; Conway et al., 2015; Howells et al., 2013; Hua et al., 2020; World Economic Forum, 2021). Additionally, certain sectors, particularly agriculture (Campbell et al., 2017; Conijn et al., 2018) and energy (Child et al., 2018; Sala et al., 2016), also contribute to climate change and resource extraction, affecting our ability to live within earth's carrying capacity. At the same time, changes in the Anthropocene, including increased population, migration, and concentration of development along coastlines, have accelerated resource degradation and impacted food and water provisioning (Simpson & Jewitt, 2019). These combined and interactive effects have necessitated the implementation of adaptations targeting the FEW nexus. Documented approaches to adapt FEW systems have primarily considered each of these sectors individually or have considered connections across a small case study, raising concerns about broad counteracting influences and tradeoffs that may occur between systems (Rasul & Sharma, 2016). Existing FEW studies have acknowledged the limited use of FEW nexus approaches when planning, implementing, and appraising development plans and policy (Albrecht et al., 2018; Leck et al., 2015; Liu et al., 2020), suggesting that consideration for the FEW nexus in implementing adaptation to climate change is also limited. To our knowledge, however, this has not been empirically studied systematically beyond individual case studies.

This study provides a quantitative and qualitative analysis of adaptation drivers and their role in addressing the FEW vulnerabilities reported in academic literature. We do this to provide a foundational understanding for future evidence-based adaptation decision making. To achieve this goal, we utilized a subset of the GAMI data set of documented climate adaptations to present the first assessment with a large sample size in scientific literature that synthesizes and analyzes the types, characteristics, tradeoffs, and synergies of climate change adaptations across the FEW nexus. This study presents quantitative and qualitative analyses on a global scale to answer the following research questions: (a) How are adaptations targeting FEW vulnerabilities? (b) What tradeoffs or synergies can be inferred from significant correlations between adaptation characteristics and FEW security? (c) Are there FEW nexus approaches that consider tradeoffs and synergies implemented in the adaptation practices?

## 2. Materials and Methods

### 2.1. FEW Adaptations: Data Set Creation

The GAMI data set (Berrang-Ford et al., 2021)comprising empirical records of adaptation in academic literature from 2013 to 2019 ($n$ = 1,682) was used to create a subset of responses that specifically target FEW security vulnerabilities (Torhan & Grady, 2021). We coded the exposure/vulnerability variables in the original GAMI data set for the following keywords: food security; food insecurity; food scarcity; energy security; energy insecurity; energy scarcity; clean water and sanitation; water security; water insecurity; water scarcity. This resulted in a subset of FEW-related articles ($n$ = 1,204; 72% of the original GAMI data set) consisting of 1,064 food-related articles (88% of subset), 318 water-related articles (26% of subset), and 45 energy-related articles (4% of subset) with overlap between topics as shown in Figure 1. The food-related articles, energy-related articles, and water-related articles were further separated into three additional FEW subsets for a total of four subsets that were analyzed. The detailed protocol for this subset creation, data processing, analyses, and variables used is included in the Supporting Information (Text S1 and Figures S1–S4 in Supporting Information S1; Table S1).

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### 2.2. Characterizing How FEW-Related Adaptations Are Related or Differentiated

The GAMI variables were processed into 78 binary categorical responses/variables (0 not applicable to article; 1 applicable to article) for data analysis (Figure S2 in Supporting Information S1). R statistical software (R Core Team, 2017) was used to perform chi-square tests with a Benjamini and Yekutieli correction to test for statistically significant ($\alpha < 0.05$) associations between categorical responses of all variables and the categorical responses of hazards and exposure/vulnerability for each subset (Figure S3 in Supporting Information S1). The Benjamini and Yekutieli correction was used to correct for type-1 errors while comparing *p*-values across a large number of variables, as it is the most conservative correction and also accounts for possible dependency between variables (Benjamini & Yekutieli, 2001). Categorical responses with less than five observations were excluded from the analyses because of the chi-square test limitation for small frequencies of observations (White et al., 2019). All not applicable or no information categorical responses were also removed from analyses. Cramer's V effect sizes were also calculated to further identify moderate and strong associations between variables (Berkson, 1938). According to Rea and Parker (2014), an effect size is weak or negligible for values between 0 and 0.2, moderate from 0.2 to 0.4, and strong for values between 0.4 and 1.0. The resulting significant relationships with moderate and strong associations from the chi-square tests and Cramer's V associations were visualized by creating network diagrams.

### 2.3. Comparing Relationships of Adaptation Characteristics for Synergies and Tradeoffs Across FEW Exposure Types

We analyzed the correlation between variables by deploying an interactive binary generalized linear model (GLM) in R (Figure S4 in Supporting Information S1). Three binomial GLMs were employed with food security, clean water and sanitation, and energy security as the dependent variables and adaptation characteristics across exposure, hazard, response, sector, actor, cross-cutting topic, implementation phase, geographic region, maladaptation, limits, and risk reduction as the predictors. All not applicable or no information categorical responses and responses with small frequencies of observations (<5) were removed for analysis to correct for perfect collinearity and split probabilities of 0 or 1. Interactions were input to the GLM as identified by the significant chi-square and strong or moderate Cramer's V associations. Interactions that did not return as statistically significant after running the model once were removed to improve model performance. Statistically significant interactions in the model were interpreted as trumping the main effects of either predictor involved in the interaction (Tsai & Gill, 2013). The correlation coefficients of the significant relationships were compared and assessed across the models for potential synergies and tradeoffs between FEW vulnerabilities and adaptation characteristics.

### 2.4. Assessing for Tradeoffs and Synergies Across the FEW Nexus

To further our understanding of whether documented adaptations report consideration for synergies or tradeoffs when targeting FEW exposures, we qualitatively assessed selected articles documenting adaptations at the FEW nexus. We selected these articles by first collecting all records coded as applicable to all FEW exposure types ($n = 12$). To expand this, we added an additional subset of energy-water, food-energy, and food-water articles which included a discussion of co-benefits or maladaptation for a total of 22 articles ($n = 22$). These articles were assessed to answer three questions: (a) What is the nature of the FEW vulnerabilities, and how do they interact? (b) Which FEW vulnerabilities do adaptation responses target and how? (c) What FEW-related tradeoffs or synergies are considered as a result of adaptation responses? These summaries were aggregated to understand where and how synergies and tradeoffs are considered relative to the FEW nexus in adaptation responses.

## 3. Results and Discussion

Out of the 1,204 publications, the highest frequencies of documented literature on adaptations targeting FEW vulnerabilities by continent occurred in Africa ($n = 495$) and Asia ($n = 492$; Figure 2). Food security was the most frequently mentioned FEW exposure across all continents, followed by clean water and sanitation. Adaptations addressing energy security resulted in the lowest number of publications worldwide. These results suggest a global urgency to adapt agricultural and food systems to accommodate a changing climate to meet immediate

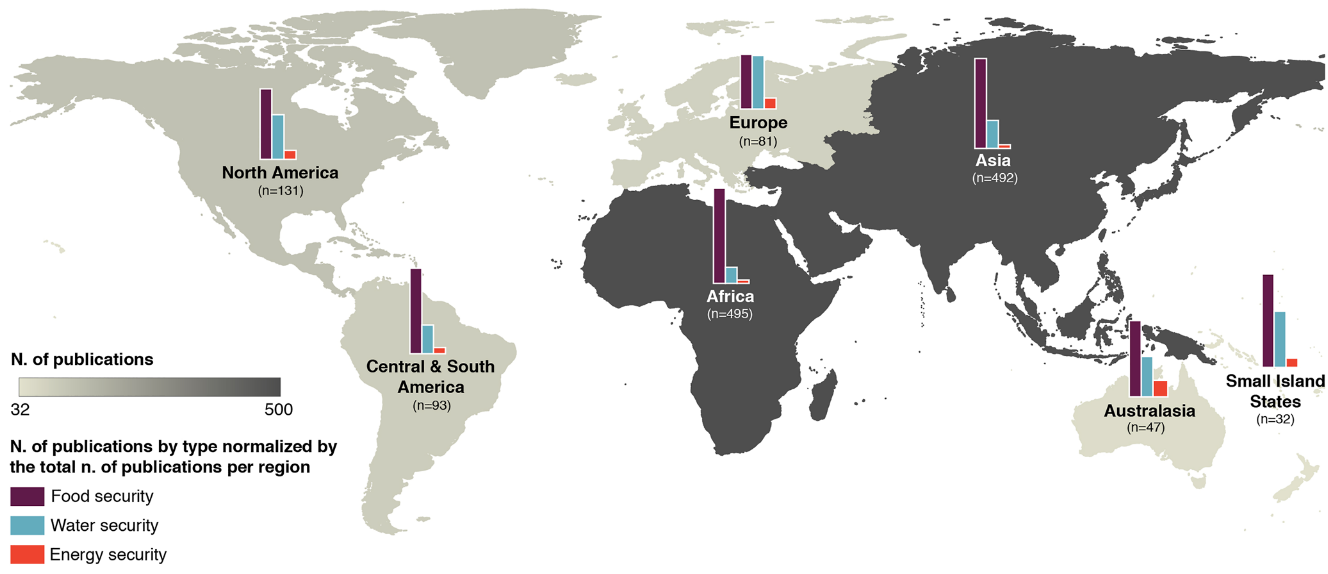


**Figure 2.** Number of publications involving food, energy, and water (FEW) exposure types across continents. The bar charts represent the relative percentages of food security, energy security, or clean water and sanitation related exposures within each continent. The analyzed publications can apply to multiple geographic regions and/or multiple FEW exposures (Figure 1), thus percentages can exceed 100%.

food security needs of vulnerable communities. Exposure to food security is an urgent problem for agrarian communities, resulting in a higher number of on-the-ground adaptations (Mkonda et al., 2018). Additionally, scholars have collaborated with organizations such as the United Nations (UN) Food and Agriculture Organization to produce research focused on understanding household food security, particularly in Africa, which may also contribute to a higher level of formal documentation (Gennari et al., 2019). In addition to this geographic distribution, summary statistics of all GAMI variables included in this study can be found in the Supporting Information (Figures S5–S14 in Supporting Information S1).

### 3.1. How Are FEW Systems Interconnected or Differentiated in Their Adaptation?

Drought, general climate impacts, precipitation variability, and extreme precipitation were the most frequently cited natural hazards in the overall data set (Figure 3). General climate impacts referred to articles where extreme events with no specific hazards are mentioned and overall exhibited that many adaptation records are not specific about the hazards that they are targeting (61%). Precipitation variability (56%) and drought (69%) were relatively more cited for adaptations affecting food security in comparison to other FEW exposures, potentially reflecting the challenges to manage events of more or less precipitation over varying temporal periods for agricultural production. Extreme precipitation and flooding was more frequently cited for energy (53%) and water (54%) related adaptations, which suggests more risk of these exposures during extreme precipitation events. The hazards relating to loss of Arctic sea ice, rising ocean temperatures, and ocean acidification were rarely mentioned as targets for FEW adaptations. This highlights an area of both concern due to the importance of oceans for FEW security (Evengard et al., 2011; Laffoley & Baxter, 2016) and opportunity for future action due to the potential to target climate adaptations across multiple UN Sustainable Development Goals (Pradhan et al., 2017). The loss of Arctic sea ice, changes in ocean temperatures, and sea level rise are drivers of the Gulf Stream current, affecting weather patterns globally (IPCC, 2021). The differences in the frequency of documentation could represent how adaptations target extreme weather events that are directly experienced by communities while not reporting that global warming and oceanic impact could causally also be related. This trend might reflect a gap in understanding of how certain climatic elements affecting risk are coupled to affect one another yet are not being assessed in adaptation responses.

FEW related responses documented in the academic literature are primarily behavioral/cultural (81%; Figure S10 in Supporting Information S1). This is predominately evident for food-related responses, where behavioral/cultural

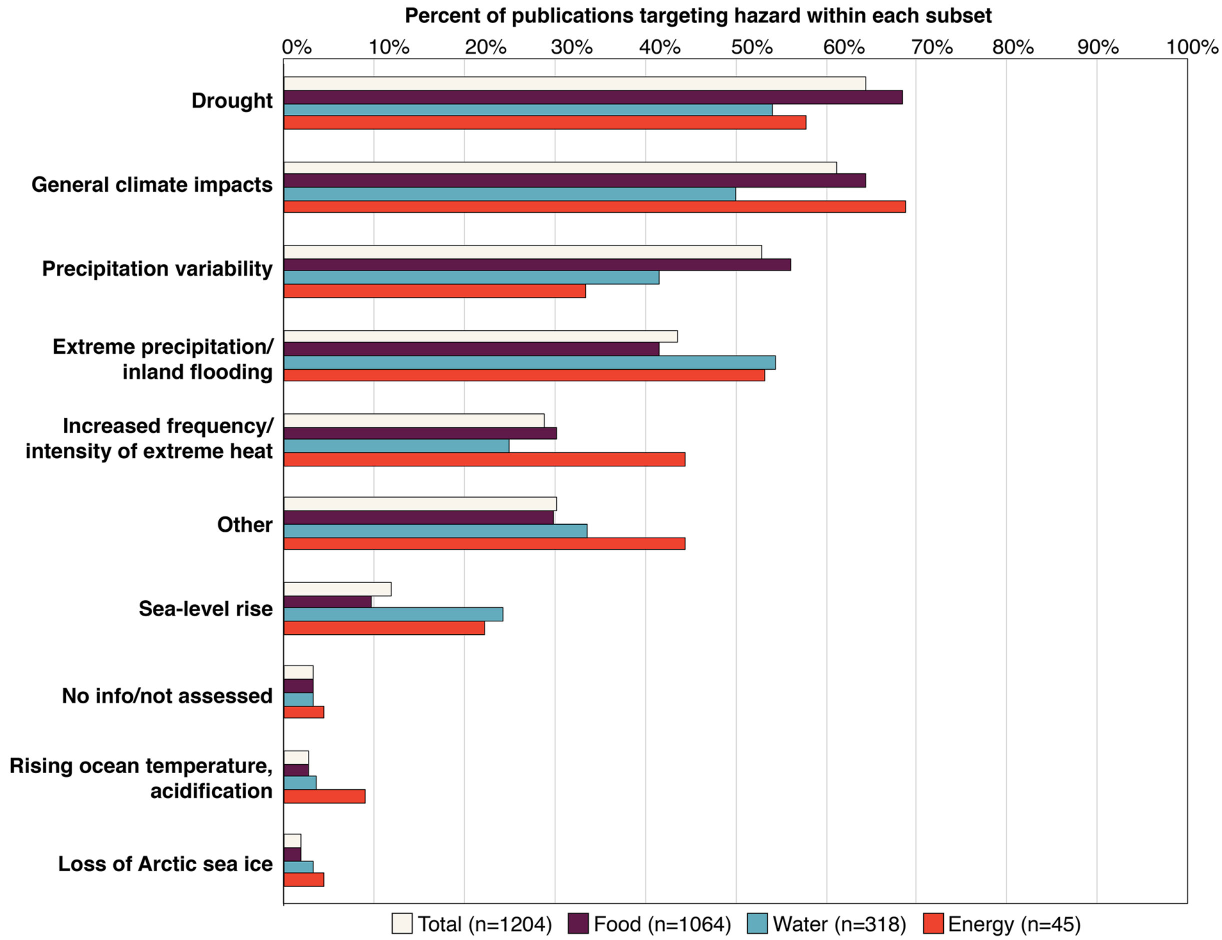


**Figure 3.** Types of hazards addressed by articles. The number of publications for each categorical response were normalized by the number of publications within each respective subset.

adaptations may include actions such as adopting specific drought-resistant crops or changing water conditions (Arku, 2013; Chengappa et al., 2017; Dube et al., 2018; Kattumuri et al., 2017), abandoning fishing for farming (Sereenonchai & Arunrat, 2019), or diversifying income streams to mitigate risks to livelihood (Arku, 2013; Chengappa et al., 2017; Kattumuri et al., 2017). Technological and infrastructural responses and institutional responses were more commonly adopted within the energy (80%) and water (76%) subsets (Figure S10 in Supporting Information S1). The majority of documented adaptations (82%) cited more than one type of response, and almost half of all adaptations (48%) were recorded as having more than two types of responses (Figure 4). The documentation of multi-response adaptations explains the high frequencies distributed across FEW adaptations and represents the implementation of interdisciplinary adaptations, for example, by showcasing the coupling of behavioral/cultural responses with technological/infrastructural responses and ecosystem-based responses (47% and 40%, respectively).

Individuals and households represented the greatest proportion of actors deploying the FEW climate adaptations (Figure 4). Over 90% of the food security adaptations were deployed at the local level by individuals and households. Local governments served as a prominent actor for water and energy responses, particularly in urban areas. For example, to improve access to water, centralized and distributed storage facilities, including detention ponds and storage tanks, were constructed in the city of Kampala, Uganda (Mugume et al., 2016), and local councils in New South Wales, Australia developed and implemented climate adaptation plans (Fallon & Sullivan, 2014). National governments were also involved in roughly half of all water security related responses and approximately 40% of energy security related responses. National government engagement included responses such as top-down policy or institutional requirements (Fallon & Sullivan, 2014) as well as major infrastructure projects

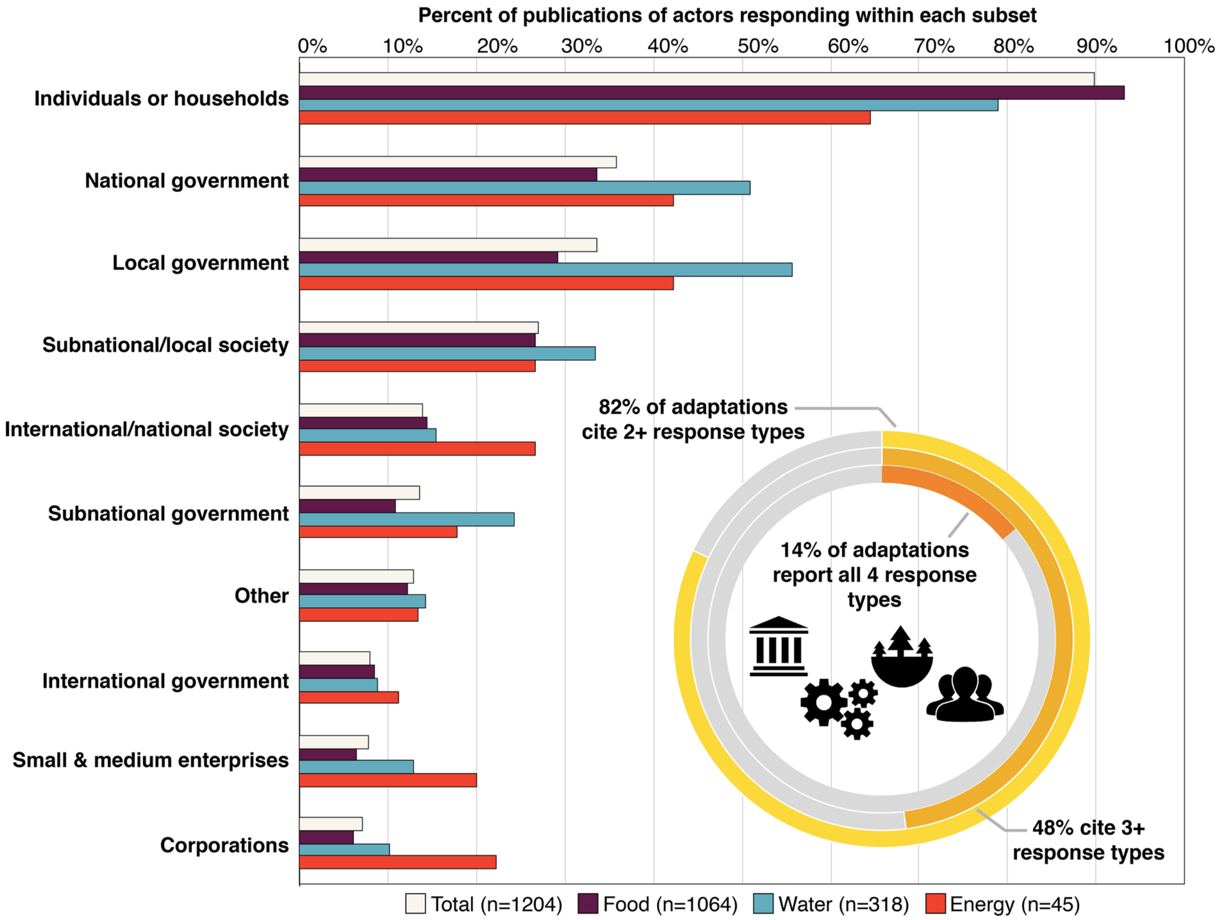


**Figure 4.** Actors and percent of coupled response types involved in adaptations. The number of publications for each categorical response were normalized by the number of publications within each respective subset in the bar charts. The percent of response types reflects the entire food, energy, and water (FEW) subset.

like construction of sluice gates and dykes to prevent saltwater intrusion and inundation from sea level rise (Renaud et al., 2015). Numerous partnerships existed throughout these responses, as shown by the total number of actors exceeding the number of articles. On average, the water security responses had three actors per article, while energy and food averaged 2.8 and 2.4 actors, respectively.

The network visualizations represent all statistically significant associations between adaptation characteristics with moderate or strong effect sizes (Figure 5). The significant associations indicate if categorical responses occur relative or independent of one another beyond what randomly occurs and cannot infer directionality (e.g., direct vs. indirect relationships), only that an association exists. We specifically evaluated these results for network properties such as patterns of interconnectivity and categorical responses with the highest degree of association. For documented FEW related adaptations, sustainable cities and communities, clean water and sanitation, food security, sea level rise, cities, settlements, and key infrastructure, and ocean and coastal ecosystems showed the highest degrees of association (Figure 5a), indicating that these exposures, hazards, and sectors are relatively interesting characteristics across FEW adaptations. For example, a strong, significant association described the relationship between clean water and sanitation and food security, and these exposures shared similar connectivity patterns and associations with other characteristics (i.e., sustainable cities and communities exposure and urban/infrastructural and water/sanitation sectors). Food and water vulnerabilities, as well as sea level rise, showed the highest number of associations with adaptations across cities, settlements, and key infrastructure sectors. The results exhibited a lack of association between food security, drought, and precipitation variability, suggesting that despite the high frequency of adaptations targeting these exposures and hazards, they do not show significance more than expected.

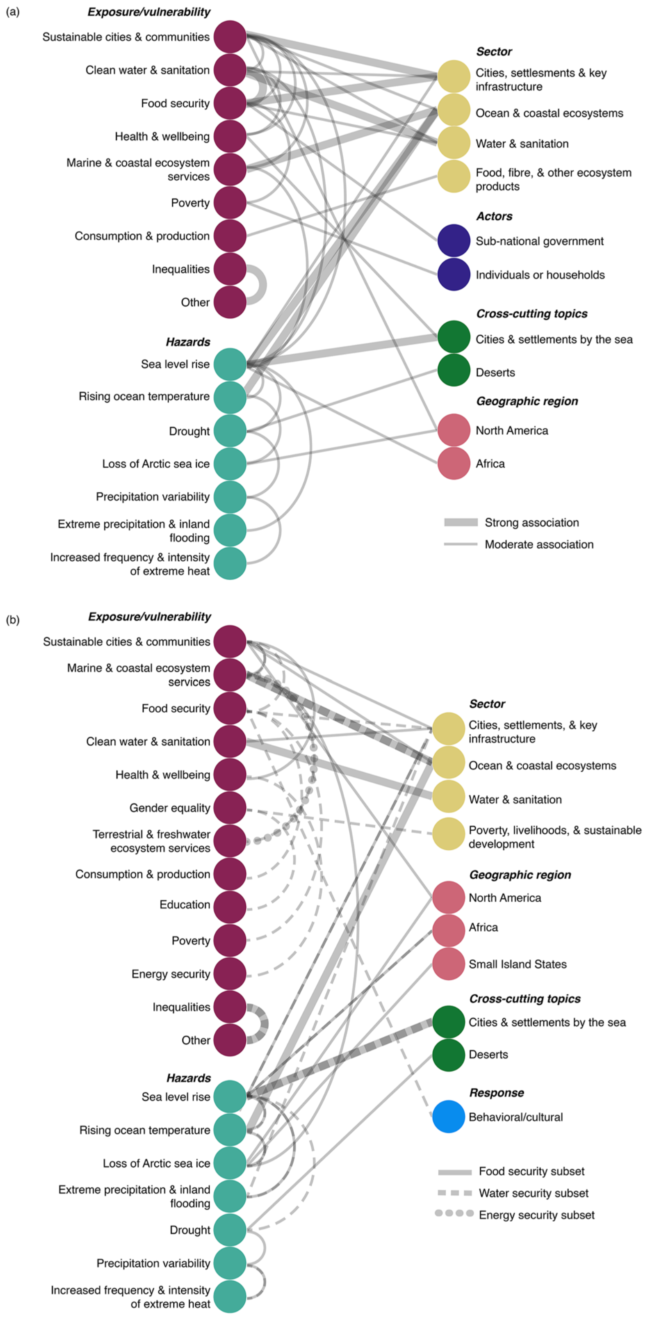


**Figure 5.** Network diagrams showing the resulting statistically significant associations with strong or moderate effect sizes between adaptation variables in the (a) entire subset and (b) the subsequent food, energy, and water subsets. The thick edges represent strong associations (Cramer's V 0.4–1.0) while the thinner edges represent moderate associations (Cramer's V 0.2–0.4).

Given the dominance of the food subset within the majority of the entire subset (88%), the resulting associations from analyzing the food subset alone share the most similarities with the entire FEW subset (Figure 5b). Sea level rise, cities, settlements and key infrastructure, and sustainable cities and communities had the highest number of significant associations in the food and water subsets. This result is backed by examples such as, in Bangladesh, resettlements due to sea level rise resulted in the creation of more sustainable communities with better access to water and food (Islam et al., 2014). In Thailand, both physical barriers and household adaptations such as increasing food storage or switching to flood-resistant crops were adopted to protect against sea level rise (Kulpraneet, 2013). The food and water subsets also had significant associations across sectors, geographic regions, and cross-cutting topics related to adapting to specific vulnerabilities or climate hazards, suggesting that these adaptations are more robustly documented.

The water security subset showed multiple groupings of significant associations between exposures, hazards, and sectors. In this subset, food security had associations with sustainable cities and communities, cities, settlements and key infrastructure, poverty, consumption and production, and behavior/culture response, as well as associations within these exposures. This could be indicative that food security, industries, sustainability, and infrastructure show relation to one another in the face of water insecurity. For example, when prolonged drought events present challenges such as water scarcity, multiple strategies need to be employed to ensure food security and industry in a sustainable manner (Opiyo et al., 2015). Additionally, the improvement of water quality can improve both marine and freshwater ecosystems, and in turn, provide improved resources for fisheries and coastal agriculture industries (Berry et al., 2015). Investing in infrastructure and urban planning for climate change adaptation has been shown to alleviate these stresses on food and water security (Lee & Kim, 2018). A separate component between gender equality having a significant association with the poverty, livelihoods, and sustainable development sector and education vulnerability was also a notable pattern in the water subset. It showcases the associations of additional exposures within adaptations addressing water security. For the energy security subset, due in part to its small size ($n = 45$) compared with the large number of variables, we only found one significant association related to aquatic ecosystems. The complete chi-square results are summarized in the Supporting Information (Table S2).

### 3.2. What Tradeoffs or Synergies Can Be Inferred From Significant Correlations Between Adaptation Characteristics and FEW Exposures?

The statistically significant predictors of the three GLMs are shown in Figure 6, and the full results are included in Tables S3 and S4. Positive correlation coefficients indicate a direct relationship between the predictor and dependent variable, while negative correlation coefficients indicate an indirect relationship. We interpreted these results by identifying statistically significant relationships and their correlation coefficients. A statistically significant predictor means that the independent variable can predict the outcome of the dependent variable with 95% confidence ($\alpha = 0.05$). The magnitude of the correlation coefficient is a measure of the strength or extent of the relationship. Significant interactions are interpreted as moderated statistically significant relationships, or in other words, significant associations between a predictor and dependent variable that would not exist without the presence of the other predictor involved in the interaction. The

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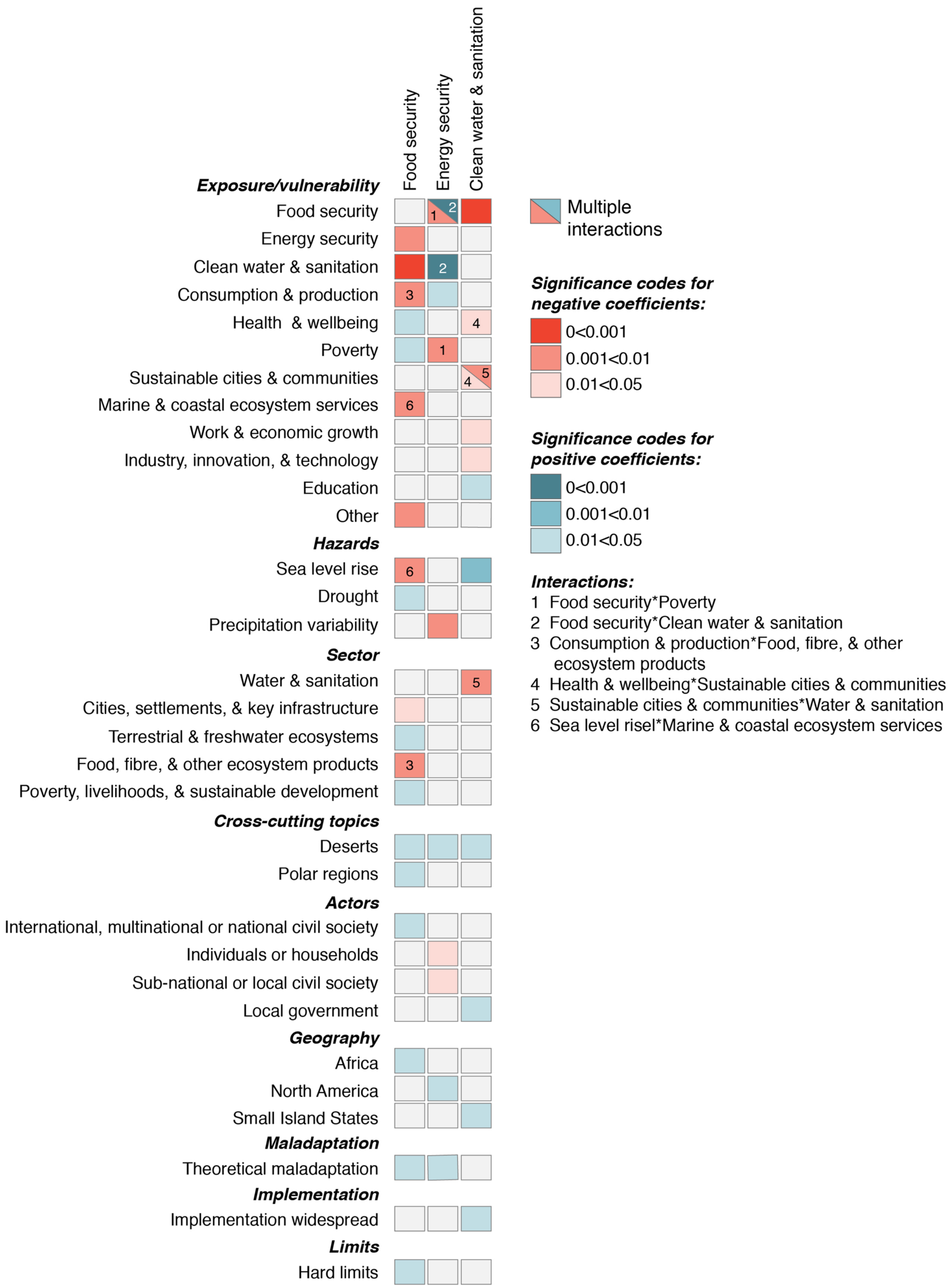


**Figure 6.** Comparison between the three generalized linear models (GLMs) with food, energy, and water (FEW) dependent variables. The blue colors represent positive correlation coefficients while the red colors represent negative correlative coefficients. The footnotes in the columns represent relationships with interactions.

directions of the correlation coefficients across all three models were compared and contrasted for explanations of opportunities for tradeoffs and synergies across FEW vulnerabilities.

The results in Figure 6 showcased that FEW exposures all have varying statistically significant relationships with one another and that FEW vulnerabilities experience synergies and tradeoffs with one another across adaptation characteristics. In both food and water models, exposure to clean water and sanitation and food security had negative coefficients with one another ($\beta$ −3.63; −2.83), showcasing that targeting water vulnerabilities when addressing adaptations relating to food security (and the inverse) are generally not documented together, despite studies recognizing the importance of potential tradeoffs between water withdrawal and increased food production (Ashraf & Routray, 2013; Van Steenbergen, 2006). This highlights a potential for better prioritization and documentation of the interconnectedness of adaptations to consider both water and food security related vulnerabilities. However, in the energy security model, the interaction of food security and water security had a strong positive correlation ($\beta$ 4.56) with energy security, suggesting documented complementary targeting for energy security when the entire nexus is considered.

FEW vulnerabilities also had varying significant relationships across different actors involved in the documented adaptations. The regression results demonstrated that individual and household and sub-national or local civil society actors involved in adaptation have negative correlations ($\beta$ −1.58; −1.31) with energy security, which may indicate that current adaptations targeting energy security have favored infrastructure and technology and more institutional support and are not documenting actions of individual or local actors. In contrast, local government had a positive correlation ($\beta$ 0.50) with clean water and sanitation, aligning with the high frequency of local government actors being involved in responses throughout the water subset (Figure 5) and that municipal and local government actors are generally responsible for water distribution management and assuming responsibility for influencing those responses (Lethoko, 2016; Michalak, 2018). For addressing food insecurity, international civil society was positively correlated ($\beta$ 1.27) with food security, highlighting the importance of international organizations participating in global food security initiatives with local stakeholders (Balaji et al., 2015; Nyantakyi-Frimpong et al., 2019). These results, coupled with the descriptive statistics, revealed that there are opportunities for various actors to collaborate in partnerships to incorporate multiple types of responses that simultaneously address FEW vulnerabilities being exacerbated by the effects of climate change.

All FEW exposures exhibited significant relationships and a positive correlation with deserts ($\beta$ 1.26; 2.21; 0.56), suggesting that adaptations related to deserts predict targeting of any or all FEW exposures. This cross-cutting topic describes this biome from a regional perspective and also may infer anthropogenic changes to biomes in the form of desertification. Deserts and desertification are susceptible to hazards such as extreme heat, precipitation variability, and droughts exacerbated by climate change (Huang et al., 2016). The environmental conditions posed by deserts and semi-arid landscapes have been shown to increase risk to food, water, and energy insecurity from climate change, and these regions are documenting adaptations to meet these needs (Emam et al., 2015; Rubio & Recatala, 2006; Segnon et al., 2020).

While both food security and energy security share statistically significant relationships with consumption and production and poverty, the observed relationships are inverse in their correlations. Consumption and production had a positively correlated relationship ($\beta$ 2.49) with energy security, indicating synergetic documentation between these two exposures. An interaction between consumption and production and the food, fiber, and other ecosystem products sector had a significant relationship with food security with a negative coefficient ($\beta$ −2.91), potentially signifying that adaptation responses occurring in the food and fiber sector may not be directly targeting food security and are more likely targeting industry. Similarly, energy security's relationship with poverty included interaction with food security and resulted in a negative correlation coefficient ($\beta$ −2.86), which predicts that poverty and food insecurity are not addressed when energy security is targeted. On the other hand, adaptations that target poverty are positively correlated with food security ($\beta$ 1.00), indicating mutual consideration of these two exposures. Food security also presented significant associations across a range of sectors, unlike water and energy security, alluding to a diversity of sectors interested in prioritizing food provisioning. These results may suggest competing interests between sectors and FEW exposures.

Implementation widespread was only statistically significant with a positive correlation ($\beta$ 0.85) for adaptations related to clean water and sanitation, which may imply that evidence of adaptations for this exposure is further implemented than others in the FEW nexus. Energy security and food security had a significant relationship and strong positive correlation ($\beta$ 2.71; 2.70) with a theoretical link of maladaptation mentioned or inferred by author or coder, insinuating potential tradeoffs with other exposures or vulnerabilities. Finally, hard or intractable limits had a statistically significant positive relationship ($\beta$ 0.88) with food security, implying that there may be governance challenges, lack of institutional accommodations, or insufficient funding in addressing this exposure.

### 3.3. Are FEW Nexus Approaches Evaluating Synergies and Tradeoffs Considered in the Documented Adaptations?

In the subset of articles documenting multiple food, energy, and/or water exposures as well as maladaptation and/or co-benefits ($n = 22$), the majority of publications included responses that only focused on a single segment of the nexus (Figure S15 in Supporting Information S1). In 14 out of 22 articles, adaptation responses only concentrate on a single vulnerability, even in systems with clear interlinkages. For instance, in response to flooding and sea level rise, households in Sweden are moving fishing sheds to higher elevations, improving insulation of their houses, and installing water purification systems, separately targeting FEW security but not in an integrated fashion (Wamsler & Brink, 2014). Becker et al. (2017) discussed the adaptation of ports for trade that can affect food and energy security with a discussion of the importance of maladaptive considerations but without specific evidence detailing tradeoffs between systems. Several articles reported evidence of several adaptive responses as a case study approach documenting the adaptations but not assessing the cases from a nexus perspective (Lee & Kim, 2018; Li & Song, 2016; Poudel, 2015). Additionally, some of these studies, such as Robinson (2018) and Sovacool et al. (2017), included large-n aggregated adaptation overviews and documented the adaptations by sector but by not considering potential interconnectedness.

For articles that did consider interconnectedness, we found that only five articles were identified as related to the entire FEW nexus and explicitly considered synergies or tradeoffs within the documented adaptations. Four publications discussed water-related adaptations where the goal was to improve food security by diversifying crops (Ashraf & Routray, 2013; Fisher & Snapp, 2014) and more efficient irrigation methods (Chen & Davis, 2014; van Dijl et al., 2015). Two articles discussed energy-related adaptation efforts to enhance food security (Chen & Davis, 2014; Holler, 2014). In Uganda, the National Slum Dwellers Federation has advanced the production of matoke briquettes as a substitution for charcoal to use as household fuel and income generation, which improves food and energy security (Dobson et al., 2015). In a review of coastal cities around the world, decisions to build seawalls were shown to protect both water and energy infrastructure (Azevedo de Almeida & Mostafavi, 2016). As for tradeoffs, the most commonly documented tradeoff related to food or water-based adaptations that increased energy demand. Current approaches to protect coastal water treatment plants from floods often entail using pumps to remove floodwaters and maintain plant operation (Azevedo de Almeida & Mostafavi, 2016). Similarly, increasing water use efficiency via drip irrigation agriculture increases energy costs (Ticehurst & Curtis, 2018). There were also several tradeoffs mentioned in the context of agriculture and food security. For example, Ashraf and Routray (2013) documented that the large majority (over 92%) of farmers in their study adapt to drought by increasing the span between watering orchards leading to smaller size and lower weight fruit with implications to livelihoods and food security. They also highlight the possibility, with support from other scholars, that the provision of subsidized electricity has increased groundwater use, improving agricultural production but leading to a drawdown of the water table and abandonment of surface water irrigation infrastructure, potentially reducing future water security (Ashraf & Routray, 2013; Mustafa & Qazi, 2007; Van Steenbergen, 2006). While there were numerous other tradeoffs described in the articles, no others depicted specific interlinkages between food, energy, or water but instead described impacts to health, ecosystem function, or other sectors. Overall, only two out of the 22 articles described substantially interlinked adaptation responses by taking an interconnected systems approach to analyze policy domains (Andrew & Sauquet, 2017; Lillo-Ortega et al., 2019).

### 3.4. Applying the FEW Nexus Framework to Climate Change Adaptation

The FEW nexus framework evaluates the broader impacts of the current state and development of food, energy, or water systems (Albrecht et al., 2018; D'Odorico et al., 2018). This consideration of broader impacts requires the analysis of tradeoffs and synergies between systems and exposures. The characterization presented in this study utilized statistical associations and qualitative thematic coding to highlight the broader impacts to be considered across the nexus when addressing FEW vulnerabilities in the face of climate change. The potential for tradeoffs and synergies of adaptations targeting FEW exposures is evident from the quantitative and qualitative results

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presented in this study. However, the vast majority of adaptations did not explicitly execute or document these interactions holistically across the FEW nexus.

While records showed multiple vulnerabilities being targeted, the actions primarily focused on individual segments of the FEW nexus and did not utilize an integrated approach, yet an integrated approach can have profound benefits for how we manage these scarce resources, distribute them equitably for adaptation purposes, and preserve them for future generations. Because society is reactively responding to natural hazards and prioritizing the need to meet immediate human needs, the challenge exists to determine who is responsible for proactively implementing a nexus framework that can realistically be adopted when implementing future adaptation actions with geopolitical and financial constraints.

### 3.5. Limitations

The GAMI data set is a collection of documented adaptations to climate change in academic literature that has been tested for adequacy and coherence (Berrang-Ford et al., 2021). However, it is important to acknowledge that this data set may not be inclusive of adaptations documented in gray literature, occurring in non-academia affiliated institutions and organizations, or being realized autonomously. The resolution of the spatial distributions and characteristics of documented FEW adaptations in scientific literature vs. those that are not documented in literature is a limitation of this data set and may be of interest to more completely encompass on-the-ground adaptations.

## 4. Conclusions

In summary, this study presented the first global synthesis analyzing the interconnectedness of FEW security climate adaptation responses. We found documentation of climate adaptation responses occurring throughout the FEW nexus. The large majority of the adaptation responses analyzed related to food security hazards and vulnerabilities, suggesting an immediate need to address the risks of food insecurity. Water-related and energy-related adaptations were documented in far fewer numbers highlighting the need to focus future efforts in water and energy climate adaptation pursuits worldwide. Most FEW-related responses were occurring through individuals and households and exhibited collaboration across actors implementing interdisciplinary responses.

The statistical analyses showcased a variety of significant associations and correlations, indicating potential opportunities for tradeoffs and synergies across adaptations, while the qualitative analysis revealed a lack of actual implementation using a nexus framework assessing this interconnectedness. The implications of these findings are two-fold. The first implication questions whether adopting a nexus approach to adaptation is realistic for vulnerable populations experiencing hardships to meet immediate FEW security needs, such as food security, presenting a challenge to incorporate perspectives across multiple scales. Conversely, the other implication suggests the importance of intentionally applying a nexus framework to capture the broader impacts of FEW adaptations. This effort could ensure adaptations that benefit multiple systems can be efficiently designed or that increase the risk of other systems can be avoided. Both implications amplify the urgency that governments, organizations, and civil society need to act to plan adaptations that optimize the use of funding and resources needed to adapt on larger scales so that individuals and communities are not only in situations to adapt reactively. This reflection also aligns with achieving SDGs that aims to "strengthen the means of implementation and revitalize the global partnership for sustainable development" (Pradhan et al., 2017).

This body of work presents various future opportunities in a way that serves multiple objectives simultaneously and holistically. The quantitative associations and relationships may suggest areas where tradeoffs between two exposures or hazards may occur or opportunities where co-benefits may exist. The same may be inferred in the connection between different sectors or types of adaptations. For example, the urban development and infrastructure and the food, fiber, and ecosystem products sectors share significant responsibility for addressing FEW vulnerabilities and promoting sustainable cities and communities. This suggests that a conscious effort is essential to capture the broader impacts of FEW adaptations, especially within the FEW nexus, so that changes that have potential benefit for all systems can be efficiently designed, and reversely, changes that may cause harm to other systems can be avoided. Finally, future analysis on climate adaptations across scales, at a country or even regional level, could enhance policy and management outcomes relevant to future adaptation planning behavior.

## Data Availability Statement

The data sets for this research are available online at Torhan and Grady (2021)

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