Weathering the Storm: A Systematic Review of Climate Change Adaptation in Agriculture. Methods, Metrics, and Impacts.

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record.

Please cite this article as:

Waring T., Biagini L., Bozzola M., Severini S. (2025). Weathering the Storm: A Systematic Review of Climate Change Adaptation in Agriculture. Methods, Metrics, and Impacts, Bio-Based and Applied Economics, Just Accepted. DOI:10.36253/bae-16753

Abstract

Much attention has been paid to the impact of the agriculture sector on the environment and its contribution to climate change. However, the sector is also vulnerable to the impacts of climate extremes. Thus, a growing number of studies have focused on adapting to these changes. We conducted a systematic literature review and assessment of the evidence gathered from 124 studies on the impacts of and adaptation to climate change in the agriculture sector in OECD member countries. Results highlight a significant knowledge gap in understanding the full economic effects of climate change as the impacts of climate change on input costs is not extensively studied in the way that impacts on farm output is. Additionally, there is a need to understand the indicators used to assess climate impacts in agriculture for easier comparison across studies. We recommend targeted research and funding to close this knowledge gap including conducting long term

analyses to evaluate the costs and benefits of adaptation strategies as well as capacity building and knowledge exchange.

Key words: systematic review, climate change, adaptation, agriculture, impacts

JEL codes: C10, 013, Q12

1. Introduction

Agricultural production is sensitive to weather and therefore directly affected by climate change (Nelson et al, 2014; Malhi et al, 2021). With rising temperatures, shifting rainfall patterns, and the increasing prevalence of extreme weather events such as floods and droughts, not to mention the growing scale of potential climate impacts, it is critical to assess the risks posed to the sector and evaluate the effectiveness of adaptive practices (World Bank, 2010) to aid decision-makers in resource allocation. Given that budgets are often constrained (Mysiak et al, 2018), understanding the risks and potential adaptation strategies within the agriculture sector can allow policymakers to understand where funds and resources are most needed and can be most effective. Challenges for effective adaptation policy for agriculture include financial constraints, lack of coordination and knowledge gaps. These factors often lead to maladaptation whereby the sector becomes more vulnerable to climate change (OECD, 2023). To minimise the risk of maladaptation, adaptation policies that are flexible and suitably robust across a range of climate scenario outcomes should be prioritised (Ignaciuk, 2015). To aid policymakers in avoiding maladaptation in this way, this review aims to present a range of climate risks faced by farmers and the effectiveness of adapting to these risks with specific adaptation strategies. Furthermore, understanding the impacts of climate change on agriculture and how detrimental effects can be mitigated by investing in appropriate adaptation strategies is crucial not only for the sector itself but also for the wider economy (Gallic & Vermandel, 2020), and for global food security.

Historically, much attention has been paid to the agriculture sector's impact on the environment and its contribution to climate change. However, there is now a growing body of literature on the impacts of climate change on agriculture and how adapting to climate change affects farm businesses (Burke & Emerick, 2016; Cogato et al, 2019; Chatzopoulos et al, 2020). Where previously the economic literature has rarely included weather or climate extremes in analysis, there is now development of literature on the effect of climate extremes on agriculture. This shift in focus reflects the increasing awareness and acknowledgment of agriculture being severely impacted by climate change and not just a driver of climate change. As farmers attempt to cope with the growing impacts of climate change on their enterprises, it has become more pertinent to explore the impacts of this in the literature. While numerous empirical analyses exist in the literature, the methods, metrics, and case studies are highly heterogeneous, making it challenging to compare findings across studies and formulate consistent recommendations for decision-makers.

Therefore, one of the aims of this review paper is to identify and summarize the methods and metrics used, highlighting gaps and the latest advancements in the literature. We scrutinize a large number of studies that meet our inclusion criteria, synthesizing and discussing the diversity in metrics used to capture climate change, the variety of adaptation strategies, and the range of outcome variables included in models to assess impacts. This approach allows us to identify less-studied areas, observe methodological trends in the literature driven, among other factors, by the availability of new and more sophisticated data, and recommend directions for future research. Finally, we outline the economic costs and benefits associated with climate change adaptation strategies, as well as comparing the impacts of climate change on agriculture with and without such adaptation.

Unlike previous reviews, our study examines both climate change impacts and adaptation, with a focus on OECD member countries. This broader scope enables a more comprehensive assessment of agriculture in relatively comparable socio-economic contexts, improving the potential for cross-study and cross-country comparisons. Such an approach supports policymakers in making decisions based on the capacity and resilience of agricultural systems, rather than prescribing specific adaptation strategies—a best-practice approach given the challenges of determining which strategies are most effective at the local level (OECD, 2023). In addition, easier comparison between studies strengthens the findings surrounding the effectiveness of adaptation strategies. By focusing on both impacts and adaptation, we add value to previous analyses, as it is well known that the impact of climate change heavily depends on the effectiveness of adaptation strategies employed. Furthermore, a key aspect in formulating policy recommendations is the need for a deeper understanding of the costs and benefits of adaptation strategies.

Ultimately, our work aims to explore the following areas; a) the methods and metrics used in the literature to assess the impact of climate change on agriculture and the effectiveness of climate change adaptation measures; b) the effects of changes in the climate system; c) the adaptation strategies employed to reduce the effects of climate change; and d) the effectiveness of these strategies in reducing different types of detrimental socio-economic losses. By assessing the effectiveness of these measures, we provide an indication of the potential economic savings of adaptation to boost farm resilience. The findings and recommendations of this review are addressed to the scientific community to inform future research and efforts to identify the adaptation strategies that are the most appropriate under different conditions. This is perceived as useful also for stakeholders and policymakers who can design, and finance measures aimed at encouraging the use of the most promising strategies.

The review continues as follows. In section 2, we outline the methodology employed to identify, process and extract relevant studies conducted. In section 3, we present the results of the review including a bibliometric analysis and outline of the effectiveness of adapting to climate change in the agriculture sector. Finally, in section 4 we conclude with a summary of the main findings and their implications for policy and future research.

2. Methodology

In order to gain a better understanding of the climate impacts affecting agriculture and how farmers are adapting to these changes, we conducted a systematic review of the literature according to PRISMA guidelines (Page et al, 2021). The framework facilitated transparent and complete reporting of the findings (Fig. 1). Inclusion criteria for the review was designed to identify studies that analyse the impacts of climate change and adaptation in the agriculture sector. The population of interest was the agri-food sector in OECD countries. As mentioned in section 1, We focus on OECD countries to enable a broader examination of agriculture in settings with more comparable socio-economic conditions, environments, and policy frameworks, making cross-country and cross-study comparisons easier. The outcomes considered in the review were determinants (i.e. weather and climate shocks such as drought and flood events, changes in precipitation patterns and increases in temperature), impacts (i.e. impact on profit/farm income, yield, land value), model estimation of impacts (e.g. long difference approach, fixed effects panel approach, Ricardian approach), adaptation strategies employed (e.g. drought resistant crops, irrigation), and the effectiveness of these adaptation strategies. Full details of the inclusion criteria can be found in the supplementary materials. We included empirical research published worldwide in English up to November 2024. Paper retrieval was conducted from April 2024 to June 2024 and again in October 2024 to check for further relevant papers published after this time. Only empirical research papers were considered for inclusion in the review, i.e. not letters to editors, commentaries, responses and so forth. The Web of Science and Scopus electronic databases were searched to identify relevant literature. Details of the full search strategy can be found in the supplementary materials including the search queries and keywords employed.

Identified studies were screened in two steps according to best practice guidelines: firstly, by titles and abstracts, and secondly by the full text. Potential biases were addressed by using more than one reviewer during the screening process as recommended by PRISMA guidelines. Publication information, study characteristics, and findings from included studies were recorded in a standardised data extraction form using Covidence™ (Veritas Health Innovation, 2016), a software programme used to organise and manage systematic and scoping literature reviews. Extracted data gathered information on three main areas: impacts, adaptation, study characteristics. Data on impacts included the type of weather or climate shock analysed, the impact type analysed, timing of the impact, and quantification of the impact. Data on adaptation included the tool or strategy implemented, timing of the strategy, and effectiveness of the strategy. In terms of study characteristics, we gathered information on publication year, country of origin, study objectives, currency units, farm type, level of analysis, and model employed for analysis. We employ a narrative synthesis approach as this is better suited to reviews where the subject area is broad (El Chami et al, 2022).

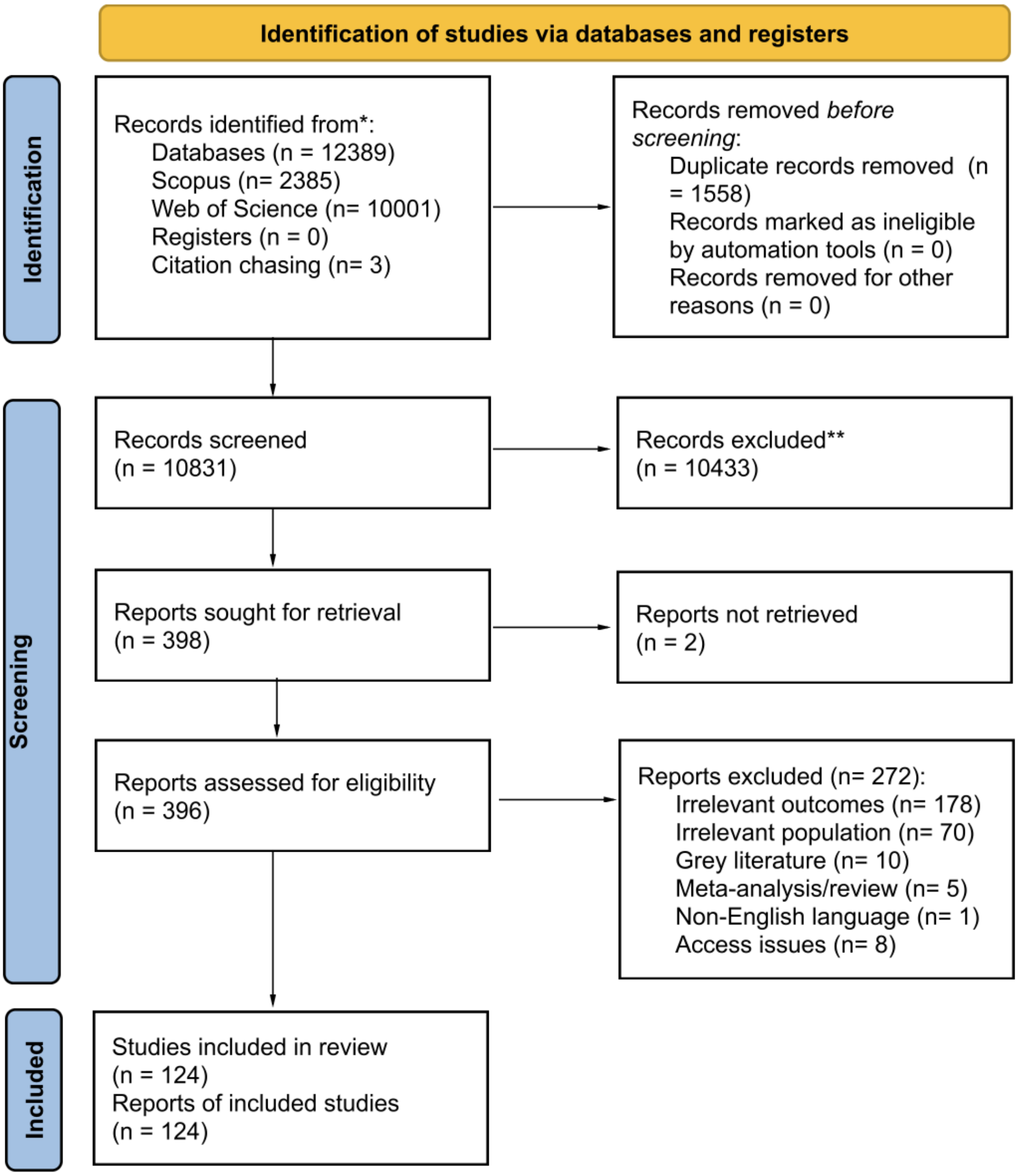


Fig. 1. PRISMA flow diagram

The database searches yielded 12,389 records. After removing duplicates this was reduced to 10,831 records which were screened according to the methods outlined above. Robust screening of the records resulted in 124 studies being included in the review. This process was carefully and transparently documented and has been schematically summarised for simplification according to the diagram above (Fig. 1).

The reasons for excluding studies from the final review as outlined in Fig 1 can be defined as follows. 'Irrelevant outcome' refers to studies that do not indicate an impact of either climate change or adaptation practices. 'Access issues' refers to studies that we were unable to gain access to within the timeframe of the review process. 'Irrelevant population' refers to studies that focused on other aspects of the agri-food sector such as trade or did not focus on an area within the scope of OECD countries. 'Grey literature' refers to working papers, commentaries, conference abstracts or other non-empirical papers. 'Non-English studies' refers to studies conducted and published in a language other than English.

3. Results: the state of evidence on impacts and strategies

In this section we begin with a bibliometric analysis to outline the temporal and spatial trends in the literature. We then examine the climate parameters explored in the literature and the impacts of these changes in the climate system. We follow this with an examination of how these impacts can be adapted to and indicate the effectiveness of these strategies.

3.1 Bibliometric analysis

The first relevant study which captures the research questions of this review was published in the mid-nineties. The number of studies by publication year (Fig. 2) shows that interest in both climate impacts and adaptation has fluctuated over the years, however adaptation studies are lagging behind climate impact studies despite a more recent increase in interest. It is most likely that adaptation studies are simply fewer in number rather than there being slower in development or impact. Given that the impacts of climate change need to be understood before adaptation measures can be planned or implemented, it is not surprising that there are more studies on impacts than adaptation.

Relevant studies did not cover all OECD member countries with 13 countries not represented in this review (Austria, Costa Rica, Denmark, Estonia, Iceland, Ireland, Israel, Latvia, Lithuania, Luxembourg, Norway, Slovak Republic and Slovenia). This does not indicate that studies are not available in these regions, but rather that they did not meet our robust inclusion criteria specific to this review. For example, some studies in these countries have focused less on observed impacts in the climate system and therefore were excluded from this review. The United States offers the most publications (n=36). Many studies are also conducted across Europe without focus on one specific country (n=12). Germany offers 9 studies, Australia and Spain offer 7 studies each and Türkiye offers 6 studies. The countries which are covered the least with only one study each are Colombia, Czechia, Japan, New Zealand, Poland and Portugal (Fig 3).

The publications can be divided into four subject areas (Fig. 4). The most common is economics (n=62), followed by agronomy and agricultural sciences (n=34) and climate and environmental sciences (n=26). The remainder are classified as biology/plant/soil sciences (n=4). It is unsurprising that the majority of studies have been conducted within the economics field as the financial impacts of climate change and adapting to climate change are crucial for farmers and their farm enterprises and thus this aligns with perceived needs.

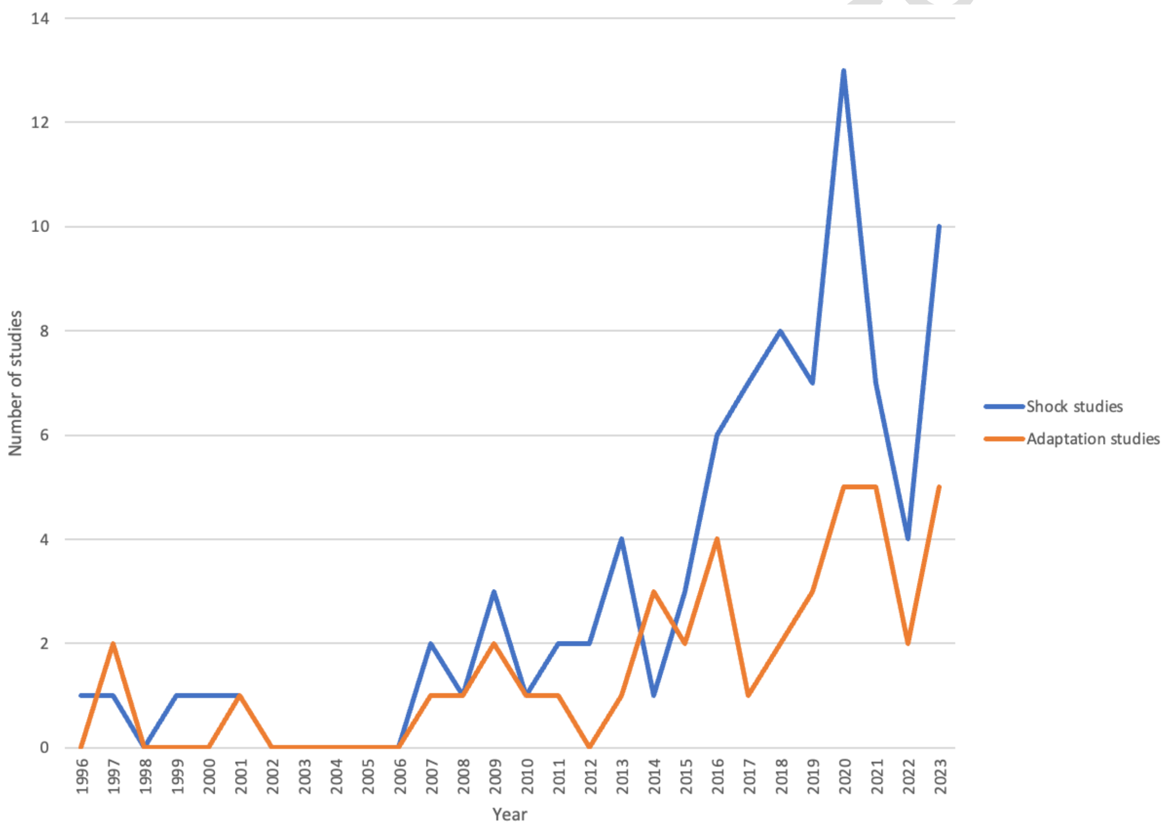


Fig. 2. Number of studies by publication year

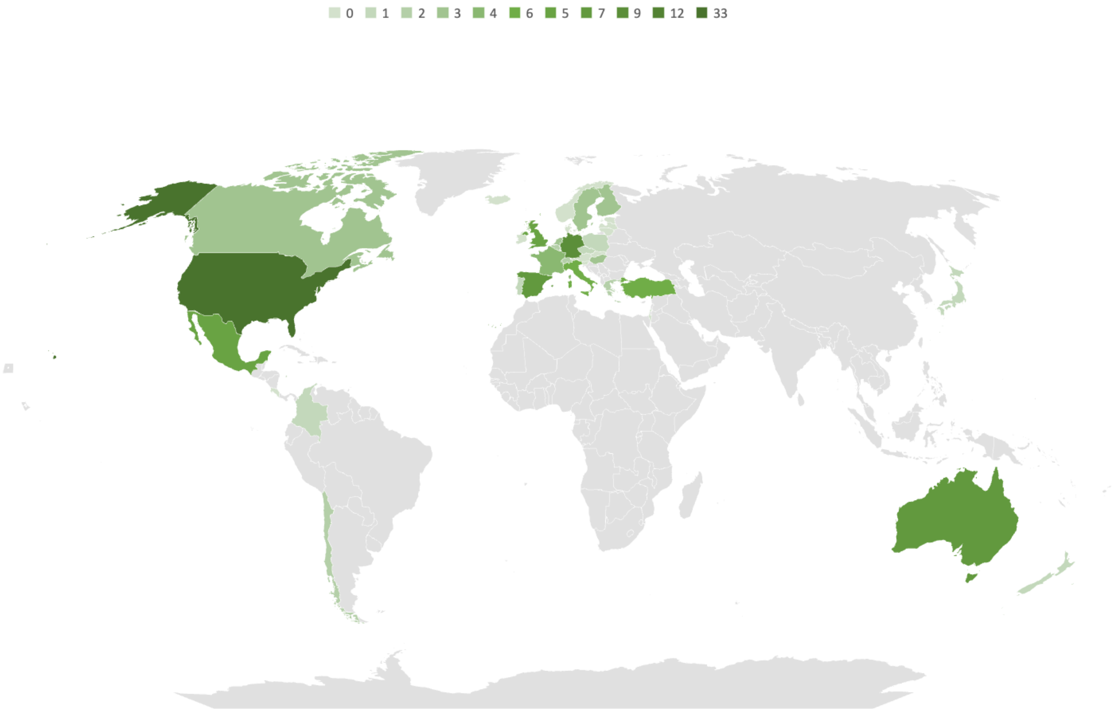


Fig. 3. Number of studies by OECD country

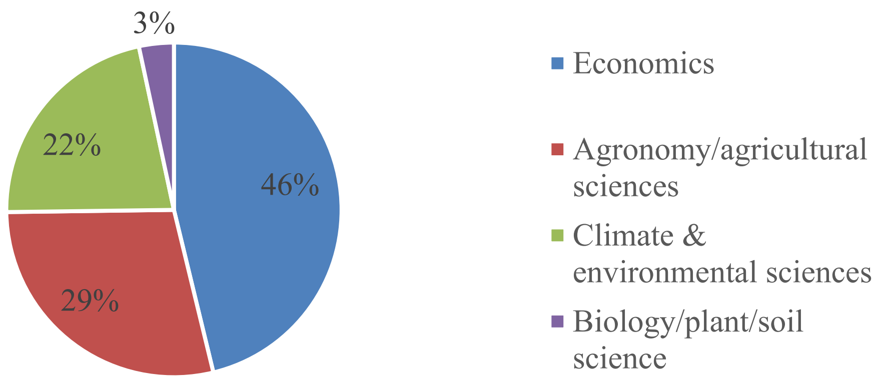


Fig. 4. Number of studies by subject area

3.2 Impacts of climate change

A total of 89 studies explored climate change impacts on agriculture. In terms of the farm types that are explored, arable farms tend to dominate (n=64). Nine studies examine dairy farms, and four studies examine other types of livestock farms. Three studies are based on mixed crop/livestock farms and the remaining nine studies either cover all farm types or do not specify. The studies also analyse impacts across a range of levels

(Table 1). Most studies were conducted at the region or county level (n= 42). Many studies were also conducted at the farm level (n= 17) and at the national level (n= 15). The remaining studies were conducted at the individual plot or crop level (n= 9) or other levels, namely the European level (n= 7).

Table 1. Level of analysis of climate impact studies

Level of analysis	N of studies	References
Individual crop/plot	9	Ahmed et al, 2022; Alayon-Gamboa, 2020; Gulino et al, 2023; Ruiz et al, 2019; Vanongeval et al, 2023; Alidoost et al, 2019; Bencze et al, 2010; Klatt et al, 2021; Schlenker et al, 2009
Individual farm	17	Chatzopoulos et al, 2015; Ahmed et al, 2022; Blanco-Penedo et al, 2020; Bozzola et al, 2018; Durant et al, 2018; Mukherjee et al, 2013; Papadopoulou et al, 2021; Pourzand et al, 2020; Schauberger et al, 2021; Wang et al, 2021; Dalhaus et al, 2020; Eakin et al, 2012; Hill et al, 2014; Huitu et al, 2020; Perez-Uribe et al, 2024; Skoufias et al, 2013; Vroege et al, 2023
Region/county level	42	Akbar et al, 2020; Beillouin et al, 2020; Burke & Emerick, 2016; Demirdogen et al, 2024; Dono et al, 2013; Espe et al, 2017; Gonzalez et al, 2008; Harkness et al, 2023; Himanen et al, 2013; Huszvai et al, 2020; Jiang et al, 2020; Kaufmann et al, 1997; Lee et al, 2018; Li et al, 2018; Linnenleucke et al, 2020; Maqsood et al, 2020; Mendelsohn et al, 1996; Meng et al, 2017, Mourtzinis et al, 2016; Nguyen et al, 2023; Ortiz-Bobea et al, 2019; Polsky et al, 2001; Ray et al, 2018; Wang et al, 2016; Zalud et al, 2017; Albers et al, 2017; Changnon et al, 2000; Di Poala et al, 2023; Feng et al, 2018; Galushko et al, 2022; Hamed et al, 2021; Heil et al, 2023; Lobell et al, 2011; Murray-Tortarolo et al, 2019; Plastina et al, 2021; Quiroga et al, 2009; Schaub et al, 2020; Sharma et al, 2019; Thomasz et al, 2020; Van Oort et al, 2012; Zipper et al, 2016; Finger et al, 2018
National level	15	Benito-Verdugo et al, 2023; Vaakan et al, 2024; Chandio et al, 2020; Dogan et al, 2010; Himanen et al, 2013; Karahasan et al, 2023; Mayer et al, 1999; Nasrullah et al, 2021; Chavas et al, 2017; Kalbarczyk et al, 2015; Powell et al, 2015; Reinermann et al, 2019; Sheng et al, 2019; Villa-Falfan et al, 2023; Deschenes et al, 2007
Other (e.g. European level)	7	Massetti et al, 2018; Quiédeville et al, 2022; Reidsma et al, 2007; Reidsma et al, 2009; Van Passel et al, 2017; Wu et al, 2017; Fabri et al, 2022

We build on the work by Ortiz-Bobea (2021) to classify the methods used in the existing literature to analyse climate impacts. They are categorised as follows: biophysical approaches (n= 2), Ricardian approach (n= 8) (e.g., Mendelsohn et al, 1996; Van Passel et al, 2017; Massetti et al, 2018; Fabri et al, 2022), standard panel approaches (n= 57) (e.g., Powell et a;, 2015; Zipper et al, 2016; Ortiz-Bobea et al, 2019; Pourzand et al, 2020; Gulino et al, 2023; Karahasan et al, 2023; Demirdogen et al, 2024), time series approaches (n= 2) (Hamed et al, 2021; Vanongeval et al, 2023), joint estimation of short and long run responses (n= 5) (e.g., Chandio et al, 2020; Çakan et al, 2024) , mixed statistical and biophysical approaches (n= 1), machine learning approaches (n= 4) (e.g., Feng et al, 2018; Beillouin et al, 2020) and other econometric approaches (n= 10) (e.g., Durant et al, 2018; Ray et al, 2018; Wang et al, 2021). While these categories are not an exhaustive list of all empirical approaches, they are useful for classifying the methods identified in this review. For a more in-depth discussion of some of these approaches, see Ortiz-Bobea (2021).

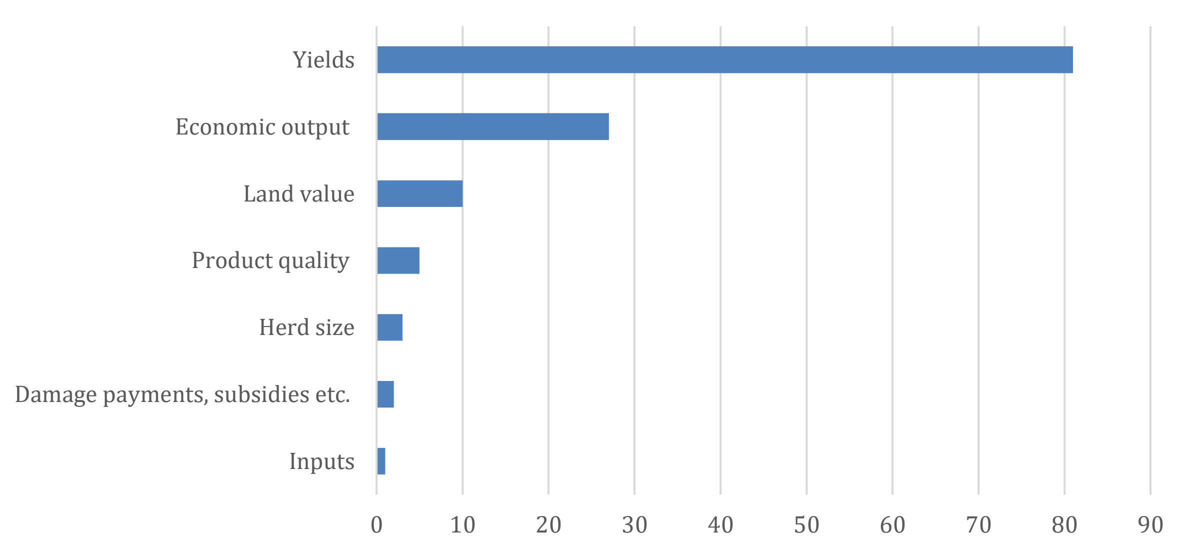
Standard panel approaches are the most commonly used method when analysing the impacts of climate change on agriculture. This result is unsurprising given that there is a long tradition of using longitudinal data to analyse weather conditions in agricultural economics, with a surge in interest within the scope of climate change following Deschênes & Greenstone's (2007) seminal work on the impacts of climate change in the agricultural sector. Jiang et al (2020) use a multiple linear regression model to quantify the relationships between corn yield and meteorological factors in the USA. They find that on average, extreme heat (KDD) is estimated to be the most stressful meteorological factor in most districts. Corn yield reduces by 0.011, 0.020, 0.022, and 0.008 Mg/ha for one unit of KDD increase in four growth phases, respectively. Increasing precipitation reduces yield by 0.002 Mg/ha per mm at the early vegetative stage, yet additional precipitation promotes yield by 0.006 and 0.005 Mg/ha per mm at the grain filling stage and 0.001 Mg/ha per mm at the late dry-down stage. Using a standard panel approach has allowed for the examination of climate impacts on corn yields over the course of the growing season. In a similar vein, Demirdogen et al (2024) estimate the impact of climate change on wheat production (yield and land) in Türkiye over the past 25 years using a panel data model with fixed effects. Results indicate that a 1°C increase in temperature is associated with a yield loss of approximately 6% and the observed 1.5°C temperature increase over the past 25 years has led to a yield loss of nearly 9%. They also find that temperature changes and drought events during May have a particularly significant impact on wheat yields. An increase of 1°C in May temperatures results in a reduction of approximately 4% in wheat yields and contribute to a decrease in the size of the harvested area, exceeding 6%.

In most of the models in environmental economics, weather and climate measurements are solely based on temperature records. In agricultural economics these measurements are often supplemented by rainfall observations in order to characterise agricultural returns patterns (Gallic & Vermandel, 2020). The climate changes analysed in the literature can be categorized as changes in weather patterns (i.e. fluctuations in temperature and precipitation), and extreme weather events (e.g. drought, heatwaves, floods etc) (Lucas et al, 2021). It is important to note that some studies consider more than one metric for instance, many examine both temperature and precipitation changes, or precipitation changes and drought. Both temperature and precipitation are widely explored in the literature (n= 50 and 53 respectively). Given that agriculture is dependent on weather conditions it is unsurprising that marginal changes in temperature and precipitation have been extensively studied. We observe a pattern among studies examining these changes that increases in precipitation in the short term tend to bring positive impacts for crop yields (although not in the long term), whereas crop yields tend to be negatively impacted by increases in temperature (Burke & Emerick, 2016; Çakan et al, 2024; Chandio et al, 2020; Dogan et al, 2018).

Among extreme weather events, drought is the most widely studied (n=14) (e.g., Zipper, 2016; Sheng, 2019; Schaub, 2020; Nguyen, 2023) followed by heatwaves and heat stress (n= 10) (e.g., Mukherjee, 2013; Finger, 2018; Schauberger, 2021; Fabri, 2022), storms/hurricanes (n= 5) (e.g., Durant, 2018; Huitu, 2020; Klatt, 2021), flooding (n= 3) (e.g.,Klatt, 2020; Wang, 2021; Pérez-Uribe, 2024) and frost events (n= 1) (e.g., Dalhaus, 2020). These studies suggest that drought has an overwhelming negative impact on agriculture in terms of yield and economic output (Benito-Verduga et al, 2023; Nguyen et al, 2023; Quiroga et al, 2009; Pérez-Uribe et al, 2024; Schaub et al, 2020; Sheng et al, 2019). Where drought may have the opposite effect on yield, other factors such as crop type (Ray et al, 2018) or location (Zipper et al, 2016) are at play. Far less attention has been paid to extreme weather events such as flooding, storms and hurricanes, and frost events. This lack of information on the potential impacts of these shocks represents a gap in knowledge and impedes preparation for adaptation.

The majority of studies assessed the impact of climate change on production (yield change, variability, or loss, including milk yields on dairy farms) (n= 81). A considerable proportion also assessed the impact of climate change on economic output (farm profitability, income, crop prices) (n= 27). Only one study examines the impact of climate change on input costs, for example fertiliser costs, which is also important for understanding the full financial impact of climate change and are also affected by changes in weather patterns and climate change (Schaub et al, 2020). Additional outcome variables include changes in farmland value (n= 10), herd size on livestock farms (n= 3), damage payments or subsidies (n= 2), and changes in product quality (n= 5). These results are summarised in Fig 5 below. As the main focus in the literature is on arable farming, there is also a gap in information on the livestock sector, in which understanding climate impacts and the need for adaptation is pivotal. Livestock systems face distinct climate risks—including heat stress, altered disease dynamics, and feed shortages—that require tailored adaptation strategies (Rojas-Downing et al, 2017). Neglecting this sector undermines food security, especially for smallholders and pastoralists who depend heavily on animal production and often have limited adaptive capacity. Moreover, livestock and crop systems are interdependent in many mixed farming contexts, meaning insufficient attention to livestock resilience can compromise whole-farm adaptation. In addition, a wide range of output variables have been used to convey the impacts of climate change on agriculture. Nevertheless, there is no standardised set of indicators to compare and contrast these impacts, or the climate metrics involved, making it difficult to quantify the exact economic consequences of changes in weather and climate conditions.

We also classify the climate impacts by timing- short, medium and long term. We define these as seasonal impacts (short term) (n= 48), annual impacts (medium term) (n= 28), and multi-annual impacts (long term) (n= 24). Some studies, especially those which employ long difference methods and joint estimation approaches, can be classified in more than one category. Long term impacts are the least studied within the literature and tend to focus on climate impacts on outcomes such as land value (Mendelsohn et al, 1996; Gonzàlez et al, 2008; Bozzola et al, 2018), which require analysis over a longer time period and/or use methodologies which lend themselves to analysing longer term impacts such as the Ricardian approach (Chatzopoulos et al, 2015; Massetti et al, 2018; Fabri et al, 2022). On the other hand, short term impact studies tend to focus on changes in yields as would be expected with seasonal impacts (Wu et al, 2017; Beillouin et al, 2020; Benito-Verdugo et al, 2023).



	Inputs	Damage payments, subsidies etc.	Herd size	Product quality	Land value	Economic output	Yields
Number of studies	1	2	3	5	10	27	81

Fig. 5. Types of impacts explored

*Some studies examine more than one impact

3.3 Adaptation strategies

A total of 47 studies explored adaptation in the agriculture sector. As is the case for climate impact studies, the majority of adaptation studies focus on arable farms (n=36) while dairy and livestock farms are less studied (5 studies respectively). The remaining studies explore mixed crop/livestock farms (n=1) or cover all farm types (n=5). In terms of the level of analysis conducted in these studies (Table 3), the largest proportion was conducted at the region or county level (n= 20), followed by at the farm level (n= 12), and the individual crop or plot level (n= 8). Fewer studies were conducted at the national level (n= 3) or European level (n= 4).

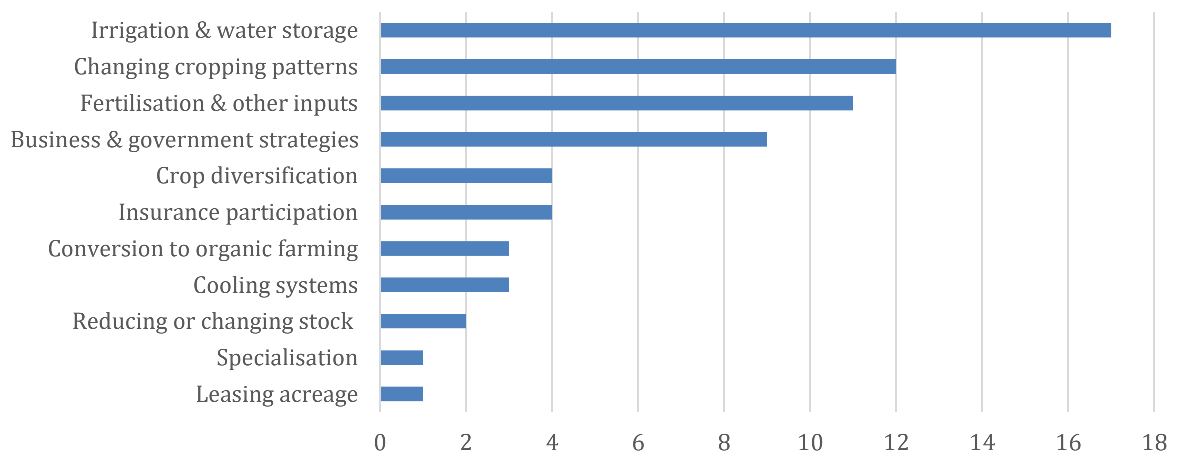
Table 3. Level of analysis of the adaptation studies

Level of analysis	**N of studies**	**References**
Individual crop/plot	8	Fernandez-Ortega et al, 2023; Petonen-Sainio et al, 2014;

		Quiroga et al, 2014; Ruiz et al, 2019; Wittwer et al, 2023; Bowles et al, 2020; Alayon-Gamboa et al, 2011; Domingos et al, 2021
Individual farm	12	Auci et al, 2023; Bouttes et al, 2019; Di Falco et al, 2014; Gafsi et al, 1997; Jordan et al, 2021; Láng et al, 2023; Mukherjee et al, 2013; Pexas et al, 2021; Vanschoenwinkel et al, 2018; Perez-Uribe et al, 2024; Skidmore et al, 2022; Zhang et al, 2018
Region/county level	20	Akbar et al, 2020; Burke & Emerick, 2016; Harkness et al, 2023; Kaugmann et al, 1997; Lee et al, 2016; Li et al, 2020; Lu et al, 2020; Parker et al, 2017; Patanita et al, 1029; Polsky et al, 2011; Smith et al, 2021; Wang et al, 2016; Wang et al, 2021; Jacobs et al. 2022; Kath et al, 2018; Whitbread et al, 2015; Zhang et al, 2015; Karapinar et al, 2020; Wheeler et al, 2014; Won et al, 2024
National level	3	Michalopoulos et al, 2020; Harkness et al, 2021; Matsushita et al, 2016
Other (e.g. European level)	4	Reidsma et al, 2007; Reidsma et al, 2009a; Reidsma et al, 2009b; Reidsma et al, 2010

In terms of the methods used in the studies examining the effectiveness of adaptation, a range of approaches have been implemented. The studies employed the Ricardian approach (n= 2) (Polsky et al, 2001; Vanschoenwinkel et al, 2018), standard panel approaches (n= 29) (e.g., Reidsma et al, 2010; DiFalco et al, 2014; Wang et al, 2016; Karapinar et al, 2020; Wittwer et al, 2023), time series approaches (n= 1) (Matsushita et al, 2016), joint estimation of short and long run responses (n= 4) (e.g., Di Falco et al, 2008; Foudi et al, 2011), machine learning approaches (n= 1) (Akbar et al, 2020), and other econometric approaches such as sensitivity analysis and principal-agent models (n= 12) (e.g., Zhang et al, 2018; Pexas et al, 2021). As is the case for impact studies, standard panel data approaches have been the most used methods throughout the included literature. Joint estimation of short and long run responses as introduced by Moore & Lobell (2014) combine elements of panel approaches and cross-sectional methods to jointly estimate the short- and long-term impacts of climate change and adaptation (Ortiz-Bobea, 2021). Di Falco et al (2008) investigate the effects of rainfall shocks on agroecosystems productivity and how increasing the level of spatial crop diversity can mitigate negative impacts in Italy using the joint estimation approach. They find that crop biodiversity ensures that the agroecosystem remains productive when facing low or scarce rainfall both over the short and long term. These findings indicate crop diversification can be a long-term adaptation strategy that can continue to bring benefits to farmers beyond a seasonal timeframe. This can encourage investment in this strategy and increase adoption. While several of the included studies employ this method there is scope for this approach to be utilised further to conduct longer term experiments and better understand the costs and benefits of adapting to climate change.

An array of adaptation tools and strategies have been adopted to cope with the impact of climate change. In response to droughts, irrigation (e.g. Auci et al, 2023; Jordan et al, 2021; Lu et al, 2020), water storage (e.g. Smith et al, 2021; Wheeler et al, 2014) and crop diversification (e.g. Di Falco et al, 2008; Bowles et al, 2020) have been studied. In response to more frequent heat waves, some economic agents have installed cooling systems (e.g. Li et al, 2020; Mukherjee et al, 2013; Pexas et al, 2021). Additionally, certain strategies are policy-driven rather than driven by the autonomous decisions of farmers, such as participation in agri-environment schemes and other government strategies (e.g. Won et al, 2024; Aláyon-Gamboa et al, 2011). On livestock farms, steps have been taken to reduce herd sizes (which also allows for meeting climate change mitigation goals) or change to breeds that are more resilient and better suited to new weather conditions (e.g. Akbar et al, 2020; Skidmore et al, 2022). Other strategies include changing cropping patterns and tillage systems (Whitebread et al, 2015; Ruiz et al, 2019; Peltonen-Sainio et al, 2014), participating in insurance schemes (e.g. Kath et al, 2018; Wang et al, 2021), leasing additional acreage (e.g. Zhang et al, 2018), adopting or changing fertilization techniques and/or quantities (e.g. Peréz-Uribe et al, 2024; Reidsma et al, 2009a; Reidsma et al, 2009b), and converting to organic farming (e.g. Bouttes et al, 2019; Reidsma et al, 2007). See Fig 6 below for a complete overview of the adaptation strategies identified in the literature.



	Leasing acreage	Specialisation	Reducing or changing stock	Cooling systems	Conversion to organic farming	Insurance participation	Crop diversification	Business & government strategies	Fertilisation & other inputs	Changing cropping patterns	Irrigation & water storage
Number of studies	1	1	2	3	3	4	4	9	11	12	17

Fig. 6 Adaptation strategies explored in the literature

Although adaptation may seem like a simple concept of adjusting behaviours, actions, and decisions within biological, social, and built systems in response to climatic changes (Smit & Pilifosova, 2001), it has proven difficult to reach consensus within the literature on a definition. Robert et al (2016) classify adaptation strategies through timing, temporal and spatial scopes. Timing refers to whether adaptation is proactive (anticipatory) or reactive (a response after a shock). Temporal refers to whether adaptation is strategic (long term adjustments) or tactical (short term adjustments). Spatial refers to whether adaptation is localised (e.g. a single crop) or widespread (e.g. farm system). Adaptation can also be autonomous (a decision made solely by the farmer at the farm level) or dependent (based upon changes in policies or subsidies) (Forsyth & Evans, 2013). The most used classification in the literature is reactive versus proactive adaptation (Engler et al, 2021). However, despite the agreement on the definition of reactive and proactive adaptation, the strategies that can be included in each category can vary depending on the case study. For example, the widely used practice of changing the timing of sowing and harvesting has been classified as both proactive and reactive by different scholars. Therefore, an adaptation strategy could be both depending on if it is a response (reactive) or a coping mechanism (proactive) (Carman & Zint, 2020).

Proactive refers to anticipated adjustments, also referred to as anticipatory or ex ante adaptation. Of the included studies, 29 referred to proactive adaptation including crop diversification and insurance participation. Reactive refers to adaptation performed after a shock and is also referred to as responsive or ex-post adaptation. As expected, more studies have focused on reactive adaptation such as changing stock sizes or cropping patterns (n= 34). Localised adaptation is usually conducted at the plot scale whereas widespread adaptation usually concerns the entire farm. Of the studies included in the present review, 32 studies explore localised adaptation. Examples include installing cooling systems in barns or changing cropping patterns. Twenty-eight studies examine widespread adaptation including conversion to organic farming. Strategic adaptation is the capacity to adapt in the long term (years). A total of 24 studies discuss adaptation that can be classified as strategic such as changing livestock breeds or leasing acreage. Tactical adaptation is instantaneous short-term adjustments over a seasonal to daily timescale, for example, changing cropping patterns or fertiliser use. A greater proportion of the studies discuss tactical or short-term adaptation (n= 40) (Table 2).

Table 2. Adaptation dimensions

	TIMING		**TEMPORAL**		**SPATIAL**	
	Proactive	**Reactive**	**Tactical**	**Strategic**	**Localised**	**Widespread**
Number of studies	29	34	40	24	32	28

Given the uncertainty of climate change and its impacts, it is difficult for farmers to anticipate a shock and adapt accordingly in a proactive manner. This is exacerbated by lack of knowledge or insufficient information on climate change (Robert et al, 2016). However, to reduce the impacts of climate change, it is crucial for farmers to take more proactive, anticipatory steps to minimise damages. To encourage farmers to undertake proactive steps to adapt, it is crucial that information on long term climate impacts is distributed. Within the included studies, there is also a pattern of autonomous adaptation dominating over planned, dependent adaptation. Autonomous adaptation has been a controversial topic within the literature, with economists arguing that this type of adaptation is inefficient and likely reduces the urgency surrounding necessary, planned interventions from governments or other key stakeholders (Stern, 2007; Eisenack, 2009; Forsyth & Evans, 2013). Therefore, more evidence is needed to identify how autonomous adaptation might connect with planned adaptation and there is greater need for governments to step up with efficient interventions to reduce the burden on individual farms.

3.4 Effectiveness of adaptation practices

In this section, we present the effectiveness of adaptation practices reported in the included studies. The majority of the studies reported negative effects of climate change (n= 60). Only five studies reported positive effects while 23 studies reported both positive and negative effects of climate change. The majority of studies assessing the effectiveness of adaptation strategies report positive impacts (n= 34). Only four studies reported solely negative effects of adapting (Wang et al, 2021; Skidmore, 2022) while the remainder reported both positive and negative effects (n= 12) depending on other conditions such as crop types or timing, and of course how the authors define "positive" or "negative" impacts. In an example of a negative impact of adapting, Wang et al (2021) demonstrate that participation in a crop insurance programme led to more detrimental impacts on crop yields as farmers did not feel the need to implement other adaptation strategies owing to their insurance participation. However, in Australia, Kath et al (2018) found that participating in an excessive rainfall index insurance scheme could make sugar cane farmers better off by 269.85 AUD/ha on average in years with excessive rainfall.

Irrigation was the most commonly studied adaptation measure and has proven to have a largely positive effect by enhancing revenue through increased yields (Polsky et al, 2001). For example, in the USA both Li et al (2020) and Lu et al (2020) find that irrigation leads to yield increases. Li et al (2020) find that yields are increased by 12.28% per acre while Lu et al (2020) find that crop yields increase by 147%, 139%, 132% and 124% for spring wheat, hay, corn silage and corn grain respectively. Changing cropping patterns is another commonly studied adaptation strategy and has also led to generally positive results. In Hungary, Làng et al (2021) demonstrate how when combining barley and sweet corn yields during double cropping the overall crop yield was 18.5 tonnes/ha compared to single cropping which yields 5.6 tonnes/ha. However, in Switzerland Wittwer et al (2023) find pronounced and consistent yield reductions due to experimental drought events for all cropping systems. In Table 4 below, we further compare the effects of climate change with the impacts of adaptation in order to demonstrate the effectiveness of adaptation in boosting resilience in the agriculture sector.

Adaptation is only efficient if the cost of making an adjustment is less than the resulting benefits. Results suggest that adaptation will reduce damages caused by climate change. However, while efficient adaptation responses can reduce the overall impacts associated with climate change, inefficient adaptation can increase costs (Mendelsohn, 2006), and as such maladaptation should be avoided. The example outlined in Wang et al (2021) where participating in insurance schemes led to a decrease in planned adaptation demonstrates how adaptation strategies can sometimes not have the desired effect. A similar effect can be observed in the mitigation literature where some strategies such as carbon removal can deter or delay mitigation efforts (McLaren, 2016). Therefore, this mitigation deterrence theory could also be transferred to the adaptation literature as 'adaptation deterrence'. This is particularly pertinent for insurance schemes, government strategies and subsidy payments which can prevent other adaptation strategies that aid in reducing or preventing further damage. Careful planning and further research into the effectiveness of climate adaptation can prevent maladaptation from increasing the damages associated with climate change in the agriculture sector.

Table 4. Examples of net benefit of adaptation by strategy

Main adaptation strategies	**Studies**	**Country**	**Examples of net benefit of adaptation**
Irrigation & water storage	Akbar et al, 2020; Auci et al, 2023; Foudi et al, 2011; Jordan et al, 2021; Li et al, 2020; Lu et al, 2020; Patanita et al, 2019; Pérez-Uribe et al, 2024; Polsky et al, 2001; Quiroga et al, 2014; Reidsma et al, 2009a; Reidsma et al, 2009b; Reidsma et al, 2010; Smith et al, 2021; Vanschoenwinkel et al, 2018; Wang et al, 2016; Zhang et al, 2015	USA; Italy; France; Chile; USA; USA; Portugal; Colombia; USA; Spain; Europe; Europe; Europe; USA; Europe; USA; USA	Irrigation leads to a yield increase of 12.28% per acre (Li et al, 2020). Irrigation plays an important role in boosting the crop yield, with the highest increases for spring wheat (147%), hay (139%), corn silage (132%), and corn grain (124%) (Lu et al, 2020). Arid regions with access to stored water avoided the 13% losses in crop value experienced in irrigated areas with more limited storage during droughts (Smith et al, 2021). Irrigation serves as a self-insurance. Irrigating farmers have higher means but lower variance of profits than non-irrigating farmers. However, for already irrigating farmers using more water volumes increases the variance of outcome (Foudi et al, 2011).
Crop diversification	Burke et al, 2016; Bowles et al, 2020; Di Falco et al, 2008; Matsushita et al, 2016	USA; USA; Italy; Japan	More diverse rotations increased maize yields (28.1% on average), including in favorable conditions (22.6%). Notably, more diverse rotations also showed positive effects on yield under unfavorable conditions, whereby yield losses were reduced by 14.0%, and 89.9% in drought years (Bowles et al, 2020).
Cooling systems	Li et al, 2020; Mukherjee et al, 2013; Pexas et al, 2021	USA; USA; Sweden	Cooling systems contribute to an annual increase in gross revenues of between \$106,830 and \$162,631(Mukherjee et al, 2013). Farm profitability improved by +6.79% with showers and +3.37% with increased air velocity (Pexas et al, 2021).
Business & government strategies	Alayón-Gamoa et al, 2011; Gafsi et al, 1997; Harkness et al, 2021; Harkness et al, 2023;	Mexico; France; UK; UK; USA; Europe; Europe; Europe; USA	Monetary surpluses have increased considerably thanks to the high level of MW subsidies given to farms (140000FF on average) and to bonuses from the European Union (CAP) and from the French State. The

	Polsky et al, 2001; Reidsma et al, 2009a; Reidsma et al, 2009b; Reidsma et al 2010; Won et al, 2024		increase in monetary surplus has enabled the farmers to increase their private expenditure by 90% on average and to make large investments (Gafsi et al, 1997). An increase in agri- environment payments per hectare decreases the variability of income for mixed farms by 6% whereas increases the variability income by 3% for cereal farms. Subsidies therefore have a smaller relative effect on the variability of income, in comparison to the farming practices examined in this study (Harkness et al, 2023). Counties with higher levels of government program participation have higher land values (Polsky et al, 2001).
Reducing or changing stock	Akbar et al, 2020; Skidmore et al, 2022	USA; Brazil	The hybrid breed is expected to be smaller, travel longer distance for water, use a wider variety of forage and would be more resilient to temperature; but it will take at least a decade to find out whether the hybrid was a success for the Southern Utah landscape and climatic conditions or not (Akbar et al, 2020).
Specialisation	Harkness et al, 2021; Harkness et al, 2023	UK; UK	For general cropping farms specialisation has a large relative effect; increasing specialisation by 1 standard deviation increases the variability of income by 13% (Harkness et al, 2023).
Leasing acreage	Zhang et al, 2018	USA	A one-inch precipitation increase reduces leased land by 44 acres. Projections estimate that by 2050, leased acreage on average will decline by 23% under RCP 4.5 and 29% under RCP 8.5 (Zhang et al, 2018).
Changing cropping patterns	Domingos et al, 2021; Fernández-Ortega et al, 2023; Jacobs et al, 2022; Karapinar et al, 2020; Làng et al, 2023; Lee et al, 2016; Michalopoulos et al, 2020; Parker et al, 2017; Peltonen–Sainio et al, 2014;	England, Spain, USA; Türkiye; Hungary; South Korea; Greece; Germany; Finland; Spain; Australia; Switzerland	Date and cultivar adaptation increase yields of adapter households by 16% and 31% respectively (Karapinar et al, 2020). By combining barley and sweet corn yields during double cropping, the overall crop yield was 18.5 tonnes/ha; compared to single cropping 5.6 tonnes/ha (Làng et al, 2023).

	Ruiz et al, 2019; Whitbread et al, 2015; Wittwer et al, 2023		Results indicate an increase of 46 kg ha for every day earlier that the crop is planted (Parker et al, 2017). When early sowing occurred with late maturity, yields were at their highest for all cereals (barley 5710kgha) (oat 5930kgha) (wheat 4700kgha). For barley, the yield was enhanced by a combination of early sowing and late maturity by 0.15, in oat by 0.19 and in wheat by up to 0.24. In oat and wheat, such combinations were also associated with high single grain weight (Peltonen-Sainio et al, 2014).
Insurance participation	Di Falco et al, 2014; Kath et al, 2018; Wang et al, 2021	Italy; Australia; USA	Index insurance could make farmers better off by $269.85 AUD/ha on average in years with excessive rainfall (Kath et al, 2018).
Fertilisation & other inputs	Fernàndez-Ortega et al, 2023; Harkness et al, 2021; Harkness et al, 2023; Kaufmann et al, 1997; Michalopoulos et al, 2020; Patanita et al, 2019; Pèrez-Uribe et al, 2024; Reidsma et al, 2007; Reidsma et al, 2009a; Reidsma et al, 2009b; Reidsma et al, 2010; Wang et al, 2016	Spain; UK; UK; USA; Greece; Portugal; Colombia; Europe; Europe; Europe; Europe; USA	Using fertilizer has the most consistent association with yields as it increases yields by 0.8, 0.02, and 0.24 t/h for plantains, coffee, and cassava, respectively (Pèrez-Uribe et al, 2024). Fertilizer intensive farmers can largely reduce the negative effects of higher temperatures in the UK, France and Italy, while in other regions, the effect is small or even negative (Reidsma et al, 2010). On average, a $10/acre increase in fertilizer use can lead to a yield increase around 9 kg/acre for cotton, and about 0.12 ton/acre for hay (Wang et al, 2016).
Conversion to organic farming	Bouttes et al, 2019; Di Falco et al, 2008; Wittwer et al, 2023	France; Italy; Switzerland	Following conversion to organic farming, farm self-sufficient milk productivity in 2012 ranged from 2558 to 4932 kg milk/ha/year, economic efficiency in 2012 ranged from 1.5 to 6.5, and profitability per worker in 2012 ranged from 12 to 84 EUR/year (Bouttes et al, 2019).

Source: Own elaboration

4. Conclusion

In this systematic review, our aim was to evaluate the impact of climate change on the agriculture sector and examine the effectiveness of adaptation strategies responding to these impacts. Examining 124 studies, we sought insights into the methods and metrics used to assess the impacts of climate change on agriculture, what the effects of changes in the climate system are, which adaptation strategies are employed, and how effective these strategies are.

In terms of the metrics used within the literature, marginal changes in temperature and precipitation have been studied most frequently. This is unsurprising given that agriculture is highly dependent on weather patterns. Yet it is important to note that climate change will also exacerbate extreme weather events and therefore these should be examined further. Drought has been extensively studied in the literature however other extreme events such as storms and frost events have not. While a range of methods have been identified in this review, standard panel approaches have been employed most often. We find that there is scope for further studies employing joint estimation of short and long run responses to better understand the long-term costs and benefits of adaptation.

In examining climate impacts on agriculture, it is evident that there are overwhelmingly negative effects across the sector, including decreasing yields, reductions in product quality, and loss of income. Given that the majority of studies focused on arable farming, changes in yield were most frequently examined in the literature. The least studied impact was changes in input costs, indicating a gap in knowledge surrounding the full economic costs of climate impacts on agriculture.

A wide range of adaptation strategies have been identified in the literature. Those which have received more attention have been irrigation, changing cropping patterns, and fertilisation and other inputs. Conversely, leasing acreage, specialisation and reducing or changing stock have been identified as the least studied strategies. Overall, adaptation tends to be reactive, short term and localised. Thus, there is a lack of forward planning where climate change is concerned within the sector, leaving farmers vulnerable to future threats from a changing climate. Nonetheless, we find that adaptation has a generally positive role to play in reducing the negative impacts of climate change.

Given these findings, this review highlights several important implications for future research. While there is abundant data on the impact of climate change on farm output, the effects on input costs such as fertilizer, water, and labour, have not been extensively studied. Understanding these cost variations is crucial for a more comprehensive assessment of the economic impacts of climate change, particularly given that fertilisation and other inputs have been identified as a widely used and effective adaptation strategy. In terms of adaptation strategies studied, there is a lack of research into organic farming, diversification, specialisation, leasing acreage and cooling strategies while irrigation, government strategies, fertilisation and changing crop patterns have been widely studied in the literature. Additionally, the literature suggests a need for long term experiments to evaluate the costs and benefits of adaptation strategies as current research predominantly focuses on short term investments and impacts therein. Another key recommendation is the need to understand the pros and cons of the various methods and indicators used to assess climate impacts on agriculture, as well as the opportunities and challenges that new data and technologies present to the industry and researchers. This understanding would facilitate easier comparison across studies and help in developing more effective management strategies for both farmers and policymakers. There are also other factors at play in the adoption and effectiveness of adaptation strategies that have not been the focus of this review such as extension services, land tenure security and farmer perceptions. These provide other potential avenues for future interdisciplinary research. While every effort was made to make this review as comprehensive as possible, it is limited by the decision to exclude grey literature and non-English studies, particularly in underrepresented contexts and these would provide further detail in future reviews.

This review also formulates a number of policy implications. For instance, while the majority of studies assess impacts on arable agriculture, there is also considerable evidence that climate change impacts and the need for adaptation is pivotal also in the livestock sector (aside the well-known importance of climate change mitigation). Capacity building and knowledge exchanges through participatory approaches will prove invaluable. The assessment of effectiveness and associated costs and benefits of specific impacts and adaptation strategies can contribute to forward planning both on the part of farmers and policymakers.

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