

US farmers’ adaptations to climate change: A systematic review of the adaptation-focused studies in the US agriculture context

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Highlights:

- This review aims to provide a comprehensive view of studies that focused on adaptation to climate change in the US agriculture context.
- Five broad themes are identified based on topical relevance.
- The majority of the studies concentrated on evaluating specific adaptation strategies, followed by exploring potential adaptations.
- Future studies should focus on context-specific solutions for climate-resilient food production and a robust supply chain market by integrating biophysical impacts, innovations, institutional and behavioral factors, and challenges.

Abstract

Farmers in the US are adopting a range of strategies to deal with climate change impacts, from changing planting dates to using sophisticated technologies. Studies on farmers' adaptation in US agriculture focus on a variety of topics and provide an understanding of how farmers adapt to climate change impacts, which adaptation strategies offer better outcomes, and what challenges need to be addressed for effective adaptations. Nevertheless, we lack a comprehensive view of adaptation studies focusing on US farmers' adaptations. A review of the adaptation studies in US agriculture will help us to understand current research trends and realize future research potential. To fulfill this gap, this study systematically reviewed peer-reviewed studies on adaptation to climate change in US agriculture. A systematic search on the Web of Science and Google Scholar platforms generated 95 articles for final review. These studies were categorized under five themes based on their topical relevance: i) reporting on-farm adaptations, ii) exploring potential adaptations, iii) evaluating specific adaptations, iv) challenges of adaptations, and v) perceptions toward adaptations. A skewed distribution of studies under these themes has been observed; a majority of the studies focused on evaluating specific adaptations (47%) followed by exploring potential adaptations (22%), while reporting on-farm adaptations (17%), challenges of adaptations (6%), and perception towards adaptations (8%) received less attention. In this article, key findings under each theme were presented and some areas for future research focus were broadly discussed. These findings indicate the need for more attention to documenting on-farm adaptation strategies and the associated challenges while emphasizing other themes.

Keywords: adaptation, agriculture, extreme weather, climate change, USA

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1. Introduction

Agriculture in the US is vulnerable to climate change impacts. Evidence suggests that because of climate change impacts (e.g., increased temperature, weather variability, extreme rainfall events), the US agriculture is experiencing damage in crop yields (Lobell et al. 2011). Studies found that a higher temperature is associated with decreased wheat yield (Tack et al. 2015), corn yield (Hatfield et al. 2018), and yield variability of maize, soybeans, and sorghum (Schauberger et al. 2017, Kukal & Irmak 2018). Similar to temperature, Lesk et al. (2020) claimed that extreme rainfall of greater than 50 mm/hr could cause a reduction of maize and soybean yield in the US (see also Rosenzweig et al. 2002). Over the next few decades, regardless of future emissions, the average temperature in the US will rise by at least 1.4°C (2.5°F), and the frequency and intensity of heavy rainfall will increase (Easterling et al. 2017, Vose et al. 2017). As a result, by the end of this century, US agriculture will experience more droughts, increased growing season temperature (Wehner et al. 2017), and accelerated rate of soil erosion due to increased extreme rainfall events (O’Neal et al. 2005, Gowda et al. 2018). The outcomes of these perilous scenarios will be severe damage to the crop yield- yield reduction can be more than 30% for some crops by 2100 (Schlenker & Roberts 2009, Rosenzweig et al. 2014). Because the US is one of the top producers of food crops in the world (FAO 2020), the negative impacts of climate change on food crop production will affect national and global food security. Thus, it is vital to ensure that US farmers are adopting strategies to tackle climate change impacts.

The farmers in the US are adopting a range of strategies to deal with climate change impacts. For example, in the northeastern part of the US, farmers adopted conservation agriculture practices along with frost protection measures to tackle weather anomalies- an example of climate change impacts (Jemison et al. 2014, Lane et al. 2018). On the other hand, in the Southeastern part, farmers relied on technological adaptation measures to irrigate their lands and deal with increasing droughts (van Dijk et al. 2015). These adaptation measures helped the farmers sustain or enhance crop yield to some extent, as evidenced by Ray et al. (2012). They found that crop yield increased in some parts of the US while stagnating in some parts. However, in a later work, they argued that current adaptation practices may not be enough to meet the demand in 2050 under changing climate (Ray et al. 2013). Furthermore, Burke and Emerick (2016) found that current adaptations are insufficient to mitigate future climate change impacts.

Studies on climate adaptation in US agriculture focus on a variety of topics ranging from farmers’ on-farm adaptations to scenario-based simulations to working with farmers to explore adaptations. For instance, Schattman et al. (2016) identified several climate change risks associated with on-farm adaptation strategies in Vermont, while many studies focused on adaptation in different climate scenarios (e.g., Chhetri et al. 2010) or irrigation regimes (e.g., Frisvold & Bai 2016). These studies are important to understand how farmers are adapting to climate change impacts, which adaptation strategies provide better outcomes, and what challenges need to be addressed for effective adaptations. Nevertheless, we have limited knowledge of which research areas of adaptation received more attention and which areas require more. Up until now, the review and synthesis articles on adaptation to climate change impacts in US agriculture concentrate on a particular adaptation strategy (i.e., cover crops) (Kaye and Quemada 2017), adaptation potential (Easterling 1996), capacity assessments (Parson et al. 2003), or a specific region (Elias et al. 2019). A review article on the overall adaptation literature in the context of US agriculture can provide knowledge about existing research trends and identify the areas that need to be prioritized. Furthermore, a review article can elucidate how farmers are adapting to climate change impacts across the US, what adaptation actions have been found useful, and what challenges the farmers may encounter. This article aims to address these issues by systematically reviewing the peer-reviewed literature on adaptation to climate change in US agriculture. In the next section, the methods of selecting

peer-reviewed articles are discussed. The results are presented later, followed by a discussion and conclusion.

2. Methods

A systematic literature review (SLR) of the peer-reviewed articles published on climate adaptations in US agriculture has been conducted using the ROSES (Reporting Standards for Systematic Evidence Synthesis in Environmental Research) protocol. The ROSES protocol for SLR is specially designed for conservation and environmental management to synthesize different types of environmental evidence (Haddaway et al. 2018) and it ensures the replication of research. The articles were searched in the Web of Science platform using different combinations of search keywords that are relevant to adaptation to climate change impacts (see Supplementary Table 1). Each of the search queries provided a set of articles. Only the articles that were published between 1980 and 2022 were considered in this study. Duplicate articles were removed and only peer-reviewed English-language articles were included. The focus of this research is on food crops, and thus, only those articles that focused on food crops, such as cereals, legumes, vegetables, fruits, were included and livestock or dairy agriculture-related articles were excluded. In order to ensure maximum inclusivity, articles were extracted from the Google Scholar platform using similar search keywords (see Supplementary Table 1). This study only considered primary research articles and review articles were removed. The search queries and omission of duplicated titles generated a total of 1281 articles for review (Figure 1).

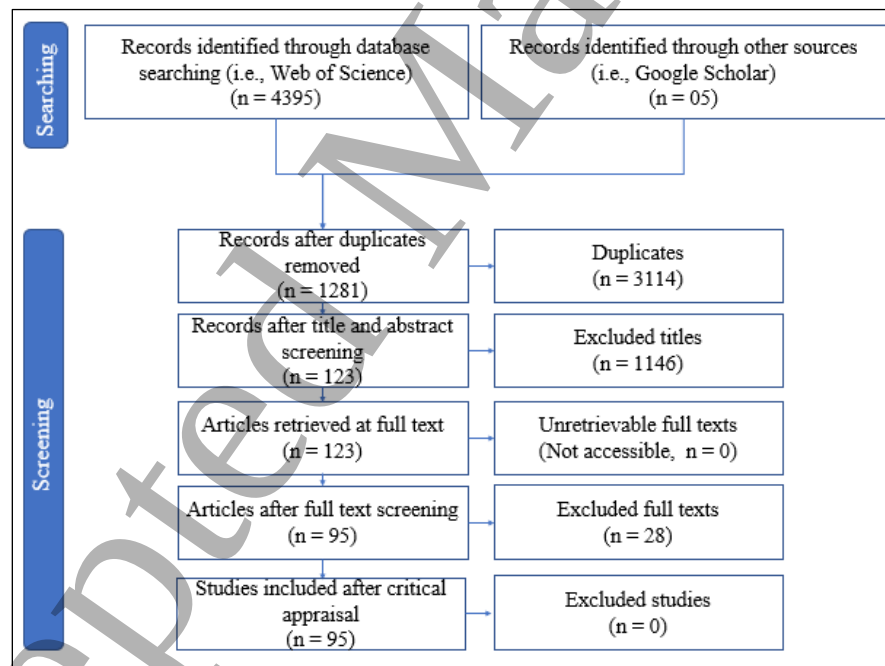


Figure 1: Systematic literature review process based on ROSES protocol.

The SLR process involves a systematic way of including and excluding articles for final review (Haddaway et al. 2014). Hence, a set of inclusion and exclusion criteria were developed based on which relevant articles for the final review were selected (see Table 1). These criteria had been established to ensure the selection of adaptation-related peer-reviewed articles and distinguish between farmers' climate change beliefs versus perceptions and farmers' adaptations, climate change impacts versus adaptation to

climate change impacts, and US-focused studies versus outside-US studies. Based on these criteria, a total of 123 articles were selected for full-text review through title and abstract screening. Later, a full-text review of these articles generated 95 articles relevant to this study’s objectives. Lastly, a critical appraisal was done to filter out articles that were methodologically weak. This final step did not yield the removal of any article for final review. In order to avoid biases, these processes were repeated three times. See Table 1 for details.

It is important to note that there are articles that analyzed climate change impacts (current and future) on agricultural yields but did not focus on adaptation but rather suggested some recommendations or concluding remarks. This study did not consider those articles as they did not examine adaptations. Furthermore, there are articles that focus on conservation agricultural practices (e.g., cover crops, reduced tillage), many of which can be considered adaptation strategies. However, if those articles did not discuss adaptation or frame their argument around it, they were not considered adaptation articles. For instance, Seifert et al. (2018) analyzed the performance of cover crops but did not discuss adaptation; thus, it was not considered in this review.

Table 1: Inclusion and exclusion criteria considered in the SLR

Steps	Inclusion criteria	Exclusion criteria	Accepted	Rejected
Step 1: Title screening	The title of the article includes a topic related to - climate adaptation in agriculture - farmer adaptation - food security - agricultural production AND - weather variability - extreme weather events - climate change The abstract of the article - focuses on agricultural adaptation. - mentions ‘adaptation’ to climate change, weather variability, or extreme weather events. - The study region is the USA.	The title of the article - does not fall within the inclusion criteria. - may include agriculture but no indication of climate change or weather variability, or extreme weather events. The abstract - may focus on agriculture but does not relate it to climate change or adaptation. - did not mention ‘adaptation’ at least once. - focused on the impacts of climate change on agriculture but does not analyze adaptation. - The study region is outside the USA.	123	1068
Step 2: Full-text review	A study that - discusses farmers’ adaptations to climate change, weather variability, or extreme weather events. - explores or evaluates potential adaptation actions. - addresses farmer perception towards adaptations - focuses broadly on agricultural adaptation. - focuses on food crops	A study that - does not emphasize climate change, weather variability, or extreme weather events. - focuses only on climate change belief and perception, but not their relation to adaptation. - does not examine adaptation actions. - focuses on non-food agriculture - is a review article	95	28
Step 3: Critical appraisal	A study that provides sufficient details on the methodology	A study that does not provide enough details of the methodology and thus, the output cannot be validated or is	95	0

		published in a predatory or questionable journal		
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3. Results

The SLR reveals that most articles focused on farmers' adaptations to climate change were published after 2010. Only 6% of the articles were published before 2010, whereas 66% were published after 2015. About 20% of the articles were published in the last two years, indicating a surging trend of research focusing on US farmers' adaptations. Although no particular reason can be attributed with certainty to this surge, one of the key reasons could be the ramping up of climate finance commitment by developed countries in 2009 which might lead to a greater interests in climate adaptation by US researchers. Figure 2 presents the number of articles published over time. This study further analyzed which states and regions received more attention by adaptation studies and found that the Northwest part of the US, comprising Washington, Oregon, and Idaho, received the greatest attention, followed by the Midwest and Southeast. Some of the states in the Northeast part and Southwest parts received more attention, such as New York, Vermont, and California. In the Northern Plains, the eastern states were of focus as the western part is mountainous. Notably, despite having large areas under food crop production, Texas and Oklahoma received little attention. Figure 3 depicts the distribution of adaptation studies.

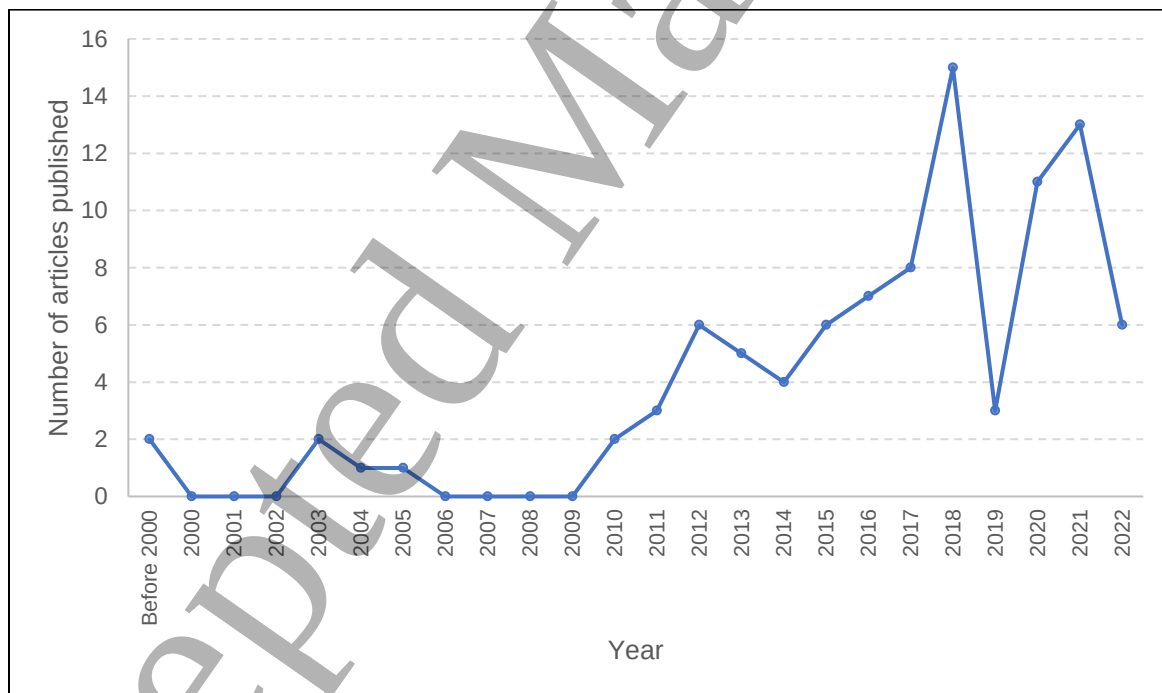


Figure 2: Number of adaptation-focused articles published in the US agriculture context over time

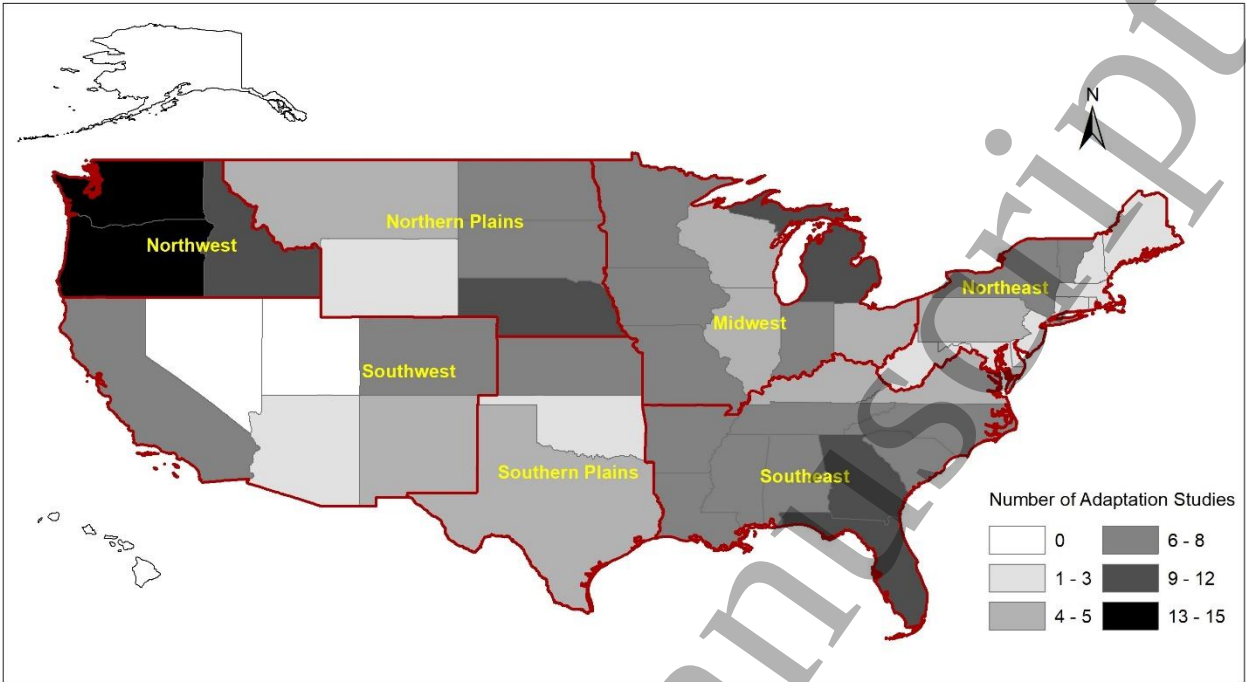


Figure 3: Distribution of adaptation-focused studies across the US. (The regions are classified based on the National Climate Assessment Report).

The SLR of the articles related to adaptation to climate change further reveals a range of topics on climate adaptation in US agriculture. These articles are categorized into five themes based on their broad topical relevance: i) reporting on-farm adaptations, ii) exploring potential adaptations, iii) evaluating specific adaptations, iv) challenges of adaptations, and v) perceptions toward adaptations (Figure 3). The *first theme* includes articles that documented farmers’ on-farm strategies to adapt to climate change impacts. The key objectives of the articles under the *second theme* were exploring potential strategies for farmers so that they can adapt to climate change-related hazards in a better way. These articles did not document what actions farmers are undertaking but rather identified what strategies could be beneficial for them through modeling approaches or opinions. These articles did not seek to evaluate specific adaptation options; instead, their primary objectives were to identify the adaptation actions. The *third theme* includes the articles in which the main objectives were evaluating specific adaptation options. Instead of identifying adaptation options for farmers, these studies selected one or more adaptation actions and evaluated their effectiveness. The articles under the *fourth theme* focused on the challenges associated with undertaking adaptation actions, and the *fifth theme* of articles dealt with farmers’ perceptions towards adaptation actions. It is important to note that a few articles can overlap in two themes. For example, articles under the first theme can discuss the adaptation challenges and thus overlap with the fourth theme. In those instances, the categorization took place based on the primary objective of those articles. Only three articles (i.e., Antle et al. 2004, Burke & Emerick 2016, Oritz-Bobea et al. 2018) did not fall under any specific theme as they focused on estimating the impacts of general adaptations and assumed the challenges of adaptations. In the following subsections, I will elaborate on the findings under each of these themes.

3.1. Theme 1: Reporting on-farm adaptations

Among the articles published on farmers' adaptations in the US, only around 17% of articles (16 out of 95) presented what adaptation strategies farmers undertake in their agricultural lands. A majority of these studies (38%) concentrated on the Northeast part of the US (e.g., Jemison et al. 2014, Schattman et al. 2016, Warner et al. 2017, Lane et al. 2018, Schattman et al. 2021) and 31% focused on the Midwest part (e.g., Mase et al. 2017, Linder & Cambell-Arvi 2021, Skevas et al. 2022), while only a few studies focused on the Southeast part (e.g., van Dijn et al. 2015), Southwest part (e.g., Vasquez-Leon et al. 2003, Nicholas & Durham 2012), and Northwest part of the US (e.g., Roesch-McNally et al. 2020). These articles primarily focused on collecting empirical data through interviews with farmers or focus group discussions.

From these studies, it is evident that US farmers are undertaking a range of adaptation strategies. These adaptation strategies can be categorized into five broad themes: *water management*, *crop management*, *nutrient management*, *technological management*, and *financial management*. Studies under this theme mostly focused on corn, soybeans, fruits, and vegetable growing regions, but they did not distinguish crop-wise adaptation strategies, instead reported the adaptation strategies for multiple crops combined or for a single crop. Furthermore, to answer '*adaptation to what?*', these studies primarily considered climate change as a whole; only a few studies focused on specific hazards, such as drought (van Dijn et al. 2015) and flooding (Warner et al. 2017). The regional comparison indicates that more adaptations are reported in the Northeast region of the US compared to other parts; however, this does not essentially mean that farmers in the Northeast US are adapting more than others. Table 2 summarizes the adaptation strategies taken by the US farmers.

Among a wide range of adaptation actions undertaken by farmers, irrigation is the most common strategy. Irrigation can mitigate the impacts of warming temperatures and rainfall variabilities induced by climate change. Depending on local contexts, farmers are adopting various types of irrigation techniques, such as traditional irrigation (Jemison et al. 2014, Schattman et al. 2021), drip irrigation (Roesch-McNally et al. 2020), gravity and sprinkler irrigation (van Dijn et al. 2015). However, irrigation alone is not sufficient to tackle climate risks. For instance, Jemison et al. (2014) found fruit growers sharing concerns that the warming temperature will severely impact blueberry production in Maine, even with irrigation. As a result, farmers bundle up multiple adaptation strategies to tackle climate-related uncertainties. Roesch-McNally et al. (2020), for example, found that farmers in Oregon not only increased irrigation but also improved soil conditions through nutrient management and shifted planting dates. Among other adaptation actions, crop diversification is widely adopted. These studies did not explicitly report the diversified crops per se, but most often, this diversification is a combination of the main growing crops with vegetables, fruits, pasture or hay, or non-food agriculture (e.g., dairy, poultry). Farmers' adaptation actions in the US often are more reactive than proactive, as found by Linder and Campbell-Arvi (2021). They argued that the farmers in Michigan 'take things as they come' and 'roll with the changes'. Similarly, Nicholas and Durham (2012) reported that farmers in California undertake reactive adaptation actions and if proactive, they undertake short-term actions.

Table 2: US farmers' on-farm adaptation strategies

Theme	Adaptation action	Crop	Region	Reference
Water management	Irrigation (e.g., traditional, micro irrigation, targeted irrigation, irrigation scheduling, drip irrigation)	Corn, soybeans, vegetables, fruits	Northeast, Southeast, Midwest, Northwest, Southwest, Southern Plains	Vasquez-Leon et al. (2003), Knutson et al. (2011), Nicholas and Durham (2012), Jemison et al. (2014), van Dijn et al. (2015), Doll et al. (2017), Sweet et al. (2017), Lane et al. (2018), Roesch-McNally et al. (2020), Linder

				and Campbell-Arvai (2021), Schattman et al. (2021)
	Irrigation infrastructures (e.g., tile drainage, bank stabilization)	Corn, soybeans, vegetables, fruits	Northeast Midwest	Jemison et al. (2014), Doll et al. (2017), Warner et al. (2017), Sweet et al. (2017), Lane et al. (2018), Schattman et al. (2021), Skevas et al. (2022)
Crop management	Changing crop varieties	Corn, soybeans, vegetables, fruits	Northeast, Midwest, Northwest	Knutson et al. (2011), Jemison et al. (2014), Lane et al. (2018), Roesch-McNally et al. (2020), Skevas et al. (2022)
	Crop diversification	Corn, soybeans, vegetables, fruits	Northeast, Midwest, Northwest	Jemison et al. (2014), Schattman et al. (2016), Mase et al. (2017), Lane et al. (2018), Roesch-McNally et al. (2020), Linder and Campbell-Arvai (2021), Schattman et al. (2021)
	Raised bed	Vegetables, fruits	Northeast, Northwest	Jemison et al. (2014), Roesch-McNally et al. (2020)
	Cover crop	Corn, soybeans, vegetables, fruits	Northeast, Midwest, Northwest	Lane et al. (2018), Roesch-McNally et al. (2020), Schattman et al. (2021)
	Reduced or zero tillage	Corn, soybeans, vegetables, fruits	Midwest, Northeast	Knutson et al. (2011), Lane et al. (2018), Schattman et al. (2021)
	Crop switching	Corn, soybeans	Entire US	Cui (2020)
	Crop rotation	Vegetables	Midwest, Northeast	Knutson et al. (2011), Schattman et al. (2021)
	Shifting planting dates	Corn, soybeans, vegetables, fruits	Northeast, Southeast	Lane et al. (2018), Roesch-McNally et al. (2020)
Nutrient management	Managing fertilizer or pesticide	Vegetables, fruits	Northeast, Southwest	Nicholas and Durham (2012), Linder and Campbell-Arvai (2021), Schattman et al. (2021)
	Soil condition improvement (e.g., organic matter, permanent mulch, compost)	Vegetables	Northeast, Southeast, Midwest, Northwest	Knutson et al. (2011), Jemison et al. (2014), van Dijk et al. (2015), Roesch-McNally et al. (2020), Linder and Campbell-Arvai (2021), Schattman et al. (2021)
Technological management	Adoption of new technology (e.g., soil moisture sensor, land leveling, hail nets, wind machines)	Vegetables	Northeast, Southeast, Midwest, Southwest, Southern Plains	Nicholas and Durham (2012), Jemison et al. (2014), van Dijk et al. (2015), Mase et al. (2017), Skevas et al. (2022)
Financial management	Crop insurance	Vegetables	Northeast	Warner et al. (2017), Linder and Campbell-Arvai (2021), Schattman et al. (2021), Skevas et al. (2022)
States surveyed by reference studies: Northeast: New York (Sweet et al. 2017, Lane et al. 2018), Pennsylvania (Lane et al. 2018), Vermont (Schattman et al. 2016, 2021), Maine (Jemison et al. 2014), Massachusetts (Warner et al. 2017) Southeast: Florida (van Dijk et al. 2015) Midwest: General (Mase et al. 2017), Nebraska (Knutson et al. 2011, Mase et al. 2017), Michigan (Doll et al. 2017, Linder and Campbell-Arvai 2021), Missouri (Skevas et al. 2022) Southern Plains: Kansas (Mase et al. 2017) Northwest: Oregon (Roesch-McNally et al. 2020) Southwest: Arizona (Vásquez-Leon et al. 2003), California (Nicholas and Durham 2012)				

3.2. Theme 2: Exploring potential adaptations

About 22% of the articles published on farmers' adaptations in US agriculture explored potential adaptation actions that the farmers can undertake. With empirical or simulated data and analyses, these studies argued what adaptation actions farmers should adopt in different climate regimes. Studies under this theme can be categorized into two based on their topical and methodological relevance: *model-based adaptation simulations* and *opinion-based adaptation plans*.

The model-based simulations articles used forecast models, crop models and/or climate models to simulate crop production under future temperature and precipitation scenarios. Analyzing yield performance in different climate change scenarios is often fundamental to model-based simulations, as evidenced by Bao et al. (2015). By analyzing the yields of six cultivars of rainfed Soybean under precipitation scenarios in 2050, they suggested three cultivars to be used in the Southeastern states, while Antle et al. (2019) argued that intercropping biofuel crops with wheat can be an effective adaptation in the Northwest. Furthermore, Easterling et al. (2003) created scenarios for technological adoption and climatically optimized adaptation and found that the adoption of technology may prove more effective than traditional climate-sensitive agricultural practices. Based on the performance of a simulated dryland wheat farm, Travis and Huisenga (2013) found that if the rate of climate change or the frequency of extreme events increases, adaptation will take place sooner. A few studies (Mu et al. 2013, 2019) forecasted agricultural land use changes and further compared representative agricultural pathways that include regional biophysical and socioeconomic developments. They found that croplands would decrease in the coming decades while farmers would focus more on pasture lands.

In the case of opinion-based adaptation plans, on the one hand, some studies inspected the policy dimensions and suggested various adaptation mechanisms that can be undertaken not only by farmers but also by decision-makers. To give an example, Chanda et al. (2021) analyzed the supply chain relationships of Tomato production in Florida and found that there is a need to reform product certification landscapes as well as diversification of fresh produce market strategies (see also Lewandrowski & Brazee 1993). On the other hand, some studies consulted with farmers and presented them with different climate scenarios to derive potential adaptations the farmers want to undertake. Davenport et al. (2022), for example, reported that farmers in the Corn belt are likely to expand current irrigation under drought conditions. Similarly, Jackson et al. (2011) identified that the potential adaptation actions of California farmers include changes in crop variety, irrigation, fertilizer, tillage, and land use. However, farmers' decisions to adapt may not be proactive or anticipatory; instead, they can adapt as a reactive response to climate change. Doll et al. (2017) found that farmers in Michigan would undertake reactive adaptations than proactive as they are unsure about future climate change impacts.

Table 3: Potential adaptations for US farmers

Theme	Region	Crop	Potential Adaptations	Reference
Model-based adaptation simulations	Southeast	General	- Crop rotation with legume incorporation	Afroz et al. (2021)
		Soybean	- The Soybean cultivars AG6702, AGS758RR, and S80-P2, are suitable for rainfed locations in this region.	Bao et al. (2015)
		Corn	- Adoption of technology	Easterling et al. (2003)
	Northwest	General	- The extent of pasturelands will be expanded while croplands will be diminished.	Mu et al. (2013, 2019)
		Wheat	- Reduced tillage, intercropping with biofuel crops	Antle et al. (2019)
Opinion-based adaptation plans	Southern Plains	General	- Additional irrigation, land use change	Anandhi (2017)
	Northeast	General	- Improved irrigation facilities, irrigation scheduling, and efficient drainage system.	Wolfe et al. (2018)
	Southeast	Tomato	- Pest-resistant varieties development, changes in dumping and immigration laws, and diversified market strategies.	Chanda et al. (2021),
		General	- Seasonal climate forecast that may lead to effective crop management decisions.	Crane et al. (2011)
	Midwest	Corn	- Expansion of irrigation under drought conditions.	Davenport et al. (2022)
		General	- Innovative water management strategies - Crop diversification	Jordan et al. (2018)
	Northwest	General	- Efficient irrigation strategies (e.g., backup generators)	Hammond et al. (2013)
	Southwest	General	- Cover crops, crop diversification, irrigation, increased N-fertilizer.	Jackson et al. (2011),
			- Desalinization of seawater to increase irrigation.	Wilder et al. (2010)

	Northern Plains	General	- Increasing cropping intensity, reduced or zero tillage, cover crops.	Wienhold et al. (2018)
	Southern Plains	General	- Improved soil health and drought contingency planning.	Steiner et al. (2018)
	Entire US	General	- Flexibility in farm programs and implementing policies to promote water conservation. - Agriculture adaptation measures must be pursued, aligning with the Paris agreement.	Follett (1993), Lewandowski and Brazee (1993), Moore (2017)
States surveyed by reference studies: Northeast: General (Wolfe et al. 2018) Southeast: Alabama (Afroz et al. 2021), Georgia (Bao et al. 2015, Crane et al. 2011), Florida (Chanda et al. 2021) Midwest: General (Jordan et al. 2018), Minnesota (Davenport et al. 2022) Northern Plains: General (Wienhold et al. 2018) Southern Plains: General (Steiner et al. 2018), Kansas (Anandhi 2017) Northwest: Oregon, Idaho (Mu et al. 2013, 2019), Washington (Hammond et al. 2013, Mu et al. 2013, 2019) Southwest: Arizona (Wilder et al. 2010), California (Jackson et al. 2011)				

3.3. Theme 3: Evaluating specific adaptation options

Of the articles on US farmers’ adaptations, 47% concentrated on evaluating the feasibilities or performances of specific adaptation actions. Among them, a majority (55%) discussed the potential of different irrigation regimes under different contexts or scenarios. These studies primarily focused on the performance of irrigations or water availability in negating the impacts of drought or erratic rainfall patterns. For instance, Frisvold and Bai (2016) analyzed irrigation data from 17 states and argued that sprinkler irrigation is a better adaptation in relatively cooler areas than in warmer states, and it is mostly adopted by large landholders. The regional differences in the performance of irrigation can be observed from these studies as well. Focusing on irrigation infrastructure, Zhang et al. (2015) claimed that advanced irrigation infrastructure can help mitigate drought impacts more in the Southwest part of the US than in the Northeast. Ward and Crawford (2016) further found that enhanced storage capacity of water can increase crop valuation by 30% in the southwest region. Storage of water can be useful in the southeast part of the country, as evidenced by Vico et al. (2020). Apart from irrigation, other studies under this theme evaluated a variety of adaptation actions, such as crop rotations (e.g., Wang et al. 2021), cover crops (e.g., Yoder et al. 2021), fallowing (e.g., Zhang et al. 2017), land leasing (e.g., Zhang et al. 2018), crop switching (e.g., Rising & Devineni 2020), and nutrient best management practices (e.g., Doran et al. 2020). Some studies considered multiple adaptation actions together as well. For instance, Antle et al. (2018) considered within-system adaptations (e.g., crop management) and between-system adaptations (e.g., crop insurance) in their adaptation analysis to assess the performance of two methods.

Overall, these studies attempted to understand the performance of a specific adaptation or a set of adaptations under different climate change scenarios. Some of these studies do not provide optimistic outcomes, such as the adoption of technology might not be effective enough to deal with climate change impacts (Chhetri et al. 2010), increased water use does not prove effective in increasing yields in the Northwest (Lauffenburger et al. 2022), or agricultural profits will decrease by the end of this century with present crop area locations (Rising & Devineni 2020). Nevertheless, studies also came up with context-specific adaptation strategies, such as sprinkler irrigation in cooler regions (Frisvold et al. 2016), smaller ponds in the southeast part (Vico et al. 2020), or cover crops in hilly areas (Yoder et al. 2021). Table 4 summarizes the key findings of the adaptation studies under this theme.

Table 4: Assessment of specific adaptations

Adaptation	Region	Crop	Key findings
Irrigation	Entire US	General, Corn, Soybean, Wheat, Rice, Sorghum, Barley	- Irrigation will increase yields and provide a significant buffer against precipitation and temperature variability (Troy et al. 2015). - In the western United States, irrigation depth could be maintained only when better irrigation infrastructure replaces 40% of the current surface irrigation infrastructure

			areas. In the northeast United States, limited changes in irrigation depth are predicted under different irrigation infrastructure scenarios (Zhang et al. 2015). - Sprinkler irrigation is a better adaptation in relatively cooler areas than in warmer states. It is less likely to be effective in drier regions (Frisvold et al. 2016). - Expected improvements in water use efficiency will be insufficient to avoid impending water shortages (Brown et al. 2019). - Irrigation is important as non-irrigated crops are more sensitive to droughts than irrigated crops, particularly in severe drought conditions (Lü et al. 2020).
	Southeast	General	- Smaller pond irrigation ensures higher yields than deficit irrigation, even if it implies a faster use of the stored water (Vico et al. 2020).
		Corn and Soybean	- The potential corn and soybean yields can be increased from 10% to 259% and 20% to 229%, respectively under different irrigation water application rates (50%, 75%, and 100% of irrigation water requirement) relative to rainfed crop yields at the counties in the Mobile River Basin during drought years (Deb et al. 2022).
	Northwest	General	- Sprinkler irrigations can mitigate extreme weather damage (Olen et al. 2016) - More efficient irrigation systems improve the agricultural economy (Malek et al. 2018) and are useful across diverse stakeholders (Malek et al. 2021). - Even with increased land and water use for irrigated crops, production decreased 0.5%, while rainfed production decreased by 2.7% (Lauffenburger et al. 2022).
	Southwest	General, Pecans, Vegetables	- Extremely long irrigation durations, inefficient irrigation practices, inadequate on-farm infrastructure, and lack of interest in making improvements to the current irrigation system or methods observed on the smallest farms (Skaggs et al. 2005). - Increasing water storage through artificial recharge of excess surface water in aquifers by up to 3km shows promise to adapt to drought (Scanlon et al. 2012). - Sprinkler irrigations can mitigate extreme weather damage (Olen et al. 2016). - Added storage capacity development can lead to a 30% higher valued portfolio of irrigation production systems as well as more sustained and higher valued farm livelihoods (Ward and Crawford 2016). - A combination of rotational delivery and flexibility in water allocations produces the most equal crop growth between irrigators (Cody 2018).
	Northern Plains	General	- With irrigation, crop yields are higher for all crops (Qiu and Prato 2012).
		Maize	- Irrigation leads to a considerable cooling on daytime land surface temperature, an increase in enhanced vegetation index, and 81% higher maize yields compared to rainfed maize (Li et al. 2020).
	Southern Plains	General	- Surface water supplies are reduced, farmers shift to aquifer pumping even when pumping raises the cost of production or reduces yield (Ward 2014)
	Midwest	Corn, Soybean	- The adaptation strategy of planting earlier increased irrigation demand and water available for transpiration, while delaying planting resulted in demand decreases for both corn and soybean (Woznicki et al. 2015).
Changing crop varieties	Southeast	Corn	- Adaptation may not be as effective as anticipated and a decrease in yield could be observed (Chhetri et al. 2010).
	Midwest	Maize, Rice, Soybean, Wheat	- Cultivars that retain growing season length under warming dates are more useful (Franke et al. 2022).
	Northwest	General	- Planting improved crop varieties may potentially increase the expected mean annual productivity in an altered climate but is not sufficient against irrigation water shortages (Malek et al. 2020).
Adoption of technology	Southeast	Corn	- Adaptation may not be as effective as anticipated and a decrease in yield could be observed (Chhetri et al. 2010).
	Midwest	General	- Without effective technological advances and operational and policy changes, agricultural production from the arid region may decline by 50% or more (Phetheet et al. 2021).
Crop area reallocation	Entire US	Corn, Soybeans, Barley, Rice, Wheat, Sorghum	- If crop locations are held constant in the future, total agriculture profits for the six crops will drop by 31% for the temperature patterns of 2070 under RCP 8.5, but reallocation can save half of this loss (Rising & Devineni 2020).
	Northeast	General	- Unadapted winter wheat yield increased by 48% in response to mid-century projected climate changes, but corn grain declined by 19% and potato by 42% (Mutibwa et al. 2018).
Double cropping	Entire US	General	- Under the RCP45 and RCP85 scenarios double cropping area will increase by an additional 126-239%, respectively (Seifert & Lobell 2015).
Changes in planting date	Southeast	Corn	- Adaptation may not be as effective as anticipated and a decrease in yield could be observed (Chhetri et al. 2010).
	Midwest	Maize, Rice, Soybean, Wheat	- Modifying planting dates helps recover yield losses (Franke et al. 2022).
	Southwest	Wheat, Corn	- Changing planting dates did not mitigate yield losses (Ko et al. 2012).
Cover crops	Northeast	Maize	- Cover crops neither ameliorated nor exacerbated drought stress (Hunter et al. 2021).
	Midwest	General	- Cover crops can control wind erosion in hilly areas with sandy soils (Yoder et al. 2021).

Crop rotations	Southeast	General	- The inclusion of C-4 crops in crop rotations and applications of biochar under wetter climate scenarios can be promising to improve soil health (Lychuk et al. 2021).
	Midwest	General	- Farmers were more likely to utilize crop rotation as an adaptive strategy to cope with water deficits and reduce soil erosion on marginal land (Wang et al. 2021).
		Corn, Soybean, Wheat	- Organic and no-till treatments are found to be climate resilient (Eeswaran et al. 2021).
	Southwest	Wheat, Corn	- No-tillage maintained higher wheat yields (Ko et al. 2012).
	Northwest	Wheat	- Diversification of cropping systems by partial replacement of winter wheat with other winter crops such as winter peas and canola should be feasible, depending on economics, replacing spring with winter crops in current rotations appears only feasible in high precipitation locations of the inland Pacific Northwest (Stockle et al. 2018)
Land leasing	Northwest	General	- Analyzing medium and high greenhouse gas emission-based climate projections, it is predicted that, by 2050, leased acreage will decline by 23% and 29% (Zhang et al. 2018).
Nutrient management	Northeast	General	- Perceived behavioral control influences nutrient best management practices by farmers and wealth, education and open-mindedness affect the adoption of it (Doran et al. 2020).
Fallowing	Northwest	Wheat	- On average, by 2050, the share of fallow in the U.S. Pacific Northwest region will increase by 1.3% under a medium climate change scenario and by 1.8% under a high climate change scenario (Zhang et al. 2017).
Soil organic carbon	Southwest and Northern Plains	General	- Growers can solve the 'soil C dilemma' by simultaneously increasing the quantity and N-content of soil input through continuous cropping with both grains and legumes (van der Pol et al. 2022)
Land use	Entire US	General	- Projected climate change will lead to an expansion in crop land share across the northern and interior western United States with decreases in the south (Mu et al. 2018).
	Southeast	General	- Medium to long term land use adaptation in the form of capping housing density and agricultural cover in the coastal (and adjacent inland) states can significantly reduce economic damages from intense hurricanes (Zia 2012).
States surveyed by reference studies: Northeast: General (Mutibwa et al. 2018), New York, Vermont (Doran et al. 2020), Pennsylvania (Hunter et al. 2021) Southeast: General (Chhetri et al. 2010, Zia 2012, Vico et al. 2020, Lychuk et al. 2021, Deb et al. 2022) Midwest: General (Franke et al. 2022), Kansas (Phetheet et al. 2021), South Dakota (Wang et al. 2021), Indiana (Yoder et al. 2021), Michigan (Woznicki et al. 2015, Malek et al. 2018, Eeswaran et al. 2021) Northern Plains: Montana (Qiu and Prato 2012); Nebraska (Li et al. 2020, van der Pol et al. 2022) Southern Plains: Texas (Ward 2014) Northwest: Washington (Frisvold et al. 2016, Olen et al. 2016, Malek et al. 2018, 2020, Zhang et al. 2017, 2018), Oregon (Frisvold et al. 2016, Olen et al. 2016, Malek et al. 2020, 2021, Zhang et al. 2017, 2018), Idaho (Frisvold et al. 2016, Malek et al. 2020, 2021, Zhang et al. 2017, 2018), Montana (Lauffenburger et al. 2022) Southwest: California (Scanlon et al. 2012), Colorado (Ko et al. 2012, Ward 2014, Cody 2018, van der Pol et al. 2022), New Mexico (Skaggs et al. 2005, Ward 2014, Ward and Crawford 2016)			

3.4. Theme 4: Challenges of adaptation

Challenges of or barriers to adaptation in the US agriculture context have not been emphasized much in the peer-reviewed literature. Only around 6% of the articles examined the challenges of adaptation. These articles suggest that farmers managed to adapt to climate change impacts to a significant extent, at least for now; however, there are challenges that may prohibit adaptations to future climate change impacts. These articles identified several challenges that are required to be addressed soon. For example, conducting research on the Southeast and Northeast part of the US, Knox et al. (2014) and Takahashi et al. (2016) found that tunnel vision about longer-term impacts of climate change prohibits farmers from adopting anticipatory adaptation strategies. Instead, the farmers prefer to undertake reactive adaptation strategies based on their past experiences. This path dependency limits the abilities of the farmers to adapt (Roesch-McNally et al. 2018). Additionally, Silva et al. (2021) and McNeely (2017) found that farmers are in need of training and climate projection-related information from agricultural organizations. Lack of training and information can lead to a narrow understanding of longer-term climate change impacts on agriculture. The training programs and information dissemination can enhance mutual

learning among agricultural stakeholders, which is crucial to ensure equitable adaptation governance (Bizikova et al. 2014, McNeely 2017).

3.5. Theme 5: Perception toward adaptations

About 8% of articles that were published on US farmers' adaptations to climate change addressed perception-driven attitudes towards adaptations. These articles found that farmers' perceptions about climate change are crucial because whether they adapt depends on their perceptions (Schattman et al. 2018). Arbuckle et al. (2013a, 2013b) found that farmers who believe that anthropogenic climate change is occurring are more likely to undertake adaptation strategies as well as support government adaptation actions. On the contrary, those who are uncertain about climate change are less supportive of individual or government-supported adaptations. It becomes further concerning because even innovations of new technologies, a key adaptation, may backfire because of farmers' perceptions about them. Gardezi and Arbuckle (2020) observed that greater techno-optimism among farmers led to a delay in undertaking adaptation strategies. They found that midwestern farmers' adherence to an abstract faith that human ingenuity will solve climate change-related challenges prevent them from making timely decisions on agricultural adaptations. One of the reasons behind the apathetic behavior could be the fact that farmers cannot perceive the long-term changes in weather variability, as evidenced by Maas et al. (2020). Thus, some farmers perceive their individual capacity to adapt uncertain (Haden et al. 2012, Eakin et al. 2016). These farmers require a more collective approach to adaptation than individual, Eakin et al. (2016) argued.

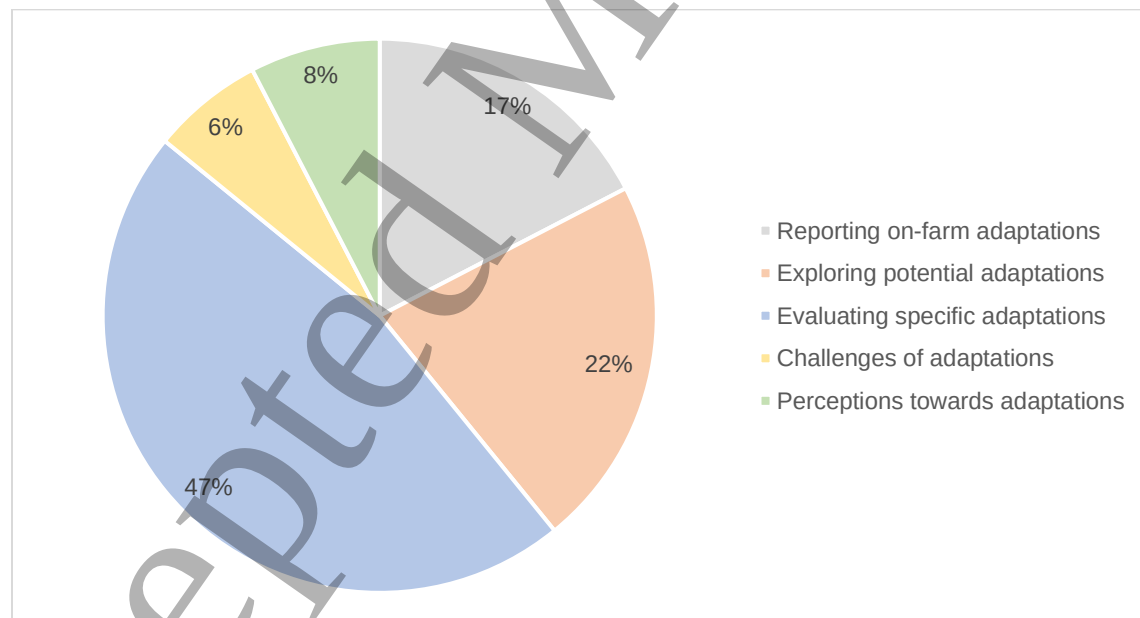


Figure 4: Percentage of adaptation studies under different themes (N = 95)

4. Discussion

This study reveals that studies published on farmers' adaptations in the US agriculture context are primarily clustered around evaluating specific adaptation strategies while reporting on-farm adaptations or examining the challenges of adaptations did not get much attention. An equal distribution of the studies among these themes is not expected, but a skewed distribution indicates a greater need for research under

certain themes. This study found that the majority of the on-farm adaptation-related studies concentrated on the northeast part of the country and examined a range of adaptation actions undertaken by farmers. However, similar studies on wheat, corn, and soybean zones in the US are scant, and thus, we have limited knowledge of what crop-wise adaptation strategies farmers are undertaking in these zones to tackle climate change-induced challenges. Majority of the studies that reported on-farm adaptations are based on small samples and thus their findings often cannot be generalized. Large-*N* studies that address crop-wise adaptations are required to address this gap (Lane et al. 2018). Future works can further focus on the role of climate change-induced extreme weather events in undertaking adaptation actions by farmers and comparison between adaptations by smaller-scale farmers and large-scale farmers (Mase et al. 2017). Furthermore, while reporting on-farm adaptations, existing studies did not differentiate among farmers based on ethnicity. Racial inequities can influence the relationship between public agencies and farmers (Furman et al. 2014), which can further impact farmers' adaptations. As such, it is important to understand whether ethnicity plays a role in determining adaptations by farmers and to what extent.

Not all adaptation actions can be similarly beneficial or regionally suitable (Yu et al. 2021). Thus, it is crucial to identify and evaluate effective adaptations. Several studies evaluated agricultural practices and recommended some strategies as adaptations, such as zero tillage (Eeswaran et al. 2021) and modifying planting dates (Franke et al. 2022) are effective in diminishing yield losses. Additionally, the articles that did not discuss *adaptation* per se but focused on evaluating specific conservation or climate-smart practices (e.g., cover crops, use of a particular fertilizer) examined those practices closely. These studies provide a rich understanding of the implications of different types of agricultural practices that are framed as climate-smart agriculture, sustainable agriculture, conservation agriculture, and agricultural adaptations. These practices are often influenced by local institutions, normative, and infrastructural conditions (Cody 2018). Future works should include direct and indirect measures of the usefulness of adaptation actions under different institutional and infrastructural conditions. While evaluating adaptation actions, the majority of the studies did not incorporate market dynamics in the analysis; but an agricultural practice or action will not be adopted by farmers unless it generates higher profit than the current practice or it is incentivized in some way. Therefore, it is important to integrate variables related to market dynamics in the modeling approach. Additionally, in future climate change scenarios, it is crucial to incorporate future socioeconomic scenarios in order to capture farmers' adaptation behavior (Antle et al. 2017). Recent global projection scenarios (i.e., Shared-Socioeconomic Pathways) might be somewhat useful, yet simulating farmers' behavior based on behavior models in decision-making science has a greater potential to be more effective in climate change scenarios (see Schlüter et al. 2017 for behavior models). In future climate change scenarios, a potential source of error may arise from assuming no change in vegetation cover (Brown et al. 2019). Future works should attempt to incorporate the changes in vegetation and their relationships with water yield into their analysis to better estimate water availability. Similarly, in the modeling approach, considering carbon dioxide-induced fertilization can provide more accurate estimates of adaptation actions, as Attavanich and McCarl (2014) showed that different crops respond differently to elevated carbon dioxide levels. Thus, further crop-specific analyses on adaptations incorporating these complex dynamics are warranted (Olen et al. 2016).

Irrigation has been the focus of the studies that evaluate specific adaptation strategies. In the US, access to irrigation water mostly depends on water regulations rather than the physical availability of water (Lauffenburger et al. 2022). Thus, water availability is often parameterized in models as crop water use by farmers instead of streamflow (Maneta et al. 2020, Lauffenburger et al. 2022). For better analysis, future works on adaptations under different irrigation regimes need to capture the biophysical effects of climate change as well as the institutional controls on water availability (Malek et al. 2020). Irrigation expansion has been suggested by many as an adaptation strategy (e.g., Ward & Crawford 2016, Rosa et

al. 2020), yet further work are required on downscaled opportunities and limitations of irrigation expansions (Troy et al. 2015, Rising and Devineni 2020). At the same time, irrigation expansion needs to be done carefully as increasing irrigation can cause greater emissions of carbon dioxide. McGill et al. (2018) found that compared to a rainfed system, an irrigated system produces 45% more greenhouse gas emissions, but it can also sequester 7% additional carbon by increasing soil organic carbon storage capacity. Additionally, examining the synergistic effects of multiple adaptation practices on the biophysical properties of soils as well as farmers' adaptive capacities are essential (Steiner et al. 2018, Huang et al. 2020). While exploring potential adaptations and assessing adaptation practices are crucial, it is also important to address how policies impact farmers' adaptations or dictate certain adaptation practices (e.g., irrigation) and how to best accomplish the integration of scientific information with governance (Schattman et al. 2021). Integration of scientific information into long-term decision-making can be accomplished when the decision-makers perceive the information as accurate, credible, reliable, useful, and timely (Kirchhoff et al. 2013). A wide variety of agricultural or crop models has been used to analyze the impacts of adaptations on crop production and each model has its own limitations. Future works should address those limitations before adopting those models (Anandhi 2017, Antle et al. 2018). Future research can address high-resolution, locally downscaled data availability and accuracy and the challenges of incorporating the information into decision-making (Gillon et al. 2016). Similarly, future research can analyze whether state-level governance approaches enable farmers to make effective adaptation decisions and whether these approaches are capable of protecting farmers during extreme weather events (Schattman et al. 2021).

The studies that focused on the challenges of adaptation documented a lack of training and information as well as farmers' denial of climate change as barriers to adaptation. We need more evidence of challenges or barriers to adopting certain practices by the farmers. For instance, because of climate change impacts, farmers are adopting practices to improve soil health in the Northwest US, and it is important to understand the barriers to the adoption of these practices and develop approaches to overcome these barriers (Yorgey et al. 2017). Cover crops can provide significant benefits to farmers against climate change impacts, yet it is poorly adopted across the US (Yoder et al. 2021). Future works can emphasize how barriers to the adoption of such adaptation practices could be addressed and how incentives could be provided to minimize abandonments. Eeswaran et al. (2021) found that organic and no-till farming are climate resilient for food crops and provide great revenues to farmers than conventional methods of farming. Yet, why the migration to organic farming did not happen faster has been explored a little. Also, further research is required on identifying and exploring strategies to address farmers' psychological barriers, existing market structures that are not favorable to organic farming, and reducing the transition cost. While we need more analysis of these kinds, we also need to examine if minority farmers encounter greater challenges. A great majority of the farmers in the US are white males, yet it is important to focus on minority farmers because inequities and discrimination can lead to agricultural abandonment by them. Studies show that black farmers experience hurdles to operating farms because of a lack of access to credit, relegation to marginal hazard-prone lands and women farmers generate less income than men farmers (Taylor 2018, Horst and Manion 2019). Similarly, future works can analyze if the challenges associated with adaptations vary between large-scale and smaller-scale farmers.

Technological innovations increased our capacity to tackle climate change impacts on agriculture with greater efficiency. Yet, more studies are required on how recent technological innovations are assisting farmers in adapting to climate change impacts. How climate-smart technologies, satellite remote sensing, big data, artificial intelligence, and machine learning can be used responsibly in farmer adaptations, need to be explored more. Additionally, it is important to focus on how the overall food

production and supply chains can be made more robust to increase resilience against extreme weather events as well as longer-term climate impacts (Mehrabi et al. 2022). Producing around 30% of maize and soybeans and around 10% of wheat globally, the US is one of the leading food producers in the world (FAO 2020). Increasing the resilience of food production through effective adaptation is crucial not only for national food security but also for global food security.

5. Conclusion

Although many studies addressed farmers’ adaptation in US agriculture from various angles, a comprehensive view of the adaptation research activities was absent. The main purpose of this study is to map out the current research trends in adaptation literature that focuses on US agriculture. This study systematically reviewed peer-reviewed English language articles and found that the existing research on agricultural adaptation in the US can be categorized into five broad themes. This study found that irrigation is the most common adaptation strategy across the US, and farmers adopted various irrigation techniques, including traditional, micro, and drip irrigation. Adaptation studies that focus on evaluating specific adaptation measures primarily deal with the performance of irrigation. However, farmers also take other adaptation strategies, but many farmers, if not most, undertake more reactive strategies than proactive ones. This may happen due to their perception of climate change. The farmers who believe in anthropogenic roles in climate change are more likely to support individual and government-supported adaptations. Overall, this found that more research has been conducted on exploring potential adaptations or evaluating the performance of specific adaptations than other themes. This finding indicates the need for more attention to documenting on-farm adaptation strategies and the associated challenges while emphasizing other themes. This study acknowledges two types of limitations. First, there is a plethora of research in different disciplines that focus on issues related to climate change adaptation without explicitly mentioning the term. Those research works were not considered in this study. Second, many studies analyzed the impacts of climate change on crop yield and suggested various adaptation strategies. As adaptation was not the primary focus or data-informed findings of those articles, this study did not take them into account. Future studies can address these limitations by considering those studies into their analyses.

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