

Modeling future scenarios of sustainable agricultural innovations adoption: an MCE analysis of
biodegradable mulch suitability

by

Michael Biwalib Madin

B.S., Kwame Nkrumah University of Science & Technology, 2017
M.A., University of Denver, 2020

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography & Geospatial Sciences
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KANSAS STATE UNIVERSITY
Manhattan, Kansas

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Abstract

Whilst agriculture production faces the challenge of feeding a growing population in the midst of global environmental change, farmers adoption of sustainable innovations to help adapt remain limited. Though a key constraint of adopting many innovations is suitability in a given biophysical context under current and future scenarios, there exist scarce studies on how suitability varies across spatial and temporal extent. Prior studies on factors influencing adoption of innovations have also rarely synthesized evidence on direction of effects. This paradox raises critical questions for research in human-environment geography. The aim of this dissertation is to investigate some of these questions, with particular emphasis on assessing the spatial biophysical suitability of biodegradable mulch (BDM) under recent and future scenarios, and direction of effects of adoption factors. The research combines insights from systematic reviews and GIS-based fuzzy multicriteria analysis techniques. The GIS-based model was used to assess the spatial biophysical suitability of BDM across the conterminous USA. The study identified the Plains, Pacific, and Corn Belt regions as high adoption potential sites, where favorable biophysical suitability (59–99% suitable areas) aligns with enabling socioeconomic conditions (e.g., higher net farm incomes and education levels). Overall, the results suggest that if the world takes the path of SSP370 or SSP585 representing higher emissions with limited mitigation, BDM will have increased relevance as an adaptation with potential to replace plastic mulch and enhance crop production in many areas of the U.S. Theoretically, the study sheds light on how sustainable agricultural innovations are not universally applicable but are highly dependent on local conditions and underline the need for place-based strategies. In the end, it is argued that we will risk obscuring and replicating the very mechanisms in which the current level of sustainable innovation adoption is limited if we fail to promote region-specific strategies.

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Chapter 1 - Problem, Concept, and Setting

1.1 Introduction

This chapter sets the context for the main analysis and arguments in the dissertation. It is organized around four broad sections. The first section presents the challenge of global agricultural (crop) production, drawing attention to increasing plastic mulch application, associate microplastic pollution, and barriers of sustainable innovations or practices adoption. Following this contextualization, the chapter raises key research questions and situates them within the U.S. farm production regions and the broader context of global food systems. The following sub-section outlines the modeling approach and conceptual framework for the dissertation. Particular emphasis is given to how the conceptual framework guides the research questions, frames the methodology, and shapes the modeling approach and interpretation of data. The study context is then introduced, with a description of the U.S. farm production regions and counties, and the relevance of BDM applications to regional agricultural productivity and sustainability. The final section outlines four major manuscripts that set forth the main arguments in the dissertation.

1.2 The Problem: Sustainable Agricultural Innovations Transition

The agriculture sector is facing the unprecedented challenge of feeding a growing population in the face of global environmental change— twin potentially major stressors to the food production systems. For instance, the U.S. in recent decades has experienced climate events such as droughts and precipitation variabilities, which are projected to intensify under the Representative Concentration Pathway (RCP) 8.5, where all counties could permanently exceed their baseline variability of occurrence by 2050 (Batibeniz et al., 2020; Cook et al., 2015). There is an estimated declined in dry land corn and soybeans yield by 30-46% due to droughts and

rising temperature across U.S. (Schlenker & Roberts, 2009). Warming is estimated to decrease farmland value by 27–69% (Carter et al., 2018), and reduce current annual agricultural profits by about 30% by 2100 (Deschênes & Greenstone, 2007a). The impacts on agricultural production systems and environmental degradation demand a transition towards more sustainable innovative practices (Piñeiro et al., 2020a; Smith et al., 2020). Thus, sustainable practices or innovations have long been expected to contribute to the reduction and reversal of the processes of environmental degradation (FAO, 1989a). Moreover, the potential benefits of sustainable innovations lie not only in conserving but also in enhancing natural resources (increasing soil fertility and soil organic matter) without sacrificing yield gains (Kassie et al., 2013a). These practices also have positive impacts on soil biodiversity and food security through retaining fertile and functioning soils (Kassie et al., 2013a; Piñeiro et al., 2020a). Specifically because poor soil fertility is considered as one of the main limiting factors for increasing per capita food production (Kassie et al., 2013a; Morris et al., 2007).

Innovative practices that promote better soil health and water retention for crop growth remain crucial to sustaining agriculture production. Mulching as a farming practice, in particular, serves a vital role in maintaining soil moisture and retarding soil water evaporation, which are helpful in adapting to dwindling precipitation and water-stress (Cook et al., 2015; E. Liu et al., 2021; Ni et al., 2016). It also serves as a means of controlling weeds and moderating soil temperature in marginal lands prone to weed invasion and freezing (Eswaran et al., 2019; Schettini et al., 2004a). These vital roles provide valuable services that reduce irrigation requirements, decrease the use of inorganic herbicides inputs in weed control, and minimize nutrient leaching (Samuelson, Reid, et al., 2022; Vox et al., 2013). However, low-density polyethylene-based mulches (hereafter referred to as plastic mulch) are predominantly being

used for mulching in agriculture (Akhir & Mustapha, 2022; Transparency Market Research, 2013).

For example, as far back as 1999, approximately 12.14 million hectares of global cropland were covered with plastic mulch, including over 74,866 hectares in the U.S. (American Plastics Council, 2004; Takakura & Fang, 2002). Moreover, in 2006, plastic mulch films in the U.S. were estimated to be used on 400,000 ha (Miles et al., 2007) while 2.6 million metric tons of films were applied globally as of 2005 (Briassoulis & Dejean, 2010). In recent studies, the U.S. is estimated to use 453,592 metric tons of plastic every year in the production of crops (Fessenden, 2019; Velandia et al., 2020). But plastic mulches take a longer period to degrade and are associated with ecologically and agronomically detrimental outcomes (Akhir & Mustapha, 2022; Bandopadhyay et al., 2018a). For instance, plastic mulch applications have caused a serious environmental challenge of plastic wastes in soil and landfill sites (Immirzi et al., 2009; Vox et al., 2013). Yet, when microplastics in soil exceed 37.5 kg/ha, crop productivity is significantly affected due to reduction in tiller number by 17% and reduced in emergence of seedlings by 25%. Also, while plastic mulch materials are chemically inert, accumulated fragments can affect physical soil properties and possibly enter the food chain (Duis & Coors, 2016; Huerta Lwanga et al., 2016).

Given the above, BDMs have been developed as a more sustainable alternative to plastic mulch and are designed to degrade by soil microorganisms, thereby eliminating the issue of microplastics pollution (Akhir & Mustapha, 2022; Bandopadhyay et al., 2018a; Fomin & Guzeev, 2018). BDM constitutes a family of polymers that are designed to degrade through the action of soil living organisms (Bastioli, 1998). The Food and Agricultural Organization (FAO) defines sustainable agriculture innovations as practices that produce food and nutrition for all in a way

that economic, social, and environmental bases of agriculture production for future generations are not compromised (FAO, 2018a). The adoption of BDM among farmers would help make agriculture production more sustainable by replacing plastic mulch materials— which take a longer period to degrade and are associated with ecological and agronomically detrimental outcomes (Akhir & Mustapha, 2022; Transparency Market Research, 2013).

The use of BDM as a case study presents unique opportunities for several reasons. First, BDM are more environmentally friendly because they are made from renewable feedstock and can easily biodegrade in the soil within the growing season (Akhir & Mustapha, 2022; Bandopadhyay et al., 2018a; Fomin & Guzeev, 2018). Second, the probability of farmers adopting the mulch is dependent on local climate variabilities and soil characteristics (E. Liu et al., 2021), leading to possible heterogeneity based on future scenarios. Third, the probability of farmers adopting the mulch is expected to be dependent on the rate and certainty of degradation of the materials (Goldberger & Lyons, 2017; Samuelson et al., 2022), which is mainly influenced by site specific climate and soil characteristics. For example, Samuelson et al. (2022) found that site specific soil biophysical attributes influence the rate of degradation of BDM, which in turn influences farmers' decisions to adopt.

Moreover, the likelihood of adoption is also determined by farmers' income and cost of the mulch (Goldberger & Lyons, 2017; Marí et al., 2019; Velandia, Smith, et al., 2019). Thus, potential savings from labor to remove plastic scrabs on the field and disposal fee associated with plastic mulch application make BDM a feasible replacement alternative. Despite BDM potential to improve agriculture sustainability, its adoption and application among farmers is reported to be limited (Goldberger & Lyons, 2017; A. A. Thompson et al., 2019; Velandia, Smith, et al., 2019). For instance, a survey by Velandia et al. (Velandia et al., 2020) found that

only 15% of the sampled farmers in Tennessee used BDM while over 60% reported using plastic mulch.

In broader context, Piñeiro et al. (2020) noted that farmers decisions to adopt sustainable innovations are determined by the effect of the innovation on environmental, economic, and productivity outcomes. Farmers adoption decisions were also found to be driven by their socio-economic characteristics such as education, income, and access to credits (Begho et al., 2022; Knowler & Bradshaw, 2007; Prokopy et al., 2019). On the other hand, Foguesatto et al. (2020) found adoptions to be mediated by attributes of a given sustainable innovation and farmers psychological factors. Moreover, farmer-exogenous factors such as climate variabilities and soil characteristics are found to be significant determinants of farmers' adoption of sustainable innovations. For instance, Kassie et al. (2013) and Teklewold et al. (2013) showed that both the probability and the extent of adoption of sustainable innovations among farmers are influenced by rainfall and plot-level disturbances (e.g., insects and disease shocks, land tenure, and farm size). Jin et al. (2015) indicated that higher estimations of farm losses from climate variability had positive influence on farmers' decisions to adopt sustainable innovations. Similarly, Kpadonou et al., (2017) observed that climate knowledge is positively associated with the adoption of sustainable innovations. Samuelson et al. (2022) found that site specific soil attributes influence innovation application suitability, which in turn influences farmers' adoption decisions.

Although above studies have provided important syntheses of information from empirical studies, the results on the factors that influence adoption of sustainable innovations remain too general and lack connections across various practices. For instance, enabling factors such as stronger social networks, higher educational attainment, and income are associated with farmers'

likelihood of adoption, while poor soil fertility, access to markets, and limited access to credit are often viewed as barriers. Moreover, the synthesized findings are often reported without specificity to the type of practices (Knowler & Bradshaw, 2007) or are applicable only to specific geographic contexts (Begho et al., 2022; Foguesatto et al., 2020). It also remains unclear whether the enabling and barrier factors are consistent across all practices and regions. Prokopy et al. (2019) provided some details on the consistency, direction and strength of effects of a wide range of factors on adoption but only considered conservation practices in the U.S. and did not distinguish effects across specific practices. The current evidence makes it challenging to incorporate the relevant factors into certain modeling exercises that require prior specification of the direction of influence.

While adoption decisions are multi-faceted and depend on many socio-economic and biophysical factors, one key component of adoption decisions is determining if a practice is suitable for application within a specific environmental (biophysical) condition (Fleskens et al., 2014; Piñeiro et al., 2020a). Similarly, Moxey et al. (2010) noted that farmers make adoption decisions based on technological constraints and profitability, with biophysical suitability forming a crucial part of the technological constraints of the innovation to be adopted. In the case of BDM, biophysical suitability determines the ability of the product to provide agronomic benefits for crop growth and degrade within regulatory required time limits (Hayes & Flury, 2018; Madin et al., 2024). For example, Goldberger et al. (Goldberger et al., 2015) observed varied concerns on unpredicted degradation across diverse sites, with farmers in Tennessee being more concerned about faster degradation and those in Mount Vernon, Washington and Lubbock, Texas being worried about slower degradation.

More recent studies have attempted to model the effects of biophysical factors on agriculture or their influence on farmers decision-making at plot-level including adoption of sustainable innovations (Al-Agele et al., 2021; Deng et al., 2019; Kutlu et al., 2021; Ladrera & Cagasan, 2022). Yet, these studies maintained a primarily present-tense focus, and only rarely has research directly engaged in projecting or modeling the future scenarios of the prospects of farmers adopting sustainable innovations. Among the few studies that have engaged in modeling future scenarios, Deng et al. (2019) for example simulated the effects of BDM on crop yield and water use efficiency under various future climate scenarios, employing bare land cultivation as a control. However, the study relied on validation at a single experimental site and did not provide a spatially explicit representation capable of depicting variations in the effects of the BDM use across different locations under future conditions.

Whereas a shift in the future scenarios of the aforementioned factors (particularly climate variables) is likely to influence farmers' adoption decisions, there remain limited studies on how these scenarios could possibly change in the context of sustainable agricultural innovations suitability. As such, this research seeks to model future scenarios of site suitability in a spatially explicit extent across the contiguous U.S. using BDM. To fill the above knowledge gap, this dissertation aims to assess the prospects of BDM suitability for agricultural application through the following questions:

1. What factors influence (significance and direction of effects) farmers' decision to adopt sustainable practices or innovations?
2. What biophysical factors influence BDM site suitability for agriculture application?
3. What is the extent of biophysical site suitability of BDM across the U.S. now and under different future scenarios?

This dissertation aims to analyze, model, and explain the answers to these questions. What unfolds is a comprehensive attempt to better understand the spatio-temporal variability of biophysical suitability for BDM applications within farm production regions in the contiguous U.S. The first question (1) is the focus of Chapter 2. Question 2 is examined in Chapter 3. While Question three is taken up in Chapter 4.

Research in sustainable agriculture context using geographic perspectives can significantly inform and extend the knowledge on innovation adoption amidst global environmental change. I use the vantage point of sustainable agriculture framework and GIS models to contribute to the broader debate. In many respects, the case study presented in this dissertation is a localized version of events taking place around the world although emphasis is placed on U.S. All the empirical chapters are linked to inherent problems in the global food system and further reveal the far visible changes likely to occur under various future climate scenarios. The following sub-section presents the concept and modeling approach underpinning the arguments and methodology in the empirical chapters of the dissertation.

1.3 Conceptual Framework and Adoption Theories

1.3.1 The concept of sustainable agriculture

Each chapter in the dissertation empirically focuses on specific research questions, situated in sustainable agriculture framework, and engages relevant literature to make its substantive arguments. The concept of sustainable agriculture emerged from the Brundtland World Commission Report on Environment and Development in 1987. The concept is rooted in the principle that humans must meet the needs of the present without compromising the ability of future generations to achieve their own needs (Tait & Morris, 2000). Hence, responsible management of both natural and human resources holds significant importance within

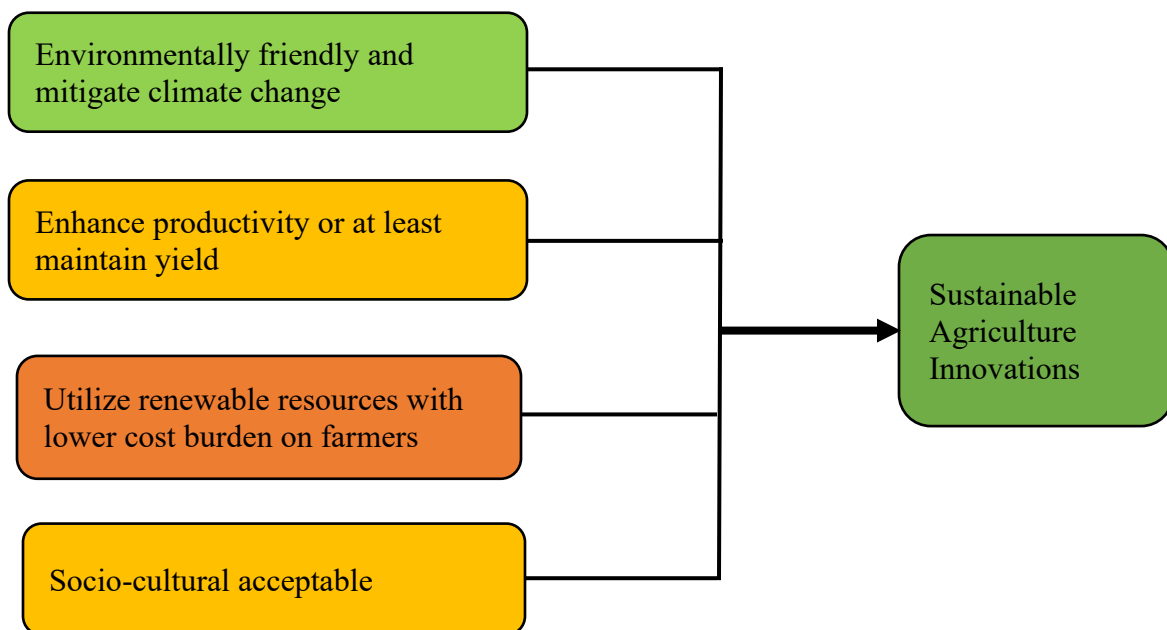
sustainable agricultural systems (Brodt et al., 2011; Goldman, 1995; Hansen, 1996). The FAO (1989) outlined that sustainable agriculture should encompass the following goals: (i) conserving land, water, animals, and plants; (ii) demonstrating environmental friendliness; (iii) adopting suitable technology; (iv) ensuring economic viability; and (v) garnering social acceptance.

According to U.S. Farm Bill, sustainable agriculture represents an "integrated system of plant and animal production practices with specific applications that, in the long run, aim to: (a) fulfill human food and fiber requirements; (b) enhance environmental standards; (c) optimally utilize non-renewable and on-farm resources, integrating natural biological cycles and controls; (d) maintain the economic sustainability of farming operations; and (e) improve the overall quality of life for both farmers and society as a whole" (U.S. Congress, 1990). Reganold et al. (1990) emphasized that for a farm to be truly sustainable, it must generate enough high-quality food, safeguard its resources, and establish a balance between environmental safety and profitability. Instead of relying heavily on external inputs, a sustainable farm maximizes reliance on beneficial natural processes and renewable resources obtained from the farm itself. MacRae et al. (2012) suggested that sustainable agriculture should encompass "management practices that collaborate with natural processes to conserve all resources, minimize waste and environmental impact, preempt issues, and foster resilience, self-regulation, evolution, and sustained production within the agroecosystem for the nourishment and enrichment of all."

Drawing from the above, a common encompassing notion is that sustainable agriculture seeks to integrate three main objectives into production: a healthy environment, economic profitability or equity, and social acceptability (Fig. 1.1). The prevailing overarching notion shows that diverse ways of applying sustainable agriculture concept can co-exist and potentially aid each other if their complementarities are harnessed (Velten et al., 2015). Nonetheless,

literature on sustainability has shown that the debate over definition and approach are marked by different conceptions of ideas (Nelson et al., 2023). Thus, the existing ambiguity within sustainability definitions poses challenges, as the concept can be interpreted in conflicting manners or might encompass a scope too extensive for practical policymaking (Aras & Crowther, 2009; Farley & Smith, 2020; Nelson et al., 2023). Specifically, the concept of sustainable agriculture remains very vague and ambiguous in the current literature, which often renders its implementation extremely difficult (Velten et al., 2015).

Figure 1.1. The pillars of the concept of sustainable agriculture



Moreover, reviewed literature on sustainable agriculture suggest that sustainability is mostly considered as a proxy for resilience and vice versa in the context of agriculture, whereby sustainability and resilience are expected to be positively correlated (P. A. Castro et al., 2019; Espiner et al., 2017; Volkov et al., 2022). This synergy is more evidence if sustainability is employed to study the environmental and social aspects of agriculture, while the resilience concept is utilized to identify economic indicators that reflect the performance, capacity, and

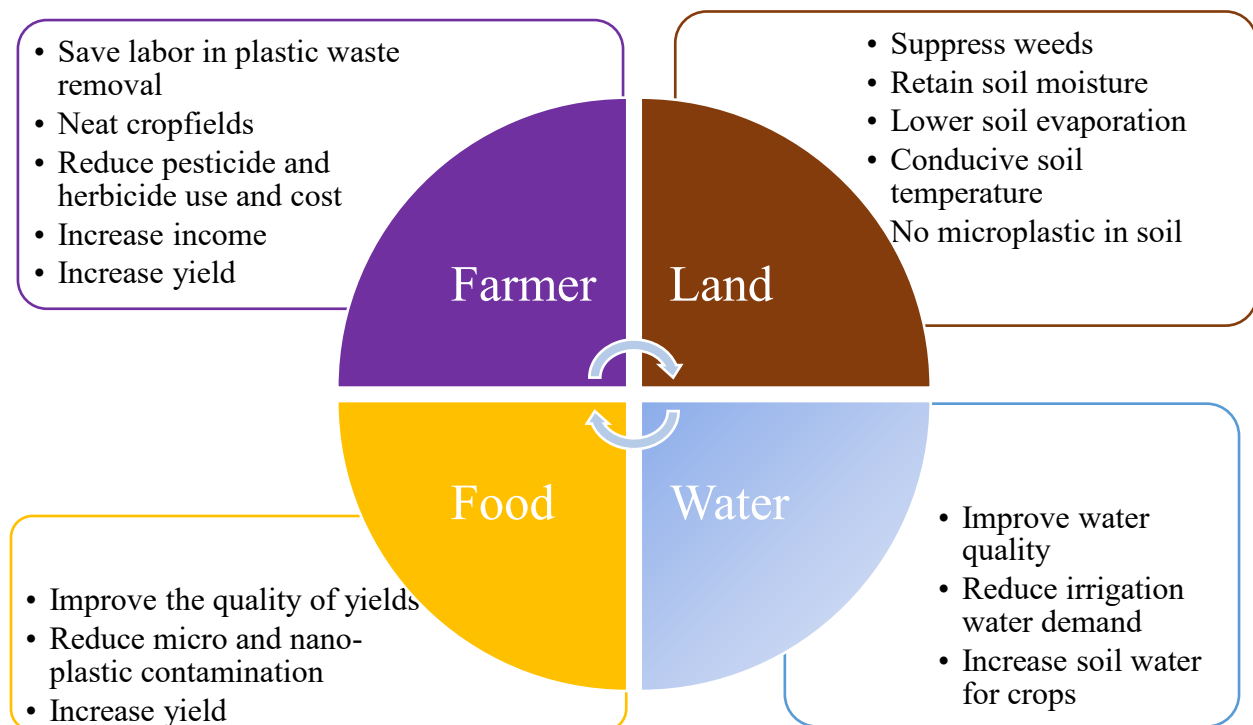
potential of agricultural systems (Volkov et al., 2022). Sustainable agriculture is best used to study how farmers adapt to climate risk and build the resilience of ecosystems needed to continue to generate services for the society (El Chami et al., 2020; M. Madin et al., 2023). However, Espiner et al. (2017) and Goldman (1995) argued that sustainability and resilience could be complementary or related but are not substitutable in all contexts. They are not substitutable because sustainability is focused on maintaining the long-term viability of agricultural systems and minimizing negative environmental impacts, while resilience is focused on the capacity of agricultural systems to respond to social, economic, and environmental changes via structural reorganization, to offset the impacts of future changes, and to engage in new opportunities to guarantee continuity for functioning agroecosystems (El Chami et al., 2020). But Castro et al. (2019) demonstrated that scientific literature could still use these concepts interchangeably contending that long-term viable agriculture systems brought by sustainable farming would result in resilience agroecosystems required for agriculture to response and bounce back from shocks.

Despite the varying views from the diverse conceptions, this dissertation dwells on the synergy in the all-encompassing notions (i.e., a healthy environment, economic profitability, and social acceptability) embedded in the concept of sustainable agriculture. Thus, sustainable agriculture is considered in this research as encompassing environmental friendliness and mitigate climate change, ensuring economic viability through the utilization of renewable resources to enhance productivity in socio-culturally acceptable context (Fig. 1.1).

Although sustainable agriculture hardly refers to a universal set of agricultural practices, there are certain innovations that are found to enhance sustainability. These include farming practices based on ecological principles that advance the sustainability of food systems (Blesh &

Wolf, 2014). Sustainable innovations work with nature and provide long-term environmental benefits while maintaining farm productivity (Brodt et al., 2011; Rodriguez et al., 2009). The overarching aim of sustainable agricultural practices is to protect the environment, enhance the Earth's natural resource base, as well as maintain and improve soil fertility (USDA- National Institute of Food and Agriculture, 2019). These practices include innovations such as BDM, improved seeds, integrated pest management, no-tillage, crop rotation, mixed cropping, soil and water conservation practices (Piñeiro et al., 2020a; Sunding & Zilberman, 2001).

Figure 1.2. Sustainability benefits of adopting biodegradable mulches



For instance, BDM applications serve a vital role in weed control, maintaining soil moisture, and retarding soil water evaporation, which are helpful in dwindled precipitation and water-stressed areas (Liu et al., 2021; Piñeiro et al., 2020). BDM application promotes soil health, minimizes water use, minimizes cost burden on farmers to remove plastic scrabs on the

field associated with plastic mulch application, maximize profits, and lower microplastics pollution levels on the farm (Fig. 1.2). For example, operator and manual labor hours related to plastic waste removal average about 42h per hectare (Madrid et al., 2022; Velandia, Galinato, et al., 2019). The average cost of landfill disposal fee for plastic waste translates into about \$12 per 907.2kg (Velandia, Galinato, et al., 2019).

Experimental research on the field shows that plastic mulch application often results in simultaneous increase in soil temperature and soil moisture, which stimulates excess soil CO₂ emission (Liu et al., 2016; Zhao et al., 2022). Soil under plastic mulch increases net global warming by 95% in organic farms, 35% in conventional farms, and 12–82% irrespective of farm system compared to no-mulching (Cuello et al., 2015; Lee et al., 2021). BDM application reduces GHG emissions from soil by 22.6% per hectare relative to plastic mulch (Dong et al., 2022). Relatedly, plastic mulching has caused detrimental environmental challenges of plastic wastes in soil and landfill sites (Immirzi et al., 2009; Vox et al., 2013). Accumulated microplastic affects physical soil properties and possibly enters the food chain (Duis & Coors, 2016; Huerta Lwanga et al., 2016). Hence, the reduction in GHG and elimination of microplastic pollution under BDM serves as invaluable sustainable benefits to the agriculture sector.

Although yield gains of crops grown under BDM are not significantly different from those grown under plastic (Matías et al., 2021; Tofanelli & Wortman, 2020), BDM application increases yields across all crops by 10-60% per hectare compared to no-mulch (Q. Li et al., 2018; Razza & Cerutti, 2017). It is anticipated that BDM application will at least maintain yields or results in minimal yield reduction in instances where farmers switch from plastic mulch. Aside from anticipated yield increases, farmers most often adopt innovations that conform with the symbolic socio-psychological value of productivist farming— such as tidiness, neatness, and

weed-free fields (Carolan, 2005; Dentzman & Goldberger, 2020a; Si et al., 2021a). Therefore, BDM is expected to be more socio-culturally acceptable among farmers because it degrades into the soil after the growing season and leaves no scrabs.

1.3.2 Adoption theories

Governments and practitioners often offer financial incentives to farmers to adopt sustainable agricultural innovations to help enhance agroecosystems in terms of creating and preserving landscapes, habitats, wildlife, and areas of historical value. A key characteristic of many of these incentives is that their uptake has since been voluntary, giving farmers the option to decide whether to adopt (Carolan, 2005). Due to the voluntary nature of the uptake of sustainable innovations, however, the actual level of adoption has been limited (Edwards-Jones, 2006; Piñeiro et al., 2020a). The challenge of limited farmers' adoption (or uptake) of innovations remains critical to sustainable agricultural development at present. Thus, practical and research efforts have been made by employing various theories to understand the factors influencing adoption (Edwards-Jones, 2006). The most widely used theories included econometric or economic constraint, innovation diffusion, theory of planned behavior, and rationale choice theory, theory of reasoned action, and utility theory. Others include ecological modernization theory and value-belief-norm.

The economic constraint model infers that the availability of required inputs will determine the adoption decision making of farmers (Ruzzante et al., 2021a). For example, credit constraints may hinder farmers' adoption of capital-intensive practices such as improved seeds or drip irrigation. Diffusion of innovations theory explains how new ideas, behaviors, or products spread through a population (Rogers, 2003). Adoption starts with innovators and early adopters, then spreads through the population to the early majority and late majority. The theory of

planned behavior is a psychological theory that explains how people act based on their beliefs (Ajzen, 1985). The theory was developed by Azjen in 1985. It suggests that farmers act rationally based on their attitudes, subjective norms, and perceived behavioral control (Edwards-Jones, 2006). It is often noted that although these factors are not necessarily considered by farmers during decision-making, they form the backdrop for the decision-making process.

The utility theory suggests that farmers make adoption decisions based on the expected change in their level of 'well-being, where the term wellbeing denotes the return (yield or environmental benefits) from the adopted innovation (Edwards-Jones, 2006). The rationale choice theory proposes that farmers are rational profit maximizers and would make adoption decisions based on the intention to increase profit margin and not necessarily the return amount of yield or environmental benefits suggested by economic constraints and utility theory (Moxey et al., 2010). The rationale choice theory or theory of reasoned action is often used interchangeably with utility theory, which enables researchers to model farmers behavior conceptually under the main assumptions that humans seek to maximize their levels of utility (Wallace & Moss, 2002).

For instance, Ma & Wang (2020) and Yang et al. (2022) employed utility theory to explore the relationship between internet use, land tenure stability, and the adoption of sustainable agricultural practices in China. Their findings revealed that internet use and land ownership have a significant positive influence on farmers' likelihood to adopt innovations in pursuit of higher income and increased productivity, as a derived utility. Kassie et al. (2013) used economic constrained theory in Tanzania and found that farmer-level resource constraints such as social capital, limited credit, and household assets determine adoption decisions. Similarly, Teklewold et al. (2013) found that the probability and the extent of adoption among farmers in

Ethiopia are influenced by resource constraints such as household wealth, labor availability, and market access. Also, Saltiel et al. (1994) employs diffusion and farm-structure variables to explain variations in Montana farmers' adoption behaviors and found that access to information and farmer education on the innovation was particularly important in determining adoption patterns. The above findings underline the importance of applying appropriate economic and sociological theories to understand the complex factors influencing the adoption of sustainable agricultural practices, revealing the need for a multifaceted theoretical approach to address the varying dynamics in different agricultural contexts.

This dissertation relies on the utility and innovation diffusion theory because the farmers are expected to adopt BDM based on the anticipated benefits such as increase in crop yields, tidy fields, and elimination of labor cost in removing plastic waste. Moreover, the results of biophysical suitability will provide farmers with valuable spatial information on BDM's potential effectiveness and boost confidence in its performance, helping to support the adoption process.

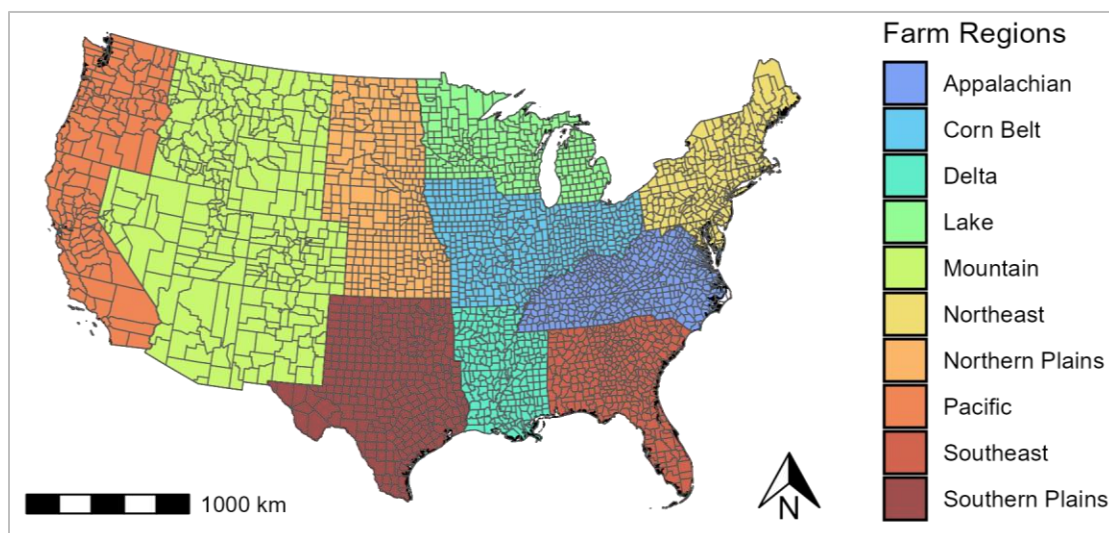
1.4 Geographical Setting

The United States is the focus of this dissertation. Specifically, the study area covers agricultural production regions and counties within the conterminous U.S. (Fig. 1.3). Although biophysical environmental data are mostly available at finer spatial resolution, socio-economic data related to farmers adoption decision making is often available at the county level. The United States Department of Agriculture (USDA) farm production regions (USDA, 2023) is used for regional contextual reference (Fig. 1.3).

The U.S. is the second-largest consumer of plastic mulch after China (American Plastics Council, 2004), and mulching practice plays a significant role in its agricultural production and

food security (Boyer et al., 2013; FAO, 2021; Fischer et al., 2014). In recent studies, the U.S. is estimated to use 453,592 metric tons of plastic mulch every year in the production of crops (Fessenden, 2019; Velandia et al., 2020). Aside the predominant plastic mulch usage in agriculture that requires replacement with BDM, some of the U.S. farm regions produce vegetables, fruits, and specialty crops that stand to benefit from BDM applications. The use of farm production regions would help illustrate how these regions would benefit from BDM application.

Figure 1.3. Map of farm production regions and counties in the conterminous U.S



The major vegetable and fruits production regions include Pacific and Sunbelt states (predominantly including California, Florida, Texas, and North Carolina), which account for over 70% of the national production (Huang et al., 2022). Southeast and Midwest vegetable production areas cover Wisconsin, Tennessee, and Minnesota as well as other areas like Washington and Oregon (USDA, 2023; Velandia et al., 2019). The Southern plains, Northern plains, corn belt, and the delta region along the Mississippi flood plains farming regions also stand to greatly benefit from BDM application based on field trials (Li et al., 2014; Samuelson et al., 2022; Sintim et al., 2020). The use of BDM in these regions will be critical to addressing the

increasing water stress (Gleick, 2010; McGuire, 2017; Scanlon et al., 2012) and invasion of herbicide resistant weeds resulting from excessive use of agrochemicals (Bagavathiannan et al., 2019; Liebman et al., 2016). More elaborated descriptions of these regions can be found at USDA (2023). While the focus of this dissertation is on the U.S., the chapter two and three covered a global context.

1.5 Methods and Modeling Approach

I first undertook an assessment of the existing literature to understand and identify factors that influence biophysical suitability of BDM and farmers adoption decisions. The literature was systematically reviewed to synthesize field trials evidence on biophysical environmental factors related to BDM agronomic effectiveness. The systematic review adopted literature review protocol established in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) standards (Moher et al., 2010). Moher and colleagues define systematic review as a structured approach to reviewing literature based on a clearly formulated question, using systematic and explicit methods to identify, select, critically appraise relevant research, and analyze data from the selected studies. Key in this method is its strict reliance on article screening by a pair of two or more people. I used this method to assess the searchable literature on BDM evaluation, with the objective of providing a comprehensive summary and synthesis of the state-of-the-knowledge on the factors that impact the suitability of BDM for agricultural applications. Details of this method and the results are presented in chapter two.

The second part of the literature assessment adopted a scoping review following the PRISMA guidelines. This approach serves as an extension of the PRISMA protocol and is used to provide overview of existing literature (Moher et al., 2009, 2010). Although preliminary article screening by a pair of two or more persons is ideal, scoping reviews allow for screening

by one person, subject to a check of screener reliability (Collaboration for Environmental Evidence, 2022; Piñeiro et al., 2020a). Scoping reviews aim to summarize studies with diverse methods and designs while emphasizing key areas for future research and engagement (Arksey & O'Malley, 2005). This methodology was used to characterize barriers and enabling factors for adoption of sustainable innovations and identified areas for potential future research. Details on the process and results are presented in chapter three of the dissertation.

I adopted a GIS-based Multi Criteria Evaluation (MCE) decision analysis technique aided by Fuzzy Overlay model to assess the biophysical suitability of BDM. MCE in GIS serves as a fundamental decision support operation used in the allocation of land to suit a specific objective or purpose based on its ability to meet predefined suitability criteria (Eastman, 1999). The MCE framework supports the integration of multiple spatial datasets— such as climate variables, soil attributes, and land use, which may include conflicting variables (Carver, 1991). The input data were reclassified into criteria raster layers and combined with OR and Gamma operators using the Fuzzy Overlay model. A fuzzy operator was selected to combine different layers based on the relationships and interactions between factors within each layer. The reclassified criteria layers were combined in a hierarchical manner using OR fuzzy operator to combine sets of related criteria into a single climate factors layer, a single soil factors layer, and a single constraint layer. The OR operator is most appropriate in situations where a condition can be satisfied by any one of several criteria, for instance temperature and precipitation are both climate factors and could be strongly correlated. The fuzzy OR operator returns the maximum value from the input criteria at each cell location. This means that if two inputs have high values, the final output is determined by the highest membership value, thereby minimizing correlations and interactions between inputs. The Gamma operator is useful for a flexible combination of dissimilar or

conflicting criteria, which requires all conditions to be satisfied. As such, I used fuzzy Gamma operator to combine the three different layer maps (i.e., climate, soil, and constraint) into the final BDM suitability maps.

1.6 Mapping the Chapters and Key Arguments

The dissertation is divided into five chapters of which three are organized into a group of integrated-manuscripts. The first chapter introduces the integrated-articles to provide readers with an overview. The three separate research articles follow this introductory chapter. All the manuscripts attempt to address the challenges of adopting and transitioning into sustainable agricultural innovations in U.S. and globally. Chapter 2 addresses the research question on factors influencing farmers' decision to adopt sustainable agricultural practices and Chapter 3 examines biophysical factors influencing BDM site suitability for agriculture application. While Chapter 4 focuses on the extent of spatial biophysical site suitability of BDM across the U.S. now and under different future scenarios. However, each manuscript uses a distinct method and approach as an entry point to answer the stated research questions. In keeping with the concept of sustainable agriculture, the empirical chapters offer a multifaceted analysis placed at different scales. While chapter four focus primarily on the conterminous U.S., chapter two and three try to understand the factors that shape biophysical suitability of BDM and adoption of agricultural sustainable innovations at a global perspective. Each manuscript is substantially unique and presents its own set of findings and scholarly advances.

Chapters two to four are interlinked in different ways. Chapter two and three involved a systematic review and scoping review, respectively, to identify factors related to biophysical suitability of BDM and farmers adoption likelihood. The results of these chapters also provided the significance and direction of influence of the identified factors. These results were used to

select the input criteria and classifications for the GIS-based MCE model in chapter four. The individual chapters key points are illustrated as follows.

Chapter two begins the integrated-manuscripts studies by conducting a systematic review of studies that evaluate the use of BDM for agricultural applications and extract data from 151 primary studies on biophysical factors that directly and indirectly influence the suitability of its use. I find that using BDM nearly always provides agronomic benefits over not mulching but rarely provides agronomic benefits over conventional plastic mulch. I also find that reported benefits vary across climate conditions, mulch type, types of crops, and agronomic factors tested, highlighting the context-specificity of BDM benefits which are not yet well understood. In addition, I argued for studies that experimentally evaluate the secondary environmental and social benefits of BDM application to help provide a better understanding of the full potential of these products for sustainable agriculture. The paper has been published in the *Journal of Agriculture and Food Research*.

Chapter three assessed 83 studies on sustainable practices or innovations to ascertain factors that significantly influence farmers (positively or negatively) to adopt. I categorized the factors into climatic, economic, socio-cultural, and environmental. The influence of these factors on farmers' adoption likelihood varied by type of innovation and study context. The results indicated that drought events, rising temperatures, higher income and wealth, perceived environmental friendliness or benefits, presence of disease, poor soil fertility, higher education, access to extension services, strong social networks, and positive psychological attitudes had significant positive influence on farmers' uptake of most of the studied sustainable practices. In contrast, limited access to credit and markets consistently served as barriers to adoption. While the findings are similar to the results of previous reviews, I provided further evidence on

direction and significance of the identified factors which are largely missing in existing literature. This chapter is currently under review in *Journal of Rural Studies*.

Chapter four argues that a key component of farmers adopting many innovations is their effectiveness within a given biophysical context and that a future shift in the biophysical conditions will shape suitability, which could affect the likelihood of uptake. This chapter contributes to the scholarly argument by assessing the biophysical suitability of BDM application under recent and future scenarios across the conterminous U.S. In line with the argument, I find that about 62% (3.35 million square kilometers) of arable land is moderately to highly suitable for BDM application under recent past conditions. The suitable areas are reduced to ~59% by 2100 under a more sustainable scenario (SSP126) and increased to ~75% under a fossil-fuel driven development scenario (SSP585). Overall, the results suggest that if the world takes the path of SSP585 representing higher emissions with limited mitigation, BDM will have increased relevance as an adaptation with potential to replace plastic mulch and enhance crop production in many areas of the U.S. The Corn Belt, Delta, Southeast, Southern Plains, and Pacific regions are anticipated to experience the highest increase in suitable areas by 2100. This chapter is published in *Journal of Cleaner Production*.

Chapter five (5) ties the four manuscripts together and discusses the thematic synergy amongst them. Through a content analysis, it puts the results of the manuscripts into direct conversation with one other, drawing connections and contrasts across cutting issues. Attempts are also made to explain what the key findings might mean for the geographies of agricultural sustainability. The chapter offers a strong call to action, providing practical suggestions for addressing each of the major challenges identified in the manuscripts. As a concluding chapter, it

also specifies the contributions of the dissertation to research in human geography more broadly, and sustainable food systems literature most specifically.

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Chapter 2 - Synthesis of current evidence on factors influencing the suitability of synthetic biodegradable mulches for agricultural applications: a systematic review

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Abstract

Mulching practice offers farmers an opportunity to minimize the effects of drought, water loss, and soil erosion on crop production. Plastic film is widely used as a mulching material; however, contamination of arable lands by residual plastic has become a serious concern. Synthetic biodegradable mulch films and sprays may offer a more sustainable alternative to plastic films, however current evidence on the factors that influence the suitability of these products for agricultural applications is fragmented, making it unclear under what conditions these products meet agronomic, environmental, and societal needs. We address this gap by conducting a systematic review of studies that evaluate the use of synthesized biodegradable mulch for agricultural applications and extract data from 151 primary studies on factors that directly and indirectly influence the suitability of its use. Like others, we find that using biodegradable mulches nearly always provides agronomic benefits over not mulching but rarely provides agronomic benefits over conventional plastic films. However, we also find that reported benefits vary across climate conditions, mulch type, and crop and agronomic factors tested, highlighting the context-specificity of biodegradable mulch benefits which is not yet well understood. In addition, we identify a need for studies that experimentally evaluate the secondary environmental and social benefits of biodegradable mulch use to provide a better understanding of the full potential of these products for sustainable agriculture.

Keywords

Biodegradable mulch, systematic review, agronomic impact, environmental conditions

2.1 Introduction

The agriculture sector is facing the challenge of feeding a growing population amid global environmental change—two major stressors to food production systems. These stressors will include increased inputs for farming, soil erosion, droughts, floods, wildfires, and heat stress resulting in decreased crop yields (Mirzabaev et al., 2023). For instance, the U.S. in recent decades has experienced climate events such as droughts and precipitation variabilities, which are projected to intensify to levels where all counties could permanently exceed the baseline variability of occurrence by 2050 under the Representative Concentration Pathway (RCP) 8.5 (Batibeniz et al., 2020; Cook et al., 2015). By the year 2050, it is anticipated that crop yields worldwide will face an average reduction of 10% due to land degradation and climate change, with certain regions potentially experiencing yield reductions of up to 50% (IPBES, 2018). These impacts on agricultural production systems and environmental degradation demand a transition towards more sustainable innovative practices (Piñeiro et al., 2020; Smith et al., 2020). These innovations should broadly contribute to the reduction and reversal of the processes of environmental degradation (FAO, 1989), food security, and soil health through maintaining fertile and functioning soil biodiversity (Kassie et al., 2013; Piñeiro et al., 2020).

Given the increasing effects of climate change and land degradation on agriculture and soil ecosystems, low-density polyethylene-based mulches (hereafter referred to as plastic mulch) could play a vital role in maintaining soil moisture, retarding soil evaporation, suppressing weeds, and controlling soil temperature in marginal lands areas (Cook et al., 2015; Eswaran et al., 2019; E. Liu et al., 2021; Ni et al., 2016; Schettini et al., 2004). These vital roles provide valuable services that reduce irrigation requirements, decrease the use of inorganic herbicide

inputs in weed control, and reduce nutrient leaching (Samuelson et al., 2022a; Vox et al., 2013a). For example, plastic film use has been shown to increase crop yields (Wu et al. 2017, Shan et al 2022), crop quality, and water-use efficiency (Steinmetz et al. 2016). In a study by Wu et al. (2017) maize yields were 15.2% to 23.2% higher under mulching with black plastic film in comparison to a control group without mulching. The same study indicated large differences in mulching effectiveness across mulch types as white transparent plastic film and maize straw mulch resulted in much smaller increases in maize yield over the no-mulch control group (Wu et al. 2017).

While the usefulness of plastic mulch in agricultural production systems has been identified in literature, plastic mulch materials take a longer period to degrade and are associated with ecologically and agronomically detrimental outcomes. For instance, plastic mulch requires more labor and financial investments for removal and disposal (Akhir & Mustapha, 2022; Velandia et al., 2020; Velandia et al., 2019). There is an additional cost associated with plastic mulch application due to the cost in waste removal after growing season and disposal fees (Madrid et al., 2022; Velandia, Galinato, et al., 2019a). In addition, micro- or nanoparticles may persist in soil and negatively affect microbial activity, physical soil properties, and nutrient availability (Gao et al., 2019; Koskei et al., 2021; Shah & Wu, 2020). As such, biodegradable mulch films are being developed as a sustainable alternative to plastic films and are designed to be integrated into the soil after use where they are degraded by local soil microorganisms (Akhir & Mustapha, 2022; Transparency Market Research, 2013). Biodegradable mulch films are designed to break down into natural components over time, leaving minimal harmful residues behind and reducing the need for labor-intensive plastic removal after the growing season. The adoption of biodegradable mulch films by farmers has the potential to provide both

environmental and economic benefits. Field studies on vegetables (broccoli, chili and garlic) in China showed that biodegradable mulch and plastic mulch showed similar effects on yield, however the biodegradable mulch had more environmental benefits than plastic mulch (Shan et al. 2022).

Despite its environmentally sustainable prospects, adoption and utilization of biodegradable mulches among farmers are reported to be limited. Among the factors impeding adoption include predictability of degradation rate across local conditions (Goldberger et al., 2015; Samuelson et al., 2022), desired physical or mechanical properties (Briassoulis, 2007; Goldberger & Lyons, 2017), impacts on yields, and effectiveness at preventing weeds or retaining soil moisture (Akhir & Mustapha, 2022; Velandia, Galinato, et al., 2019b) as well as cost and availability of desired biodegradable mulch types (Goldberger & Lyons, 2017; Velandia, Smith, et al., 2019). The cost of biodegradable mulch tends to be higher than plastic mulch, and for that reason, net income is lower with biodegradable mulch than with conventional plastic mulch (Sun et al., 2018; Cheruiyot et al., 2022). In addition, profitability also depends on climatic conditions (Cheruiyot et al., 2022). In terms of affordability, Velandia et al. (2020) indicated that because biodegradable mulches are more expensive, potential labor savings from the use of biodegradables is important in farmers' assessment of the economic feasibility of replacing plastic mulch. While the number of studies that have specifically focused on the adoption of biodegradable mulch is limited, there are some studies on the factors associated with adoption of sustainable practices in an agricultural context. The general literature suggests little consistency in the factors that are most important determinants of adoption (Prokopy et al. 2019). Some of the more consistent findings in terms of long-term adoption include farmer's attitudes

and preferences, while short-term practice adoption (such as biodegradable mulch) is more related to characteristics of the farm and/or operation (Lu et al., 2022).

Other factors influencing adoption include a need for evidence of consistent and effective results under various growing conditions as farmers are concerned about the resistance of biodegradable mulches to tearing, degradation, and weed control (Goldberger et al., 2015; Samuelson et al., 2022), the compatibility of biodegradable mulches with existing farming practices (Dentzman & Goldberger, 2020), and regulatory barriers and the ambiguity of standardized certification for biodegradable mulch materials (Dentzman & Goldberger, 2020). Although research into the degradation rates, agronomic impacts, and adoption of biodegradable mulches is ongoing, there exists limited synthesis of evidence of biodegradable mulch suitability for agricultural applications across studies and sites with varying contexts.

Recent reviews and meta-analyses have examined differences in biodegradable mulch production costs and degradation rates (Miles et al., 2017), mechanisms of polymeric mulch film biodegradation (Sander, 2019), the yield and water use efficiency impact of biodegradable mulch films in China (Liu et al., 2021), degradation rates and yield impacts of starch-based biodegradable mulch films (Menossi et. al., 2021), and the impacts of different biodegradable mulches on soil temperature, weed suppression, and crop yield relative to bare soil and plastic films (Tofanelli and Wortman, 2020). However, there remains a gap in synthesizing how differences in environmental context, mulch type, crop type, and experimental setting interact to influence the overall suitability of biodegradable mulch for agricultural applications. This impedes the ability to effectively identify gaps in biodegradable mulch knowledge, establish evidence for best-practices, and help inform policymakers and producers. Understanding the site suitability and farmers adoption of biodegradable mulch is therefore critical for realizing the full

potential of this technology. Given the limited synthesis of current studies on biodegradable mulch suitability and adoption, this review compiles evidence from the literature on:

1. the effects of biodegradable mulch use on agronomic, practice, and economic factors,
2. the effects of biodegradable mulch type and characteristics on agronomic performance and biodegradable mulch degradation,
3. the effects of climate, soil, and other contextual factors on biodegradable mulch degradation and impacts on agronomic performances, and
4. the quality of and confidence in the findings of biodegradable mulch experiments.

Biodegradable mulches impact agronomic factors during both the period of deployment during the cropping season (Tofanelli and Wortman, 2020) and after being tilled into soil (Zhang et al., 2022). Evidence shows that biodegradable mulch significantly influences agronomic factors such as soil temperature, soil moisture, weed suppression, and crop yield during deployment (Tofanelli and Wortman, 2020). After being tilled-in, Zhang et al. (2022) found biodegradable mulch to decrease soil bulk density but increase soil total nutrients and microbial contents in the long-term. In this study, we focus primarily on the agronomic effects of biodegradable mulch and associated contextual factors during the period of deployment unless otherwise indicated. The results of the study highlight existing and future challenges to this technology that may need to be overcome to facilitate its use for crop production more broadly across the United States and the globe.

2.2 Methods

To examine the suitability and factors influencing biodegradable mulch adoption, we undertake a systematic literature review focused on this topic. Our approach adheres to the

guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) standards as established by Moher et al. (2009). In the subsequent sections, we outline our criteria for study inclusion, detail the methodology employed for literature search, discuss the selection process for studies meeting our criteria, and elucidate the coding procedure applied to the collected reports. In this context, we refer to studies that fulfill all our eligibility criteria as selected studies.

2.2.1 Literature search

The selected publications were obtained from searching commonly used databases, including Scopus, Web of Science, JSTOR, ProQuest, Google Scholar, and Taylor and Francis Online (Table 1). An exported bibliography of 25 sampled relevant studies was used to create search terms and Boolean operators using an iterative procedure in the ‘litsearchr’ package available in RStudio software (Grames et al., 2019). Using common terms extracted from study keywords and titles we obtained and used the following search strings: “biodegradable mulch AND film OR spray AND condition OR suitab*” and “biodegradable mulch AND (film OR spray) AND (condition OR suitab*)”, which returned 3,333 studies. The obtained studies included peer-reviewed articles, dissertations, and theses. While we did not restrict publication date or geographical location during our search, we did confine our inquiry to encompass only full-text studies presented in the English language. Our designated search process ended on June 15, 2022.

Table 2.1. Results by Database

Database	Results
Scopus	136
Web of science	162
JSTOR	45
Taylor & Francis online	204
ProQuest (includes dissertation and theses)	1817
Google scholar	969

Total	3333
<i>Note: the literature search was concluded on June 15, 2022</i>	

We note that certain potential limitations should be acknowledged. Though the iterative procedure for search term development enhances comprehensiveness, it might still miss some relevant terms or concepts. Additionally, the reliance on keyword-provided terms from the sampled articles might inadvertently omit key synonyms or related terms. The search strings, although designed to capture a wide spectrum of relevant studies, might still introduce bias due to the specificity of terms used. Furthermore, confining the search to studies available in English could introduce language bias, excluding relevant non-English literature. Lastly, while gray literature sources (dissertations and theses) were sought, the effectiveness of this search strategy in capturing comprehensive and diverse unpublished works could vary. While these limitations do not inherently detract from the significance and practical implications of our findings, it is crucial to recognize that it does impose restrictions on the breadth of our study and the degree to which our results can be generalized.

2.2.2 Inclusion criteria

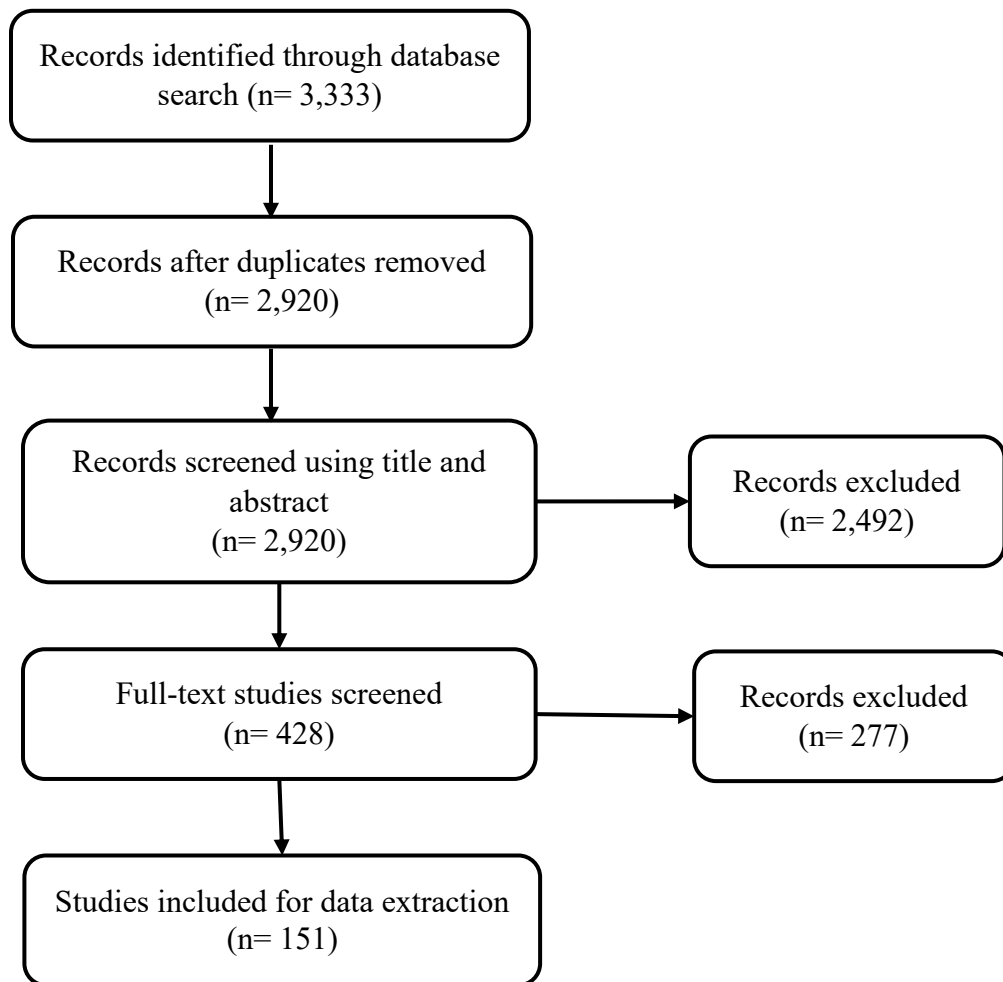
Our systematic review seeks to assess the searchable literature on biodegradable mulch evaluation, with the objective of providing a comprehensive summary and synthesis of the state-of-the-knowledge on the factors that impact the suitability of synthesized biodegradable mulch films or sprays for agricultural applications. For a publication to be selected for further examination, it needed to meet the following criteria: 1) full text available, 2) text written in English, 3) studied biodegradable mulch intended for agriculture/crop use, 4) an empirical study and not a review article, 5) focus on synthesized/manufactured biodegradable mulch film or spray, 6) examine biodegradable mulch suitability, and 7) includes field and/or greenhouse trials with soil and plants. See Table 2 for counts of reasons for exclusion.

Note that we include studies that involve human surveys or interviews if there is some associated application of the product to crops (e.g., inviting farmers to observe field trials and then getting farmers opinions on biodegradable mulch suitability for crop production and factors like cost that are associated with those opinions). A study was considered to examine the suitability of biodegradable mulch if it examined attributes of a biodegradable mulch film or spray that included (but were not limited to): degradation, physical properties, impact on soils, water, weeds, crops, production, farm management, or application feasibility.

2.2.3 Studies meeting eligibility criteria

To ensure that the quality of the studies included in the review met the set eligibility criteria for inclusion (Table 2), we used a three-step process to screen and code selected studies that met all the eligibility criteria (Fig. 1). In step one, unique studies identified in the database search were screened using title and abstract in the ‘revtools’ R package (Westgate, 2019). Pairs of coders independently determined if the title and abstract of each study met the inclusion criteria. A total of 2,920 unique publication records were screened for title and abstract suitability. Following the independent evaluation, pairs of coders checked for conflicting inclusion decisions and shared their reasons for including or excluding studies. In the case of continued disagreement on exclusion across a coding pair a third author resolved discrepancies and disagreements. Most of the excluded studies did not examine topics relevant to biodegradable mulch for agriculture application (Acosta-Martínez et al., 2011; Alpert, 1963; Fu et al., 2014) or did not involve field studies or experiments (Gilead, 1978; Huang et al., 1990; W. Qin et al., 2015). In all, 2,492 studies were excluded under step one (Table 2).

Figure 2.1. Flow chart of the systematic review process with study counts.



Note: *the literature search was concluded on June 15, 2022*

In step two, 428 studies were evaluated for inclusion using a full text reading. We uploaded PDF files of the 428 studies for full text screening in SysRev.com (Bozada et al., 2021). We coded exclusion and reasons for exclusion in the form of labels to help screen the studies in SysRev. Pairs of reviewers independently assessed whether each study fits the eligibility criteria. The SysRev project was set to randomly assign a study to two reviewers with each blind from seeing the screened results and the assigned reasons for exclusion of others. This allowed the SysRev system to mark a study as completed if there was no conflicting review label or as conflict if the two reviewers' labels lacked consensus. A third reviewer resolved

disagreements between paired reviewers. We excluded 277 studies using the full text review under step two. Thus, 151 studies were selected for data extraction after the full-text screening (See Appendix Table 2. 2). For both screening steps, a reviewer training session was held before conducting a pilot screening of ten studies for step one and five studies for step two. A post pilot discussion was used to address procedural questions and inconsistencies in inclusion/exclusion decisions.

Table 2.2. Reasons for publications exclusion in Step I and Step II

Reasons for Exclusion	Number of Publications Excluded	
	<i>Step I</i>	<i>Step II</i>
Not topical	1867	22
Review article	298	21
Suitability not examined	23	11
Not agricultural	136	5
Not in English	16	13
No full text	152	-
Only lab experiments	-	38
Not manufactured biodegradable mulch	-	35
Conventional plastic only	-	12
No field or greenhouse trials with soils/ plants	-	11
Two or more of the above reasons	-	90
Other	-	19
Total	2492	277

Note: the literature search was concluded on June 15, 2022

From the full text reviewed studies, common reasons for excluding studies included lack of biodegradable mulch experiments with soil and plants in a field or greenhouse setting, use of naturally-occurring rather than synthesized biodegradable mulch products, and non-topical or review studies. For example, Verdú et al. (2020) and Okyay et al. (2020) studied biodegradable mulch effects on agronomic factors, but the studies were excluded as the authors conducted the research only in controlled laboratory conditions. Similarly, Marral et al. (2020) evaluated effects of biodegradable mulches on soil properties, weed dynamics and yield of winter crops, however while the implications of biodegradable mulch suitability for agriculture application

were discussed the study was excluded because the authors used cotton mulches which are not synthesized or manufactured. On the other hand, a study by Cirujeda et al. (2012) was retained for further analysis as they examine the effect of a manufactured biodegradable paper mulch on weed control in field experiments with tomatoes. Although Rudnik & Briassoulis (2011) examined the suitability of biodegradable mulch for agriculture applications in field trials, the study was excluded because the researchers did not involve crops or plants. Lastly, a study by Qin et al. (2015) was excluded as it was a review paper and did not specifically focus on biodegradable mulch for agricultural use.

2.2.4 Data extraction and coding report

In step three, data were extracted from the selected studies using SysRev (Bozada et al., 2021). We coded the questions in the form of labels to help guide data extraction. Labels included open ended questions (string labels) and closed ended questions (categorical labels). Coding (data extraction) instructions and help guides (for reviewer's reference) were provided for each label as well as in the SysRev project description. All coders were trained on how and what data to extract from the studies and practiced this data extraction in a pilot screening exercise (using five sample studies). After training, pairs of coders independently extracted relevant information from each of the remaining 151 studies using the created labels schema (See Appendix Table 2.1). The SysRev project was set to randomly assign every study to two coders with each blinded from seeing the data extracted by others. The SysRev system marked a study as completed if there was no conflicting label or as conflict if the two coders' labels lacked consensus. A third reviewer resolved conflicts between labels for paired reviewers.

Key information extracted includes the study location, type of crop, research setting, and the characteristics and type of biodegradable mulch used in the study. Other extracted

information includes, biodegradable mulch physical properties evaluated, agronomic impacts/factors (i.e., yield, soil temperature, etc.) studied, studied contextual factors that may influence biodegradable suitability, and the reported effectiveness of biodegradable mulch compared to bare ground and plastic mulch controls. For more information, see Appendix Table 2.1.

2.2.5 Data cleaning and analysis

The extracted data in the SysRev project was downloaded in .CSV file format and then imported, cleaned, and processed in RStudio. Ancillary information, such as world biome types (a community of plants and animals living together in a certain kind of climate), country subregional groups, and crop groups were added to aid in further data classification and consolidation. Biomes were added to help assess the variability in the effectiveness of biodegradable mulch across different ecological regions (Dinerstein et al., 2017). Subregional divisions from the United Nations Statistics Division (UN Statistics Division, 2023) were added to examine variability of biodegradable mulch uses and its effectiveness across collections of countries. The crop groups were adopted from the United States Department of Agriculture and Natural Resources Conservation Service U.S. National Vegetation Classification (USDA NRCS, 2020) to reduce the number of unique crop categories analyzed. As many studies report multiple trials and experiments [e.g., Anunciado et al. (2021) use three crops (i.e., corn, pepper, and pumpkin) in their study and Briassoulis (2007) studied biodegradable mulch suitability in four different countries including Italy, Greece, France, and Germany] for which we were able to extract trial-specific data.

We report the frequency of individual factors across primary studies using the count of unique observations per paper. Note, however, that agronomic impact measures extracted from

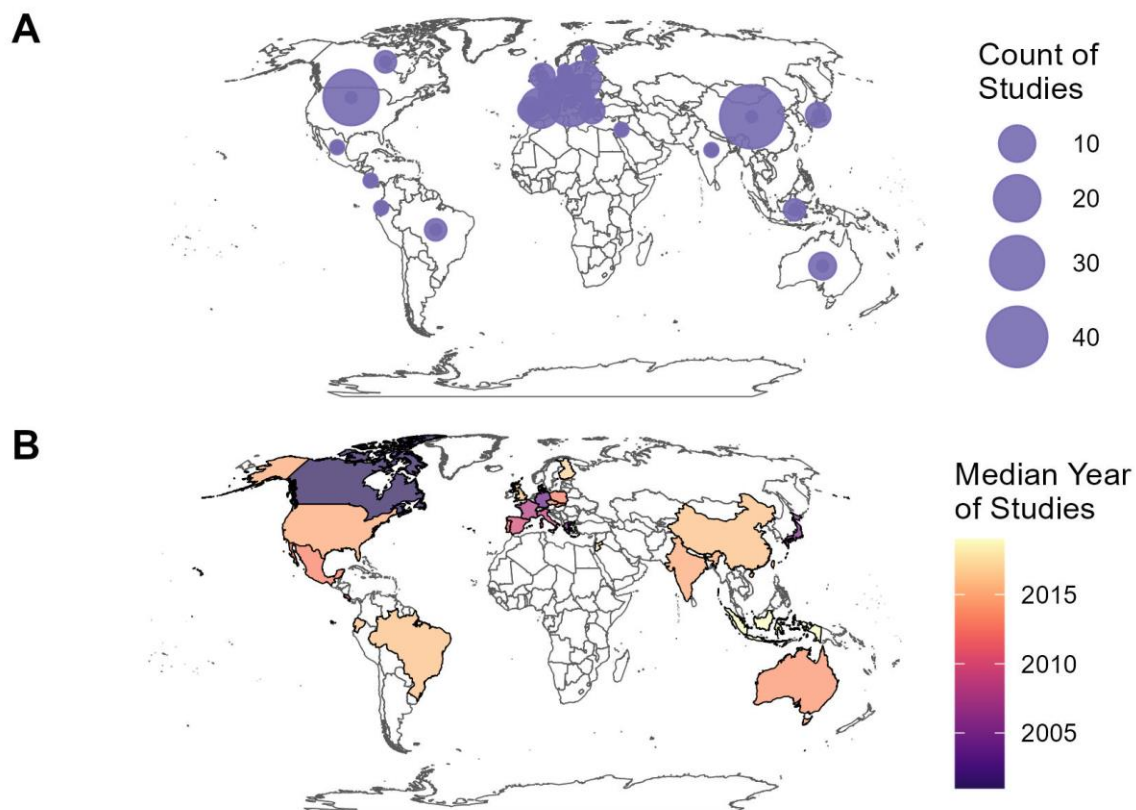
the primary studies were not recorded for individual trials described in a study. The category “positive impact” was only applied if all trials with biodegradable mulch were reported to have positive impacts relative to the comparison group (no-mulch control or conventional plastic). The neutral category was applied if the study consistently reported no significant difference between impacts of biodegradable mulch use and the comparison group while the mixed category was applied if the study reported positive impacts of biodegradable mulch relative to the comparison group for some trials and negative impacts for other trials. Data extracted as unique text strings were recategorized using common themes and terms.

2.3 Results

2.3.1 Study area and publication statistics

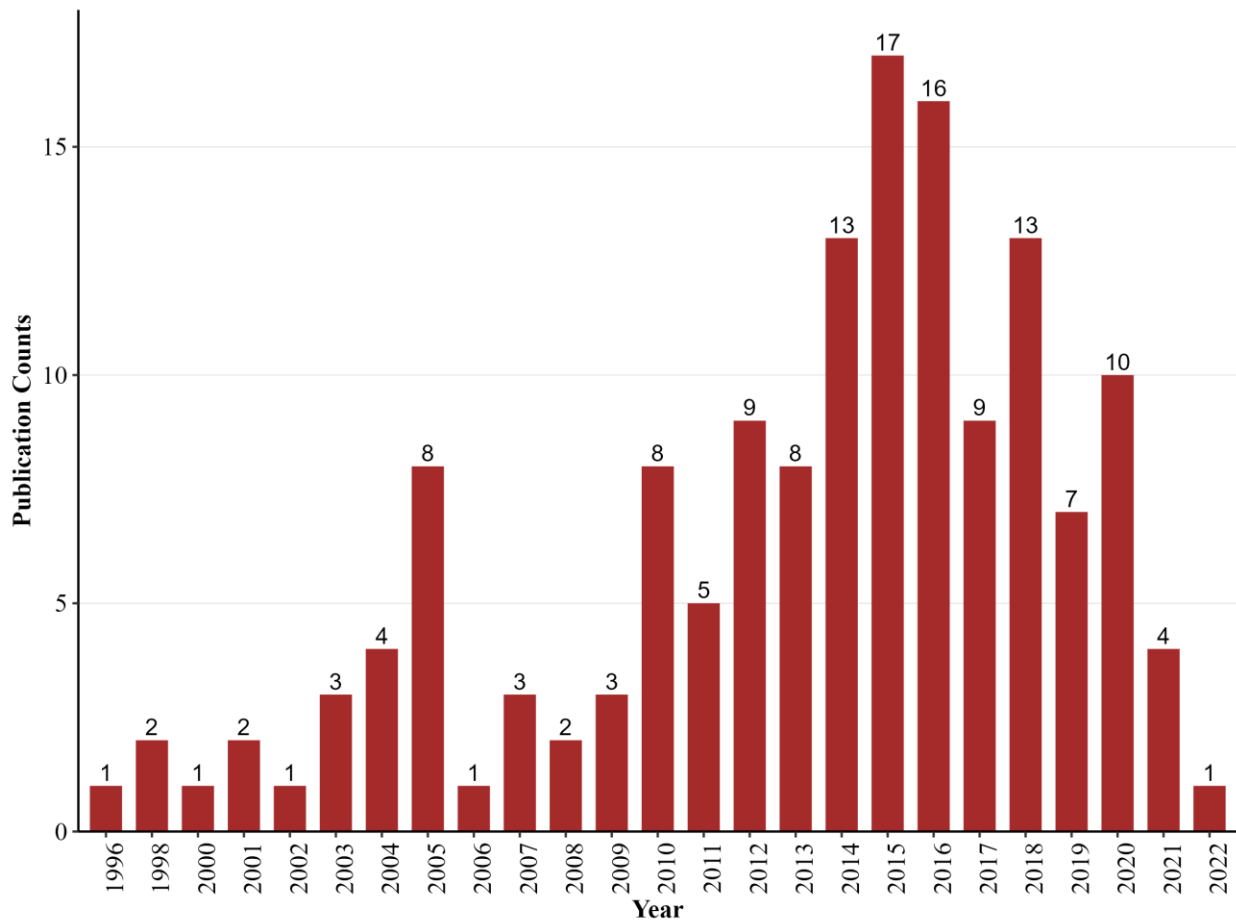
The data comprises studies conducted in 24 countries across diverse farming regions in the world. Studies in the United States, Canada, and Italy were early leaders in the field, with studies starting in 1996 to 2002, but account for only 3.97% of the selected studies. In contrast, about 29.8% (45 studies) of the selected studies were conducted in locations within China with publication dates between 2005 and 2022 (Fig. 2). Since 2009, there has also been growth in biodegradable mulch studies in Central and South America, with five (5) studies conducted across Brazil, Costa Rica, Mexico, and Ecuador (Fig. 2). The recent growth in research on biodegradable mulch (Fig. 3) may be associated with an increase in efforts to protect crops against climate change and replace plastic mulching materials (Akhir & Mustapha, 2022).

Figure 2.2. Spatial distribution of publication counts (A) and median publication year (B) by country of study.



Note: *The literature search was concluded on June 15, 2022*

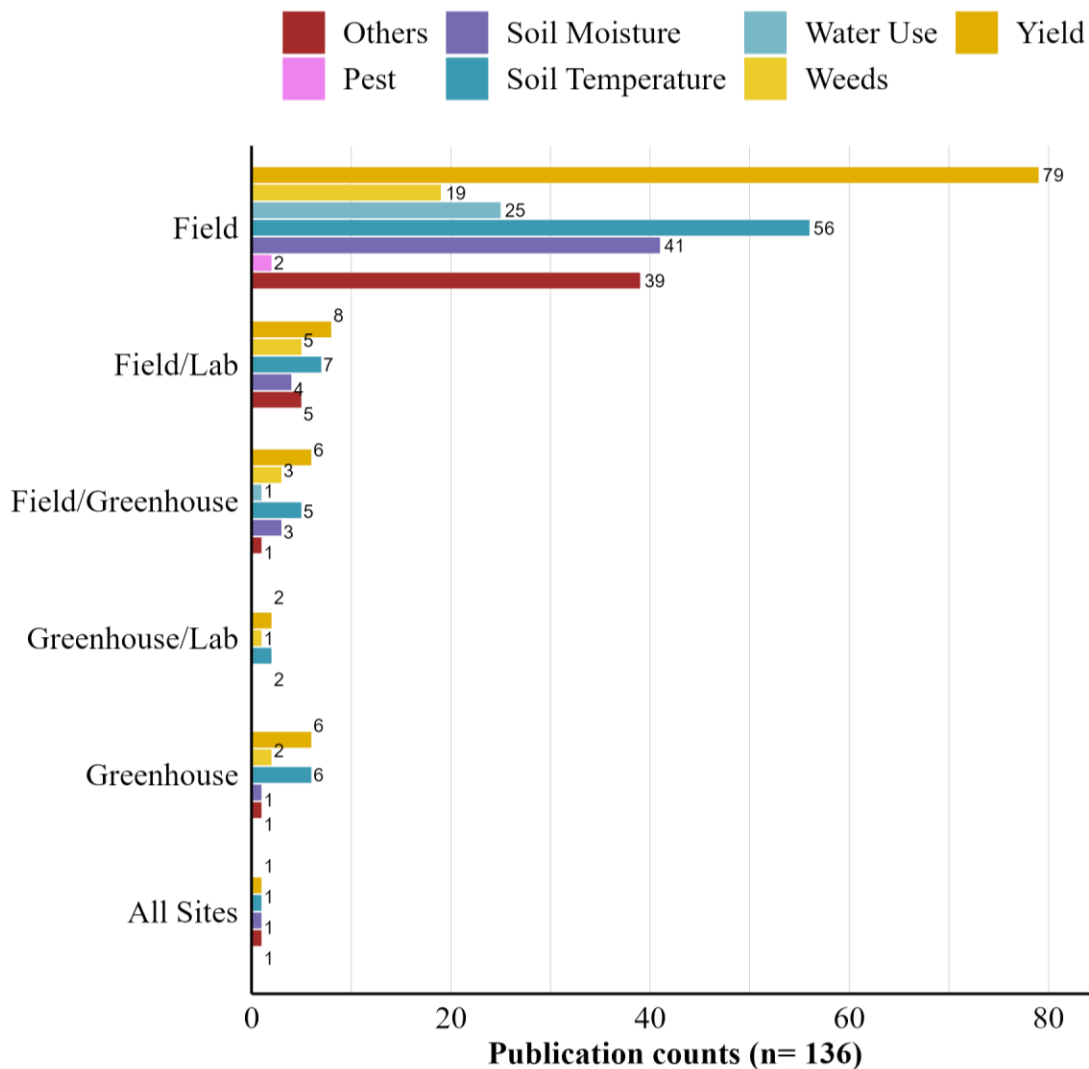
Figure 2.3. Publication counts by year of study



2.3.2 Study setting and crops of study

A large proportion (80.1%) of the selected studies were conducted in field settings (on farmland) involving different crops and soil (Fig.4, Appendix Fig. A. 1). Moreover, all the agronomic factors considered were tested under field conditions in at least one study. The most studied agronomic factor under field conditions was effect on crop yield, representing 72.5% of the total field studies, while pest and disease control were the least studied.

Figure 2.4. Study setting and agronomic impacts studied.

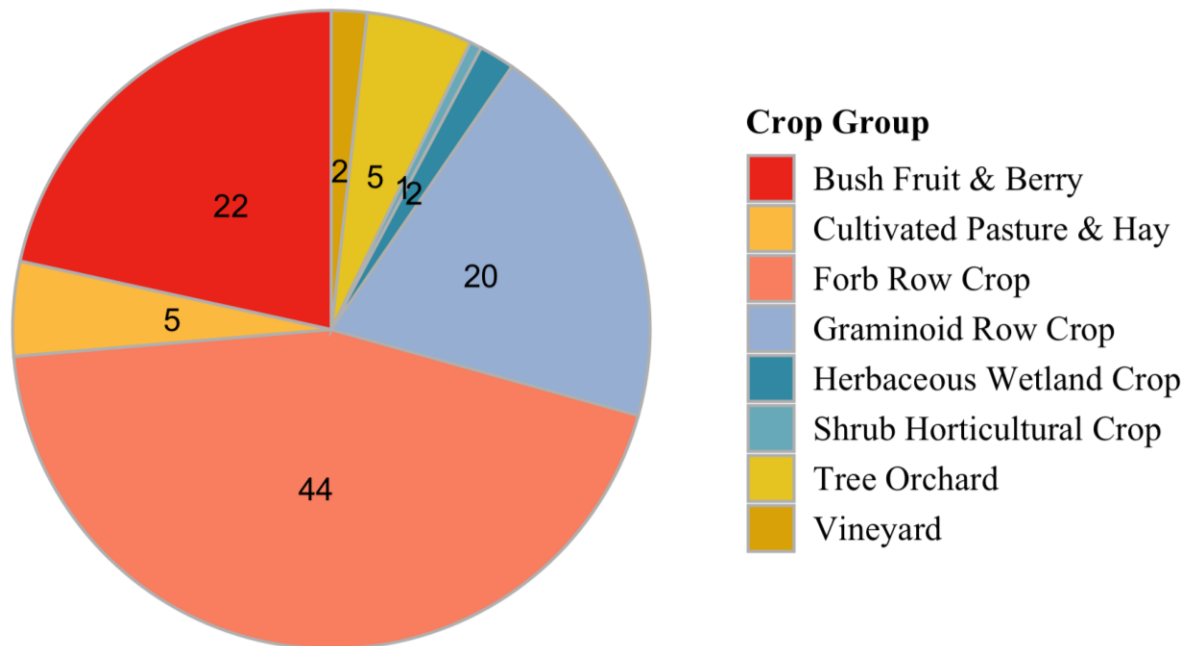


Note: Effects on crop yields [Yield], Effects on pest and diseases [Pest], Effects on soil moisture [Soil Moisture], Effects on soil temperature [Soil Temperature], Effects on weeds control [Weeds], Effects on water use efficiency [Water Use], Effects on other agronomic factors [Others]

The results suggest that biodegradable mulch application has been tested for a diverse range of crops and farming systems. Over 37 different types of crops have been used to evaluate biodegradable mulch suitability for agricultural applications (Appendix Table 2.3). Among the most studied crop groups is the Forb row crops (as shown in Fig. 5). This group encompasses a variety of crop types, including Pie pumpkin, Cotton, Lettuce, Watermelon, Potato, Broccoli, and

Peppers (refer to Appendix Table 2.3). Corn/maize was the most frequently studied individual crop as it was used in 19.2% (28 studies) of the total studies (Appendix Table 2.3).

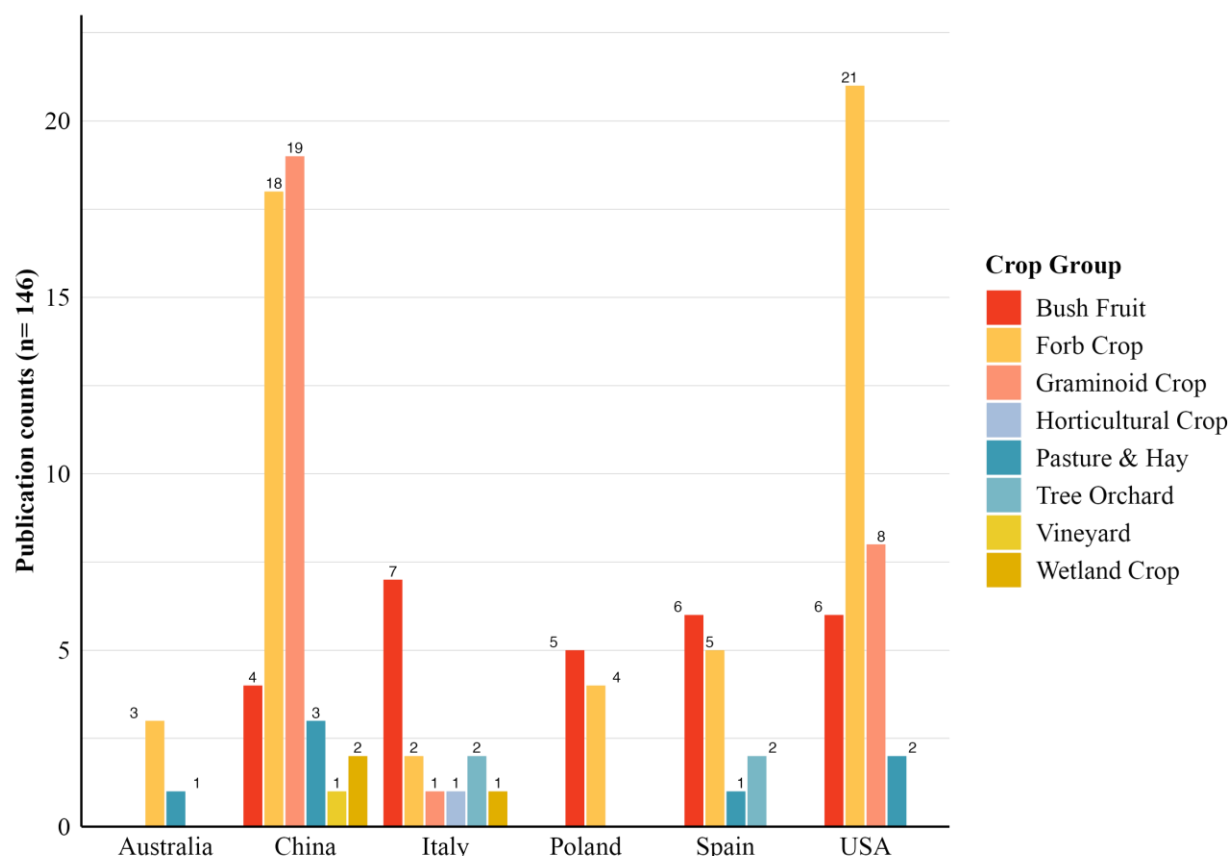
Figure 2.5. Types of crops and crop groups used in biodegradable mulch studies (figures in percentages)



Note: Forb Row Crop [Forb Crop], Tree Orchard, Bush Fruit & Berry [Bush Fruit], Cultivated Pasture & Hay [Pasture & Hay], Graminoid Row Crop [Graminoid Crop], Herbaceous Wetland Crop [Wetland Crop], Shrub Horticultural Crop [Horticultural Crop], Vineyard

In terms of differences in the studied crops by country, the Forb row crop group was the most common among studies conducted in the USA and Australia (Fig. 6). For example, the effectiveness of biodegradable mulch has been assessed with crops such as Pie pumpkin, watermelon, and pepper in USA (Anunciado et al., 2021b; Shogren & Hochmuth, 2004; Velandia et al., 2020), and cotton in Australia (Braunack et al., 2020). The Graminoid row crops were the main crops used in studies conducted in China. On the other hand, Bush fruits & berry crop group emerged as the predominant crop type among the European countries.

Figure 2.6. Crop groups and country of study



Note: *Forb Row Crop* [Forb Crop], *Tree Orchard*, *Bush Fruit & Berry* [Bush Fruit], *Cultivated Pasture & Hay* [Pasture & Hay], *Graminoid Row Crop* [Graminoid Crop], *Herbaceous Wetland Crop* [Wetland Crop], *Shrub Horticultural Crop* [Horticultural Crop], *Vineyard*

2.3.3 Biodegradable mulch

2.3.3.1 Studied biodegradable mulches

The primary studies used a wide variety of biodegradable mulches, which can be broadly classified into 14 categories of mulches (Table 3). The primary studies typically report and identify the tested mulches using commercial names, the main constituent of a polymer blend, or alternative application formats. The most frequently studied mulches, identified via the main polymer blend include Polylactic acid (PLA), Polybutyrate adipate terephthalate (PBAT), and starch-based mulches. While the most commonly studied mulches identified via commercial name were Mater-Bi® and Bionolle nonwoven mulches (Table 3). Studies reporting to have used

Mater-Bi®-based mulches were predominantly associated with experiments on tomato crops (Anzalone et al., 2010; Cirujeda et al., 2012b; Sekara et al., 2019). We further observed that Mater-Bi®-based mulch was frequently used in studies conducted in European countries such as Italy, Spain, and Poland, where tomatoes are widely employed in mulch experiments (see Appendix Fig. A. 1 and Appendix Table 2.4).

Table 2.3. Studied biodegradable mulches

Studied mulches	Percent of studies (%)
<i>Mulch identified by commercial/ trade names</i>	
Mater-Bi®/ Mater-Bi™/ BioAgri of Mater-Bi® (Mater-Bi)	13.2
Biodegradable plastic Bioflex (BPB)	1.3
Biodegradable plastic Ecovio (BPE)	1.3
Bionolle biodegradable nonwoven (BBN)	2.6
<i>Mulch identified by main polymer blends</i>	
Polylactic acid (PLA)	19.2
Polybutyrate adipate terephthalate (PBAT)	17.9
Polybutylene succinate and adipate (PBSA)	5.3
starch-based biodegradable film (BDF)	10.6
Polyhydroxy-alkanoates (PHA)	7.3
Cellulose-based biodegradable film (CBF)	2.6
Ethylene vinyl acetate (EVA)	1.3
Polyvinyl alcohol (PVA)	5.3
<i>Mulch identified by alternative format</i>	
Sprayable biodegradable mulch film (BSM)/ Liquid film (LF)	6.6
Biodegradable paper mulches (BPM)	13.2

Note: *The specific content of each polymer blend is not reported in all studies.*

Studies investigating mulch effects on Pie pumpkin mainly utilized PLA- and PHA-based mulches (Bandopadhyay et al., 2020; Hayes et al., 2017; Sintim et al., 2020). This trend is largely attributed to the fact that almost all the studies involving Pie pumpkin originate from the USA, where these mulches are also commonly studied (refer to Fig. 6, Appendix Fig. A. 1, and Appendix Table 2. 4). In terms of assessing the suitability of mulches in row crops such as corn and wheat, the predominant polymer blend mulches used were PBAT, PLA, and PHA mulches (Anunciado et al., 2021a; Qiao et al., 2022b; Ren et al., 2016).

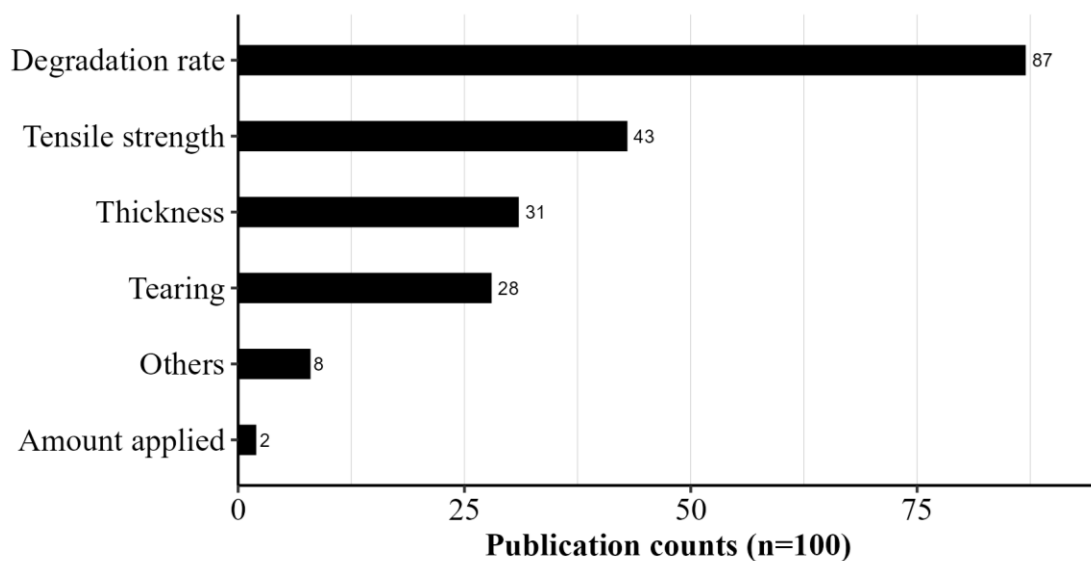
2.3.3.2 Physical properties of biodegradable films

Most biodegradable mulches are designed to be applied in similar fashion as conventional plastic mulches, but then tilled into the soil after use, eliminating waste and disposal challenges (Schettini et al., 2004; Vox et al., 2013). To achieve this aim, biodegradable mulches are expected to have certain physical and mechanical properties comparable to conventional plastic mulch in addition to being biodegradable (Briassoulis & Degli Innocenti, 2017; Hayes & Flury, 2018; Kopitar et al., 2022). As such, research has often examined the physical and mechanical properties of biodegradable mulch to assess its compliance with standard requirements, suitability for agricultural applications, and to identify properties appropriate for specific crops, climates, and farming practices. The common properties of concern for practical use include tensile strength, elongation at break, thickness, water permeability, degradation rate, UV resistance, as well as color and light reflectance. Others included porosity, puncture resistance, and adhesion strength.

About 87% of the studies that considered physical properties of biodegradable mulches examined the degradation rate (Fig. 7), which is essential to understanding the mulch's lifespan and its environmental impact. The studies measured degradation rate as an indicator of how quickly the mulch breaks down into natural components over time during deployment and or after being tilled into the soil (Fontanazza et al., 2021; Mosnáčková et al., 2019). While several studies (Sintim et al., 2019, 2020) examined degradation rate of tilled-in mulch beyond the growing season or over multiple growing seasons, the majority of the primary studies examined degradation only during the deployment period. Degradation was often evaluated qualitatively based on physical appearance through periodic inspection of the mulch during deployment for

visible signs of degradation, such as changes in color, texture, or the presence of holes and cracks (Briassoulis, 2006; C. Li et al., 2014). Relatedly, mulch degradation rate during deployment was sometimes assessed through the percent soil exposure technique (Anunciado et al., 2021a), where 0% represented soil that is completely covered by mulch and 100% represented fully exposed soil (Ghimire, 2018). The reported field trial degradation rate during the deployment period often ranges from 10% to 96% within a period of 60 days (about 2 months) to 120 days (about 4 months) (Anunciado et al., 2021a; Feng et al., 2021; Kijchavengkul et al., 2010; Sintim et al., 2020).

Figure 2.7. Studied biodegradable mulch mechanical properties



Over 43% of studies that evaluate physical properties assessed biodegradable mulch tensile strength while 31% examined thickness and suitability for agriculture application (Fig.7). Assessment of tensile strength is critical to ascertaining the mulch's durability during installation, exposure to environmental factors, and resistance to tearing (Chiellini et al., 2004; Sartore et al., 2013). The level of thickness influences the mulch effects on agronomic factors such as moisture retention and weed suppression and could vary depending on cost and the intended

application (See Table 5). Reported thickness is generally within the range of 0.015mm to 4mm (Sartore et al., 2013; Wang et al., 2019). Other properties such as much color and ultraviolet (UV) resistance were also examined by 8% of the studies. Dark-colored mulches can absorb more heat, potentially increasing soil temperature, while reflective mulches can help maintain cooler soil temperatures (Amare & Desta, 2021; Stapleton & Summers, 2002). UV resistance measures how well the mulch can withstand exposure to UV radiation from sunlight without degrading or becoming brittle (Vox & Schettini, 2007).

Whereas the amount of sprayable mulch applied (i.e., layer thickness) is noted for influencing crop yields, soil health, and weed control, we found that only two out of the 20 studies considering sprayable mulch empirically assessed the amount of the mulch applied (Fig. 7). For example, Khan et al. (2020) found that the amount of sprayable mulch applied with herbicides shapes its effects on weed control. Similarly, Giaccone et al. (2018) found that inadequate sprayable mulch application or coverage may leave gaps where weeds can emerge, reducing the effectiveness of weed suppression. Excess mulch application contributes to residue pollution if not fully biodegraded, while insufficient mulch can result in increased herbicide use to control weeds (Abduwaiti et al., 2021; Khan et al., 2020).

2.3.4 Study agronomic impacts

Effects of biodegradable mulch on crops yields was the most studied agronomic factor, constituting about 102 studies out of a total 136 studies examining suitability in terms of agronomic impacts (Table 4). For example, earlier studies such as Shogren & Hochmuth (2004b) evaluated the effects of biodegradable mulch application on watermelon yields in the field compared to plastic mulch. More recent studies including Qiao et al. (2022b) and Shine (2019) assessed the effects of biodegradable mulch on the yield of cereal crops such as corn, wheat, and

rice production. The focus of most research publications on the effects on crop yields, as opposed to other agronomic factors, could be due in part because other agronomic impacts ultimately contribute to the end goal of crop yields. We found a sufficient research interest on biodegradable mulches' effect on soil temperature, soil moisture, weed control, and water use efficiency (Table 4). The least studied agronomic factor was the impact of biodegradable mulch application on pest and disease control, with only a total of two (2) studies. Other agronomic factors examined include biodegradable mulch application effects on crop growth, soil microbes, soil nutrients, crop quality, cost and economic benefits, and germination rate.

Table 2.4. Studied agronomic factors

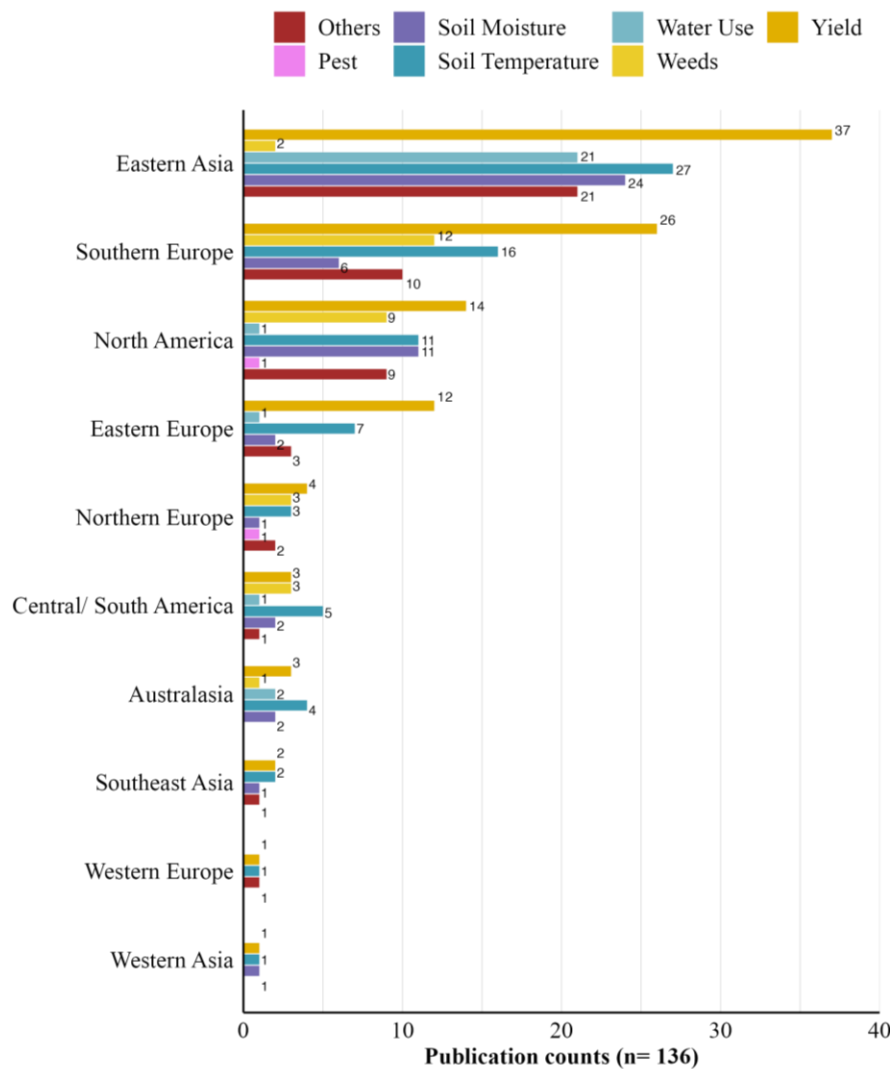
Agronomic factors	No. of studies
Effect on crop yield	102
Effect on soil temperature	77
Effect on soil moisture	50
Effect on weed control	30
Effect on water use efficiency	26
Effect on pests and diseases	2
Effect on crop growth	17
Effect on soil microbes	11
Effect on soil nutrients	6
Effect on crop quality	19
Effect on cost and economic benefits	8
Effect on germination rate	3

Note: the literature search was concluded on June 15, 2022

The focus of each study on specific agronomic factors varies based on the objectives of the studies, research priorities, and the specific region of study. All agronomic factors are analyzed at multiple sub-regions, and studies from all the sub-regions examined multiple agronomic factors (Fig. 8). However, we noticed a larger fraction of studies focusing on crop yields in regions with highly developed countries where large-scale industrial agriculture is predominant. Some of the sub-regions and countries where research on the effects of biodegradable mulch on crop yields is particularly prominent include: (i) Eastern Asia (China

and Japan have a significant focus on agricultural productivity and interest in sustainable practices, including biodegradable mulch (Fig. 2)), (ii) North America (the United States and Canada have robust agricultural research with a substantial focus on biodegradable mulch and its impact on crop yields), (iii) Southern, Northern, and Eastern Europe (European countries are at the forefront of sustainable agriculture practices, and biodegradable mulch research is common in countries like Italy, Spain, and Poland (Fig. 6)). The choice of agronomic factors to study was also dependent on local climate conditions. For example, sub-regions Central/South America, Eastern Asia, and Australasia with hot summers and humid conditions had a relatively higher frequency of studies focusing on biodegradable mulch effects on soil temperature and moisture retention (Fig. 8).

Figure 2.8. Studied agronomic factors across sub-regional divisions

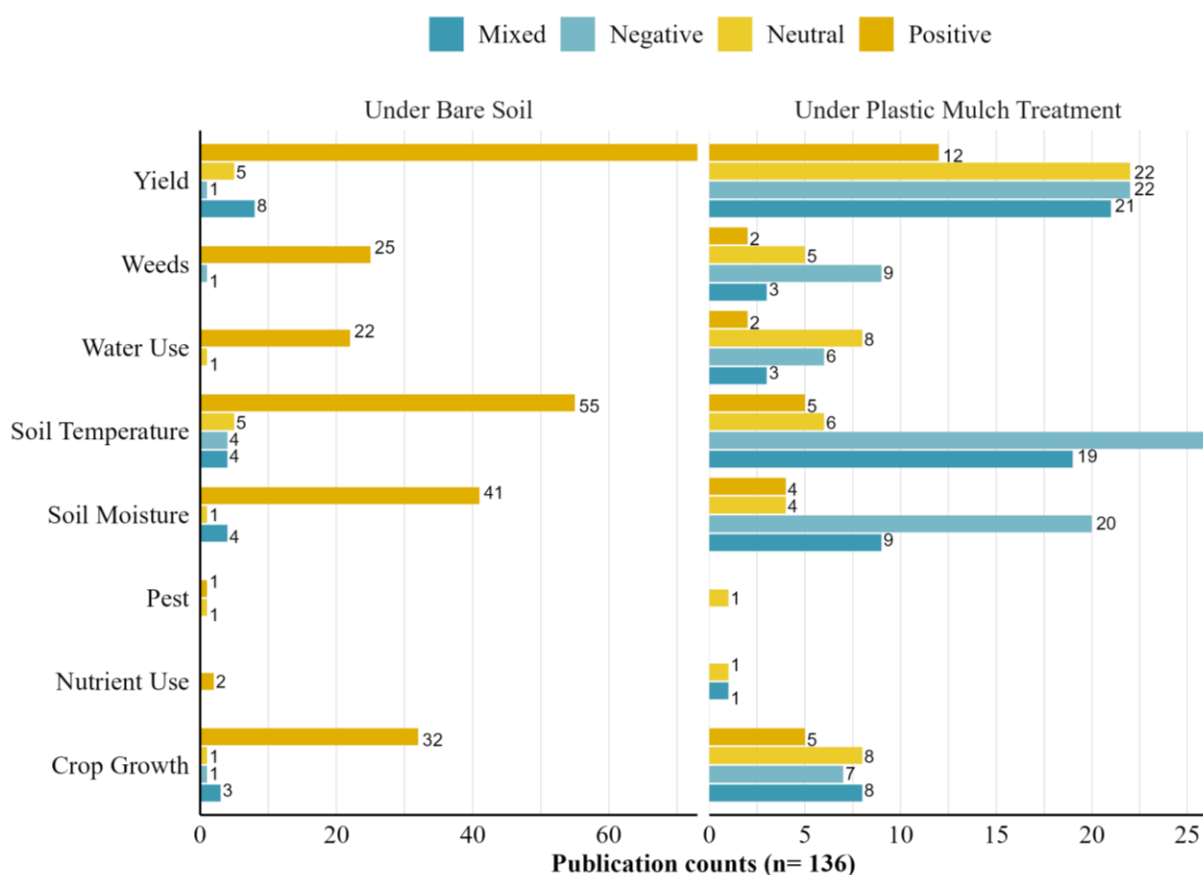


Note: Effects on crop yields [Yield], Effects on pest and diseases [Pest], Effects on soil moisture [Soil Moisture], Effects on soil temperature [Soil Temperature], Effects on weeds control [Weeds], Effects on water use efficiency [Water Use], Effects on other agronomic factors [Others]

The assessment of biodegradable mulch effects was mainly conducted through analysis of variance using one-way ANOVA to test the differences between biodegradable mulch and control effects (Kalisz et al., 2019). Among the studies evaluating biodegradable mulch effects on crop yields (Fig. 9), over 83.9% reported an increase in crop yields (positive) when using biodegradable mulch compared to bare soil (Kołodziejczyk et al., 2019; Li et al., 2021; Zhang et al., 2019), while only 15.6% indicated an increase in yield compared to plastic mulch (Cowan,

2013; Kapanen et al., 2008). Moreover, about 5.7% of the studies found no significant yield differences (neutral) between crops grown under biodegradable mulch and bare soil, while 28.6% observed no significant yield differences compared to plastic mulch (Braunack et al., 2020; Moreno et al., 2016). Similarly, 9.2% of the studies reported mixed findings (i.e., both positive and negative differences) on yield differences compared to bare soil (Bucki et al., 2018; Zong et al., 2021), while over 27.3% of studies observed mixed results on yield differences compared to plastic mulch (Abduwaiti et al., 2021; Candido et al., 2012). The mixed results were partly due to the use of multiple biodegradable mulches in a single study, differing impacts across treatment replicates, or early degradation of the mulch before the end of the growing season leading to differing impacts throughout the course of experiments.

Figure 2.9. Effects of biodegradable mulch application on studied agronomic factors compared to bare soil and plastic mulch treatment



Note: *Effects on crop yields [Yield], Effects on pest and diseases [Pest], Effects on soil moisture [Soil Moisture], Effects on soil temperature [Soil Temperature], Effects on weeds control [Weeds], Effects on water use efficiency [Water Use], Effects on soil nutrients use efficiency [Nutrient Use]*

The reported relative benefits of biodegradable mulch varied strongly for weed control, soil temperature, and soil moisture (Fig. 9). Thus, while a vast majority (96.2%) of the studies observed that biodegradable mulch-controlled weeds were more effectively (positive) than no-mulch (Kwiecien et al., 2018; Oliveira et al., 2021), only 15.8% found the mulch to have controlled weeds better than plastic mulch (Neto et al., 2019). In terms of soil temperature, 80.9% of studies found soil under biodegradable mulches to have a higher temperature (positive) compared to bare soil (Candido et al., 2012; Li et al., 2021; Zhang et al., 2019), while 8.9% studies reported a rise in soil temperature compared to plastic mulch (Feng et al., 2021). Conversely, 5.9% of studies observed lower temperature (negative) of soil under biodegradable mulch compared to bare soil (Hernández-Aranda et al., 2021; López-Marín et al., 2012), while over 46.4% observed a decreased soil temperature compared to plastic mulch (Hagner et al., 2020; Wang et al., 2019). Relatedly, a greater proportion (89.1%) of the studies found that biodegradable mulch increased or retained soil moisture (positive) relative to bare soil (Mosnáčková et al., 2019; Zhang et al., 2020), while only 7.1% found an increased in soil moisture content compared to plastic mulch (Costa et al., 2014).

There was no noticeable disproportionate reporting of positive results for agronomic effects from specific countries' sub-regional groups (Appendix Fig. A. 3 and Appendix Fig. A. 4) other than for regions located in hot climate conditions (Australia and Central/ South America), where very few negative effects were reported (Appendix Fig. A. 3). Thus, it was observed that studies conducted in global biomes with hot summer, arid, and or humid climate conditions (Woodward et al., 2004; Woodward & Lomas, 2003), were more likely to report positive effects

of biodegradable mulch application irrespective of the agronomic factor being assessed (Appendix Fig. A. 5). For example, studies in the temperate broadleaf & mixed forests biome reported neutral to positive effects of biodegradable mulch in 90.9% cases in comparison to no-mulch and in 48.8% of cases relative to plastic mulch treatment, which is higher than performance in any other biome. Also, the desert shrublands and Montane grasslands reported 100% positive effects of biodegradable mulch compared to bare soil. These results may be indicative of a greater suitability of biodegradable mulch in arid hot climate regions.

Generally, agronomic impacts relative to no-mulch were reported as positive in the vast majority of cases for all mulch types (Appendix Fig. A. 7). Mater-Bi®-based mulch products and paper mulch products tended to show the most comparable or positive impacts relative to plastic mulch, with paper mulches outperforming other mulch types for weed control and Mater-Bi®-based mulch outperforming other mulch types for yield. On the other hand, polybutyrate-based products, which were most frequently tested in experiments in China, tended to show more negative results when compared with plastic, particularly for soil moisture retention, however all mulch types displayed a high degree of variability in findings (Fig SI 8).

The comparative effects of biodegradable mulches differ across the crop groups (Appendix Fig. A. 9 and Appendix Fig. A. 10). The relative effects of biodegradable mulches across different crop groups show varying positive benefits compared to no-mulching, with Graminoid, Forb, and Bush Fruits reporting a higher frequency of positive effects (96.6%, 82.0%, and 78.7% of instances, respectively) regardless of agronomic factor (Appendix Fig. A. 9). However, all crop groups recorded fewer positive effects when compared to plastic mulch, with benefits most frequently observed for Bush Fruits (17.0%), Graminoid (15.7%), and Forb (8.5%) crop groups. In terms of crop yields, all groups except for the Vineyard group showed

increased yields under biodegradable mulching, with Wetland, Graminoid, Tree Orchard, and Pasture groups having yield increases compared to no-mulching or plastic mulch in 80.0%, 61.0%, 57.1%, and 60.0% of instances, respectively (Appendix Fig. A. 10).

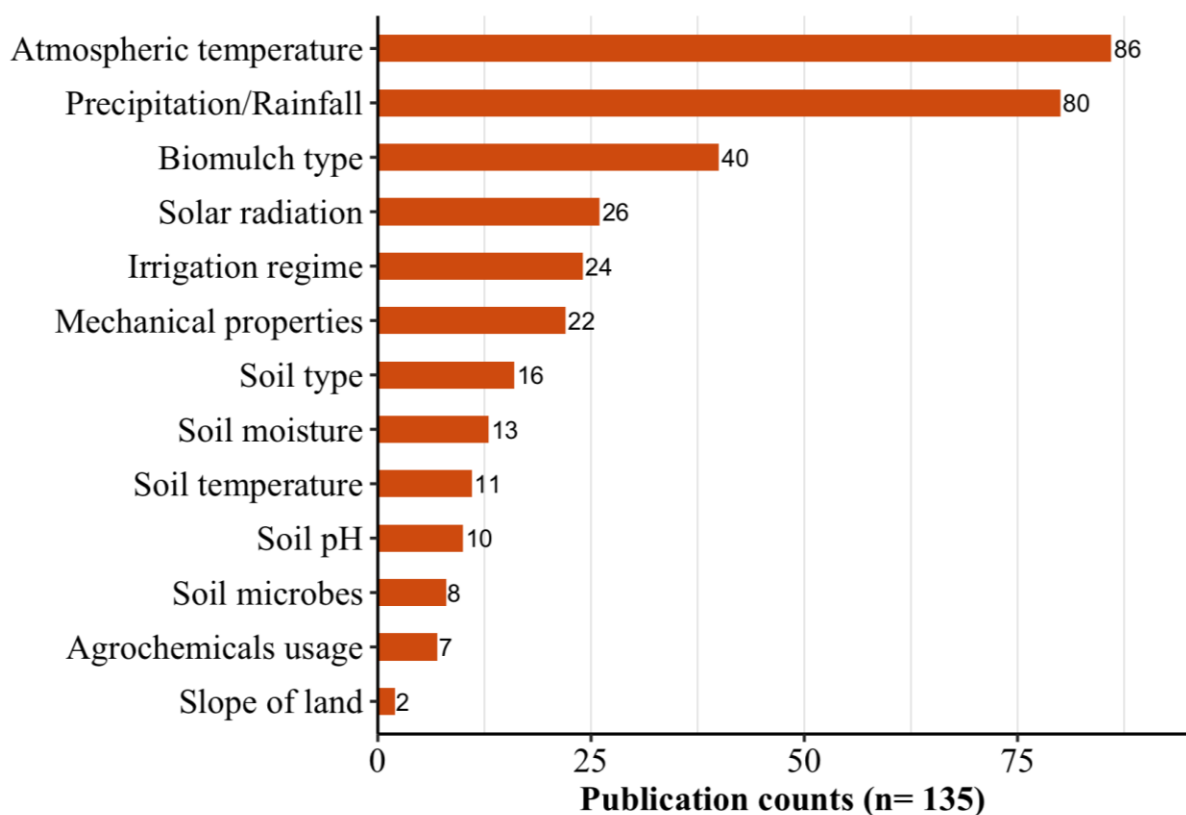
2.3.5 Factors affecting the suitability and effectiveness of biodegradable mulches

The ability of biodegradable mulches to sustain their performance and mechanical properties throughout the growing season remain crucial for their suitability in agricultural applications, especially in efforts to replace plastic mulches. Biodegradable mulches are designed to be suitable for agriculture application with minimum possible thickness aimed at reducing cost and ensuring optimal biodegradation rate while retaining satisfactory mechanical performance throughout the growing season (Briassoulis, 2007b). Field trials have demonstrated that depending on the thickness of the mulch, degradation can begin between two and three months (Kijchavengkul et al., 2008). Under irrigated agricultural soil conditions, the mulch is shown to readily degrade over 90% within four to six months in such management systems.

One of the main factors that shape the suitability of biodegradable mulch applications is the local climate conditions. Thus, over 63.7% of the studies monitored atmospheric temperature during experiments highlighting the importance of this environmental factor on agronomic factors and degradation rates (Fig. 10). For instance, Samuelson et al. (2022) observed a relatively greater degradation rate at Lincoln, Nebraska USA due in part to higher mean annual temperatures (10.6°C) compared to 8.8°C in Scottsbluff, Nebraska USA. Similarly, Li et al. (2014) found a higher deterioration rate (98%) in a study site with warmer temperatures at Lubbock in Texas, United States compared to a 11% degradation rate at Mount Vernon, Washington State USA. Considering that microbial activity tends to double with every 10°C

increase in temperature, a phenomenon often denoted as the Q_{10} , it is conceivable that there is a temperature threshold for the biodegradation of these mulches (Li et al. 2014). About 59.3% of the studies found the suitability of the mulches to be shaped by precipitation. In a field trial, Feng et al. (2021) observed a relatively higher degradation rate in 2017 under conditions with higher precipitation compared to other experimental years. Evidence showed that total monthly precipitation of 127.5 - 134.0mm resulted in a rapid loss of the mulch functionality (Zhang et al., 2008). These studies suggest that the combined effect of higher temperature and precipitation may result in rapid mineralization of the mulch.

Figure 2.10. Monitored environmental conditions during primary study experiments



The intensity of solar radiance (UV) reaching the mulch surface determines biodegradable mulch capacity to maintain its mechanical performance over the growing season. Experimental results showed UV [photodegradation] as one of the main degradation mechanisms

on field application (Kijchavengkul et al., 2008). For example, Briassoulis (2007b) found a high dose of UV radiation (above 28 MJm⁻² per day) to have detrimental effects on the elongation at break of the mulches. Soil attributes such as the level of temperature, moisture, pH, microbes' diversity, and texture class were also found to be relevant to biodegradable mulch suitability on the field (Fig. 10). For example, Samuelson et al. (2022) and Li et al. (2014) investigated the effects of soil temperature and moisture on degradation rate of biodegradable mulches, during deployment, in contrasting sites and found rapid mulch disintegration in sites with higher soil temperatures and moisture content. Soil microbes, including bacteria and fungi, accelerate the decomposition process during deployment by actively feeding on the mulch as well as producing enzymes that break down complex organic materials in biodegradable mulches (Bandopadhyay et al., 2020; Shan et al., 2022; Tang et al., 2022). Soil pH level between 6.2 to 7.5 provides an optimum condition for most of the microbes involved in biodegradation in the soil (Suzuki et al., 2014). Finer soil texture class (silt and loamy soils) are also found to be more suitable for biodegradable mulch application (Samuelson et al. (2022).

The types and mechanical properties of biodegradable mulches affect their suitability and effectiveness on the desired agronomic factors (Table 5). Different mulch colors including red, blue, infrared thermal green, brown, silver, black, and white are currently being experimented toward achieving various agronomic purposes. White transparent mulches result in increased soil temperature and early crop maturity because of the ability to solarize the soils and further serving as an environmentally friendly method of physical disinfection (Orzolek, 2017). Komariah et al. (2021) observed a higher soil temperature (26.69°C) under transparent mulch compared to black plastic mulch (26.07°C). However, there were varied reported impacts of the color of mulches on soil temperature. For example, Jahan et al. (2018) and Jia et al. (2020) reported that black and

blue plastics increase soil temperature while clear and white plastics decrease it. Moreover, mulch color affects the photosynthetically active radiation (PAR) reaching the soil under mulch. The effectiveness of mulches in controlling weeds was reported to depend on their ability to moderate the amount of PAR reaching the mulched soil (Anzalone et al., 2010; Candido et al., 2012). Biodegradable mulches with a PAR total transmissivity coefficient from 0.2 to 4.1 have been found to have a greater ability to reduce weed growth (Amare & Desta, 2021). Different color pigments can also act as UV-shielding agents to prevent or delay photo-degradation (Orzolek, 2017).

Table 2.5. Synthesis of contextual factors influencing mulch suitability or effectiveness.

*Agronomic factors	Contextual factors	Influence of contextual factors
Crop yield	1. Mulch color 2. Mulch thickness 3. Ambient temperature 4. Precipitation/ rainfall 5. Solar radiation 6. Soil microbes 7. Soil pH level 8. Crop/ vegetation cover	1. White transparent films are more effective in increasing soil temperature and early crop maturity. 2. Thicker mulches (i.e., at least 15mm) degrade slower and maintain their functionality throughout the growing season. 3. Higher atmospheric and soil temperatures cause cracks and rapid degradation of mulch before the end of the desired coverage period, thereby reducing its effectiveness. 4. Excess rainfall causes disintegration and rapid degradation of mulch before the desired coverage period, which reduces its effectiveness. 5. Higher solar radiance causes disintegration and rapid degradation of mulch, which reduces its effectiveness. 6. The presence of certain soil microbes facilitates the mulch degradation process. 7. The presence of a certain range of soil pH creates a conducive environment for the rapid disintegration of mulches.

*Agronomic factors	Contextual factors	Influence of contextual factors
Weed control	1. Mulch color 2. Mulch tensile strength 3. Weeds species 4. Crop/ vegetation cover 5. Stage of application	8. Mulch applied under crop or vegetation shade was more effective due to reduced contact with direct solar radiation. 1. Black films are more effective in controlling weeds through sunlight exclusion. 2. Mulch with lower tearing and tensile strength is likely to develop cracks and wear allowing weeds to germinate and penetrate through. 3. Nutsedges (<i>Cyperus</i> spp.) and other weeds with sharp growing points can lift mulch films or punctures and emerge through the film. 4. Mulches were more effective in weed control under vegetation or crop canopy due to enhanced blocking of sunlight reaching the mulch and soil surface. 5. Mulch application at the early stage of crop planting is more effective in weed control.
Water use efficiency	1. Mulch tensile strength 2. Field level practices	1. Mulch with higher tearing and tensile strength is likely to maintain its functionality throughout the growing season and therefore prevent runoff or provide soil more time to absorb rainwater by lowering the kinetic energy of rain or by slowing the movement of rainwater, which enhances root water absorption. 2. Crop soil water use and runoff efficiency increased with wider ridge width. 3. Mulch application in furrow ridge irrigation reduces the amount of irrigation water demand.
Soil temperature	1. Mulch color 2. Ambient temperature	1. White transparent and infrared-transmitting films allow solar radiation to reach the soil and are more effective in increasing soil temperature.

*Agronomic factors	Contextual factors	Influence of contextual factors
Soil moisture	1. Mulch thickness 2. Mulch tensile strength 3. Types of soil texture 4. Ambient temperature 5. Precipitation/ rainfall	1. Thicker mulch reduces soil water evaporation and is more effective in soil water retention. 2. Mulch with lower tearing and tensile strength is likely to develop cracks and wear resulting in soil water evaporating through those cracks.
Pest and disease control	1. Mulch color	1. White transparent films reflect radiation to help control the presence of some insect pests.
Crop growth	1. The stage of crop growth at which the mulch is applied	1. Mulch applications at the early stages of crop growth were more effective than at later stages of crop growth.

***Note:** *Only the effect of biodegradable mulch during deployment over the cropping season.*

Overall the primary studies suggest that color type significantly influences mulch effects on soil temperature, moisture and water holding capacity (Table 5). Moreover, higher crop yields are reported in the use of colored plastic mulches (Amare & Desta, 2021; Gu et al., 2016; Zhao et al., 2022). For instance, Zong et al. (2021) observed higher corn yields under black biodegradable mulch compared to transparent plastic mulch. The thickness of biodegradable mulches also influences their ability to meet various usage needs (Table 5). Thus, thicker mulch has the ability to reduce soil water evaporation and is more effective in soil water retention. Biodegradable mulches with a thickness of about 8-12 μ m have proven the potential of meeting mechanical performance requirements and effectively maintaining soil temperature and moisture at levels completely consistent with plastic mulch (Abduwaiti et al., 2021; Z. Wang et al., 2019). Moreover, Fontenot et al. (2021) observed that 13mm thicker biodegradable mulch performed (8.7 fruit, 2.4Kg) comparably to 1.0mm thick plastic mulch (5.8 fruit, 1.9Kg) in terms of both average harvested number of fruits and weights.

Moreover, field-scale management practices such as irrigation regimes, timing of mulch application, and agrochemical usages were found to influence the effects of biodegradable mulches in agriculture applications. Thus, Khan et al. (2020) showed that biodegradable mulches blended with herbicide can effectively inhibit the growth of broadleaf weed species and may be of potential importance in a wide variety of horticultural and agricultural applications. Crop canopy cover was found to mediate mulch effects on soil temperature (Abduwaiti et al., 2021). Alamro et al. (2019) noted that crop/vegetation canopy cover reduced solar radiation reaching the surface of soil under mulch, which minimized soil water evaporation (Alamro et al., 2019). Irrigation practices such as ridge-furrow rainwater harvesting together with biodegradable mulching increased soil temperature and moisture content at ridge tops as well as increasing fodder yield by 7-18% compared to flat planting (Zhang et al., 2019). The level of mulch effectiveness on the agronomic factors was also found to be dependent on timing of application and the stage of crop growth (Ao et al., 2013; Gao et al., 2015; Jia et al., 2020). The influence of mulching on lettuce biomass was dependent on the timing of sowing (Hagner et al., 2020). Ao et al. (2013) indicated that there were less significant differences in soil temperature between biodegradable mulch and plastic mulch when crops reached their jointing stage.

Lastly, in terms of adoption, the ease of application, end-of-life management, organic regulations, effects on productivity, awareness and information availability, and the economics of use were the major determinants of farmers' decisions to use biodegradable mulch. The current prices of biodegradable mulches are higher than plastic mulch, which hampers their adoption in the field (Marí et al., 2019). A survey of farmers found the cost and labor savings associated with transitioning from plastic mulch to biodegradable mulch were the primary factors that influenced the economic feasibility of biodegradable mulch adoption (Sun et al., 2018;

Velandia et al., 2020). Moreover, while biodegradable mulch is more expensive than plastic, some farmers are motivated by end-of-life management cost savings and its environmental benefits (Dentzman & Goldberger, 2020; Ghimire et al., 2020; Warnick et al., 2006). Biodegradable mulches do not require waste removal after the growing season as they can be tilled into the soil, where they degrade into water, carbon dioxide, and microbial biomass (Goldberger et al., 2019). The other major adoption barriers noted in the primary studies were insufficient biodegradable mulch information and knowledge among farmers (Chen et al., 2019; Goldberger et al., 2015). Also, the USA National Organic Program requirements for biodegradable mulch to meet certain criteria, such as being made from biobased materials and 90% degradable in a specified timeframe, affect adoption rates due to the availability and cost of products that meet these standards (Dentzman & Goldberger, 2020; Goldberger et al., 2015).

2.4. Discussion and Conclusions

Our systematic review of studies evaluating the use of synthesized biodegradable mulch films for agricultural applications illustrates a significant increase in interest in these materials across major agricultural production regions since the 1990s. The agronomic factors studied in each region vary, with a significant emphasis on crop yields in developed regions known for industrial agriculture, such as Eastern Asia, North America, and parts of Europe. Overall, we find that the majority of studies report positive effects of biodegradable mulch use on all agronomic factors when compared to a no-mulch control group. Similar to Liu et al. (2021) and Tofanelli and Wortman (2020), we find that, in comparison to conventional plastic mulch, most studies report that biodegradable mulch offers similar or reduced levels of agronomic improvements. However, soil temperature and soil moisture benefits, in particular, are notably reduced for biodegradable mulch films relative to plastic mulch. In addition, our findings point to differences

in biodegradable mulch effects across agronomic impacts studied, biomes, crop types, and mulch types. Thus, while biodegradable films have shown positive agronomic effects compared to no mulch (Khalid et al., 2009), their ability to provide benefits comparable to plastic mulch films are influenced by contextual factors. Specifically, contextual factors such as climate, crop type, and soil properties differentially influence the effectiveness of different biodegradable mulch products in controlling weeds, conserving moisture, and improving soil temperature and yields.

There was no noticeable disproportionate reporting of positive effects of biodegradable mulch use from specific countries' sub-regional groups other than for regions located in hot climates, where very few negative effects were reported. Studies conducted in global biomes with hot summers, arid, and/or humid climate conditions often correlate with more positive agronomic impacts, suggesting a higher suitability of biodegradable mulch in these conditions. However, additional field experiments with biodegradable mulch in these biomes are warranted given the relatively small number of studies conducted in these areas. We also find that Mater-Bi and paper mulches exhibited a greater degree of effectiveness for certain agronomic factors, with paper mulches excelling in weed control and Mater-Bi in enhancing yields. Relatedly, a greater proportion of positive impacts of biodegradable mulch use relative to conventional plastic film were observed specifically for bush fruits and graminoid crops which were most frequently studied in Italy and China, respectively.

Although this review suggests that biodegradable mulch almost always provides agronomic benefits relative to not mulching and can often provide comparable benefits such as conventional plastic mulch, particularly for more arid environments, the realities of interactions between environmental conditions, mulch characteristics, and crop type strongly influence the agronomic and economic benefits of biodegradable mulch use. While the details of farm practice

and management are never trivial for any adopted innovation or technology, these details may be of pronounced importance relative to alternatives such as plastic mulch films due to the importance of biodegradable mulch degradation rates on agronomic impacts and the importance of environmental conditions on degradation rates.

While there are numerous studies that have conducted experiments using biodegradable mulch films for crop production, our review points to a few areas for future consideration. In particular, for sprayable mulch films, details on the mulch application process and resulting film characteristics are often insufficient to replicate the experiment or determine if observed variations in impacts are the result of varying film thickness or consistency of coverage or mulch formulation. In many experiments, regardless of mulch type, information on dates of application, dates and methods of planting, climate conditions, and observations of degradation in the field are incomplete, leading to uncertainty about the source of variations in observed impacts across experiments. Future research would benefit from more detailed collection and reporting of information on mulch application processes and mulch characteristics at the time of application and throughout the growing season. In addition, as degradation rates are of prime importance for biodegradable mulch films and are impacted by factors that also influence agronomic factors such as yield, studies that incorporate plot or field-scale collection of environmental conditions such as air temperature, precipitation, and UV radiance may be useful for uncovering thresholds of biophysical suitability of biodegradable mulch film use.

Our finding that more positive effects of biodegradable mulch use are found in hotter and more arid climates, as well as findings that suggest non-random testing of specific mulch products, with specific crops, in specific areas of the world, lead us to urge caution in interpretation and extrapolation of field experiment results to other contexts. Future research

would benefit from not just additional environmental monitoring but also from more studies conducted using experimental designs that intentionally and systematically vary crops, mulch product, and climate conditions.

We also note a lack of field studies examining the role of microorganisms in biodegradable mulch film degradation and agronomic benefits both during the growing season and after being tilled-in, as well as limited studies examining the impact of biodegradable mulch film use on microbial ecology of agricultural fields (Zhang et al., 2022). Given that “biodegradable” suggests that degradation occurs through biological metabolic processes, the interactions between microorganisms and biodegradable mulch films as they are used in agricultural practice and the potential for long-term soil health improvements in the field should be a fruitful area of future investigation. The impacts of biodegradable mulch films on weed and pest control were also relatively understudied in comparison to studies that investigated factors such as yield, soil moisture, and soil temperature. Lastly, there was a lack of studies examining the potential of biodegradable mulch films to support environmental benefits such as reductions in carbon emissions and other water and air pollutants in field applications.

This study provides an overview of the current state of biodegradable mulch studies in agricultural settings and summarizes what the state of knowledge is regarding the potential for biodegradable mulch films to offer benefits for crop production, soil health, and farmer economics across varied environmental and experimental contexts. However, our review is limited by the search terms and exclusion criteria employed. Studies that examined biodegradation rates of biodegradable mulch films in laboratory settings, for example, were excluded from this review but may offer insight into the impact of climate conditions on degradation rates. Furthermore, while our review captures information on the direction of

biodegradable mulch use impacts on agronomic factors relative to controls and alternative treatments the magnitude of these effects for each treatment trial were not collected. While our results suggest improvements over no mulch controls and comparability with conventional plastic mulch across many contexts, information on the exact magnitude of these differences and the extent of variability across trials are highly relevant to agricultural practice and decision-making.

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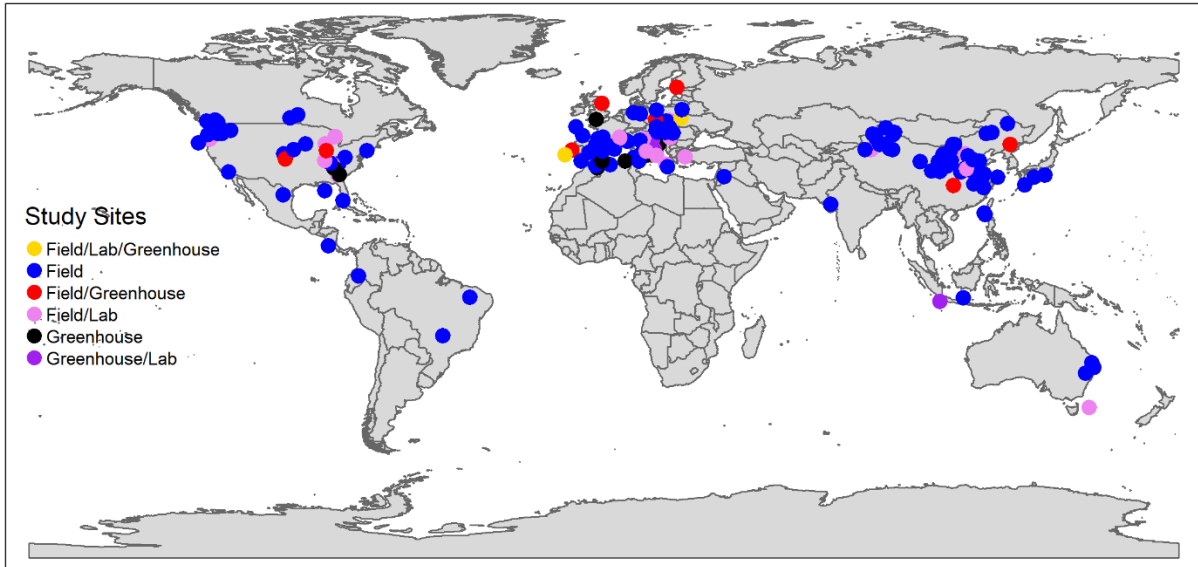
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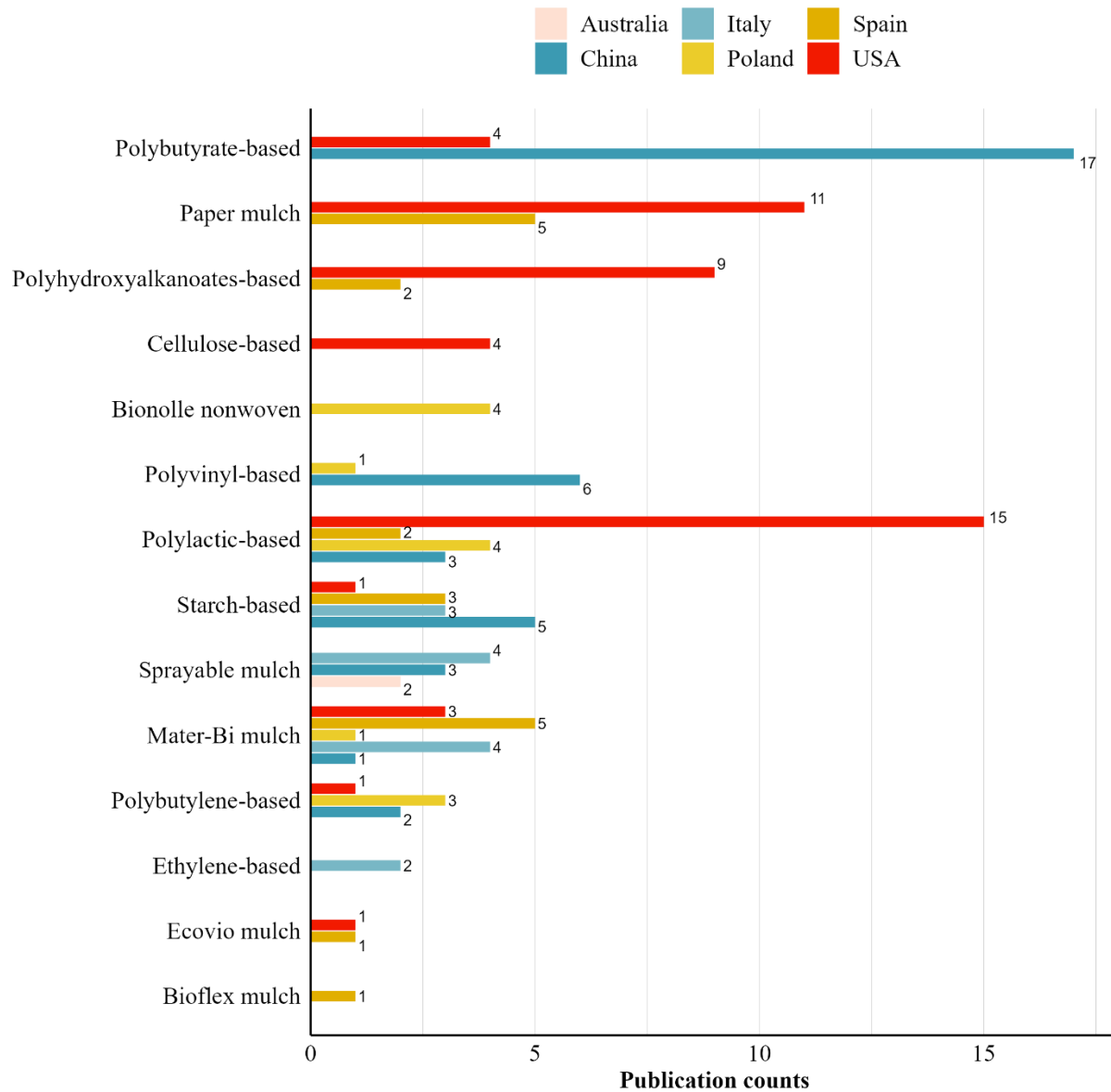
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Appendix A - Chapter 2 Supplementary Information

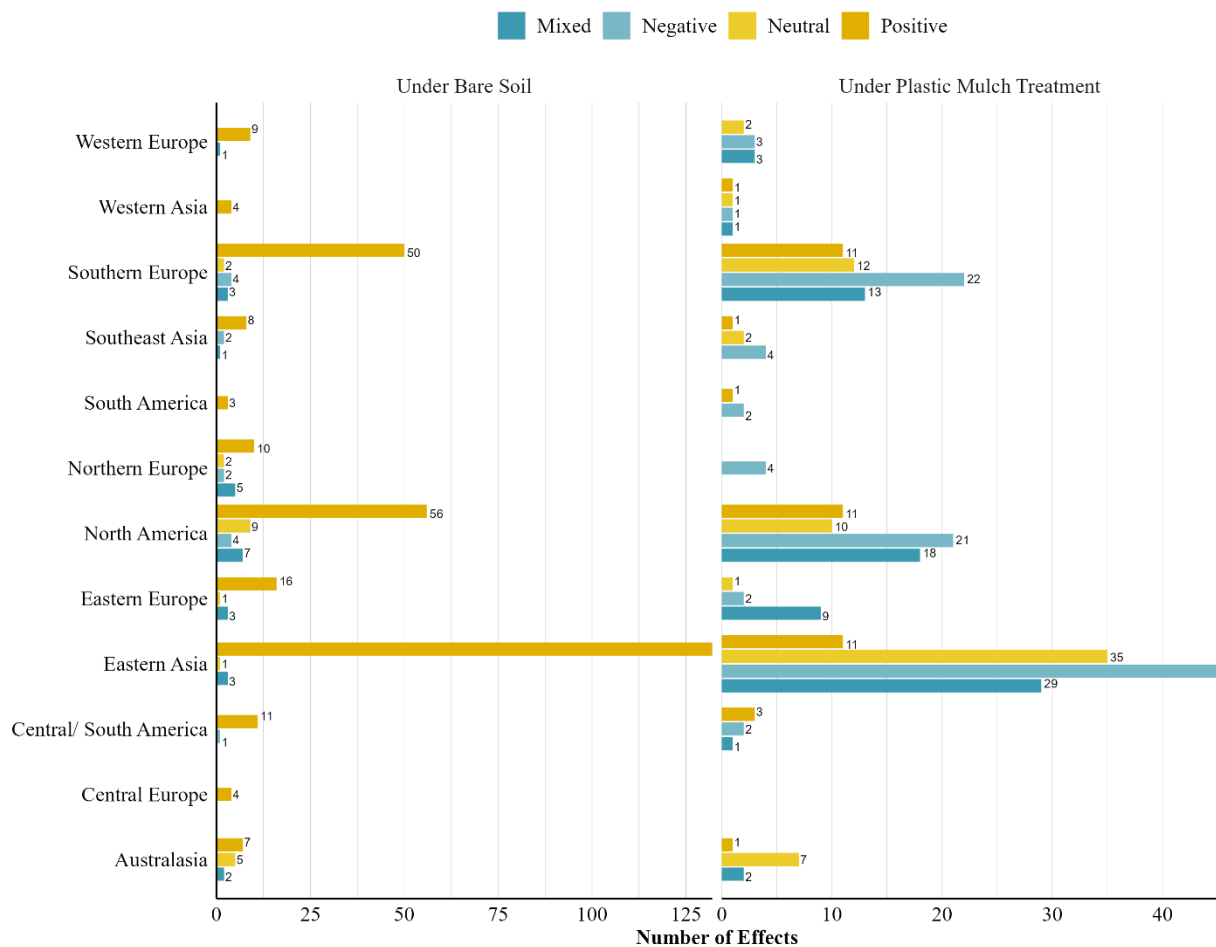
Appendix Figure 2.1. Spatial distribution of publications included in the analysis



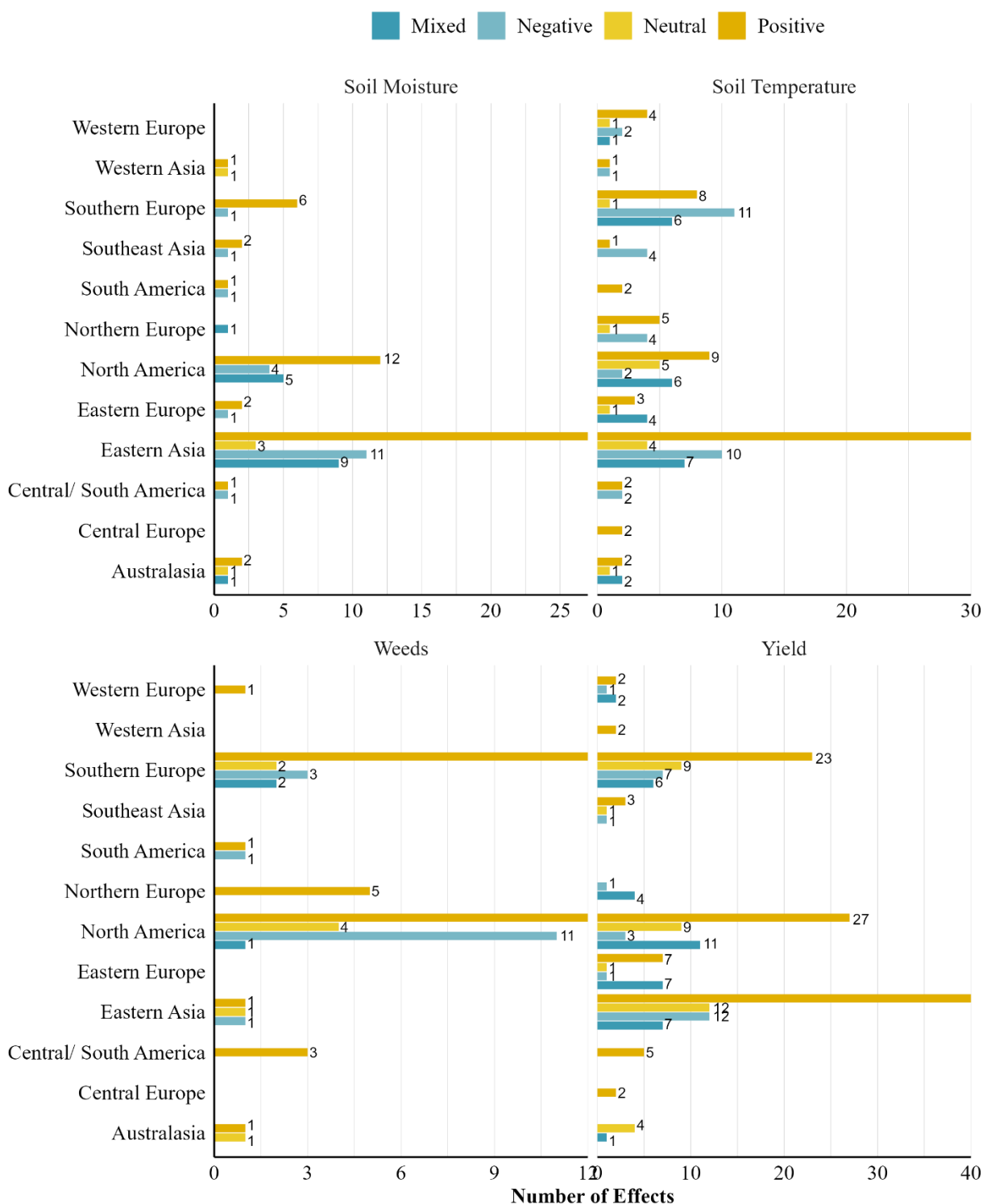
Appendix Figure 2.2. Biodegradable mulch types by country of study



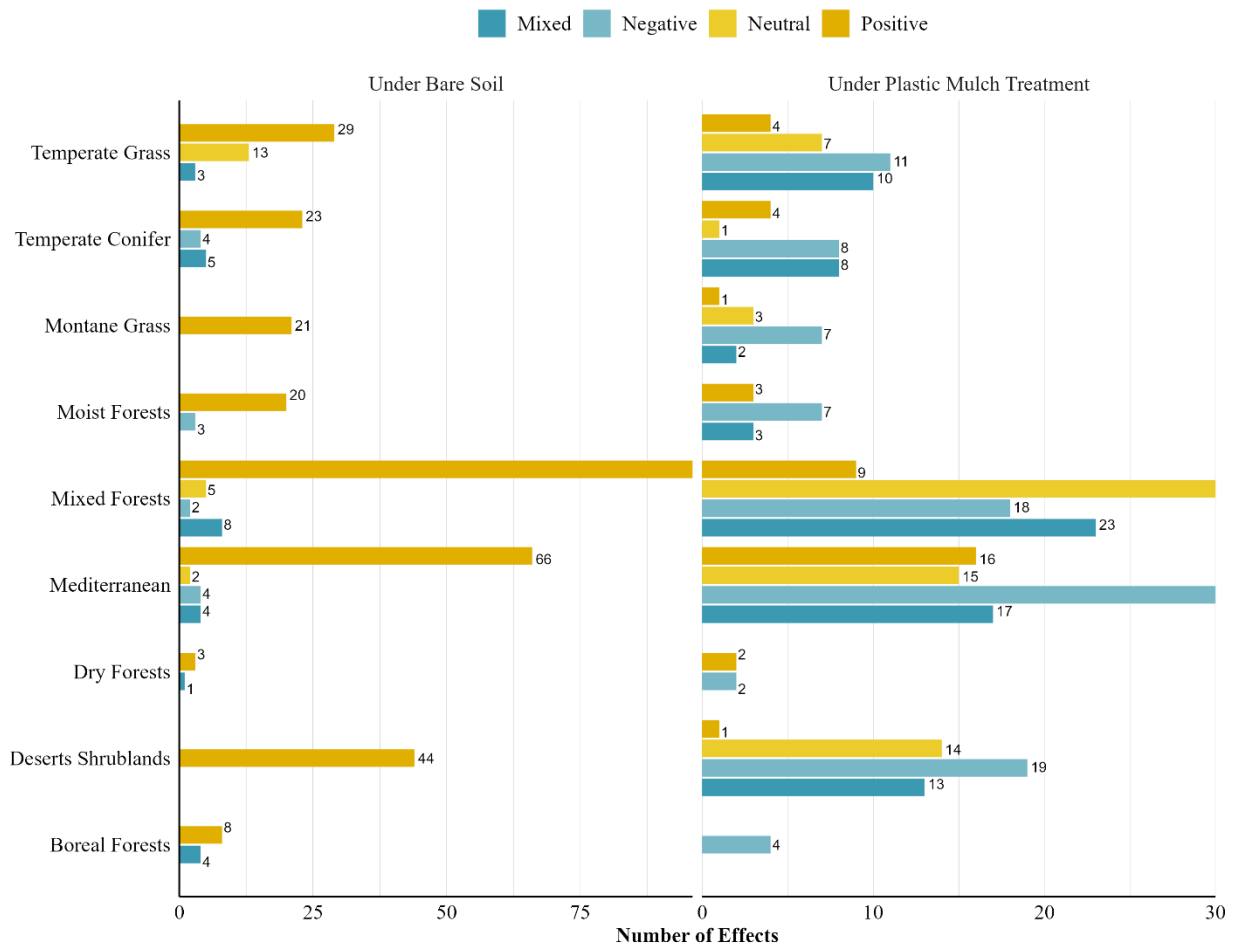
Appendix Figure 2.3. Effects of biodegradable mulch application by studied sub-regions compared to no-mulch control and plastic mulch treatment



Appendix Figure 2.4. Effects of biodegradable mulch application by studied sub-regions for the most studied agronomic factors

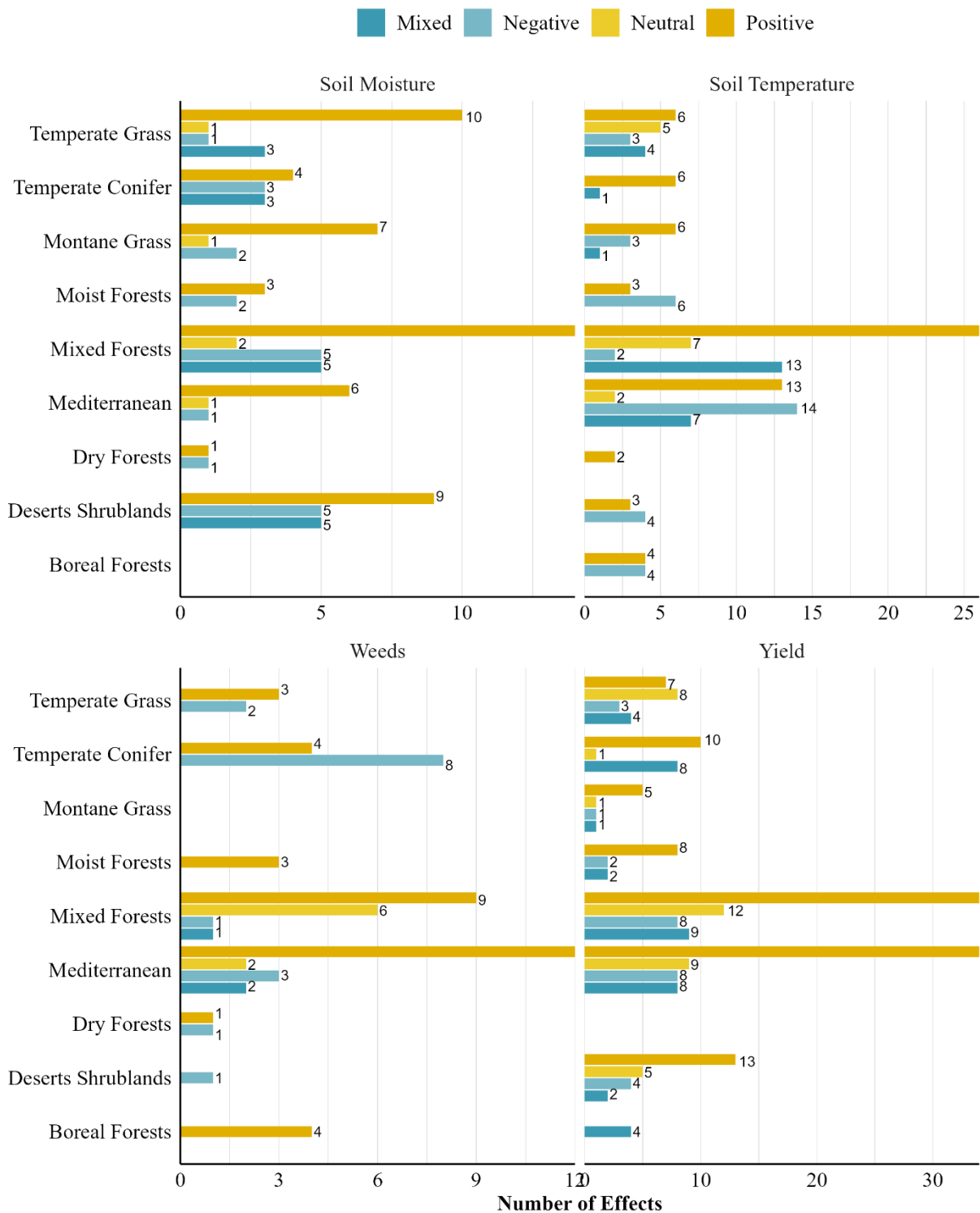


Appendix Figure 2.5. Effects of biodegradable mulch application by global biomes within studied areas compared to bare soil and plastic mulch controls.

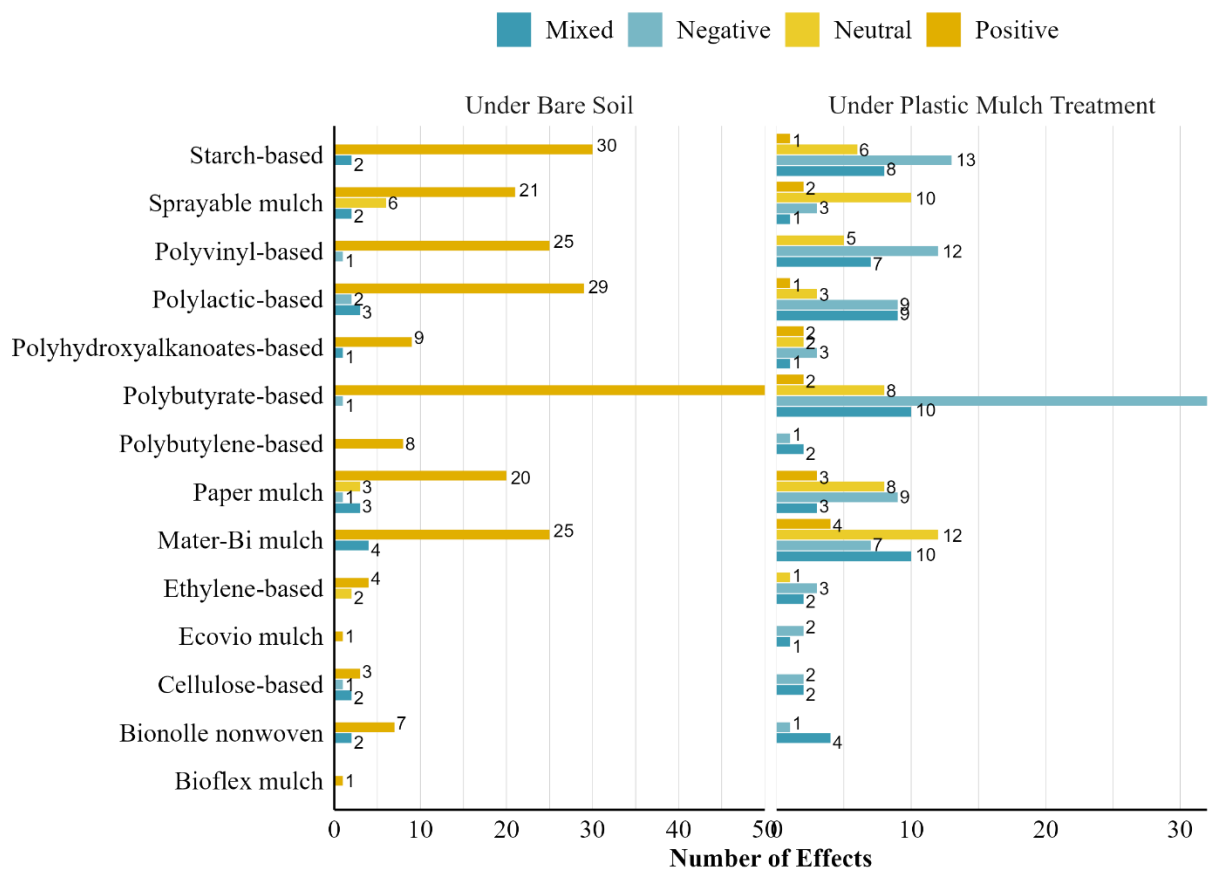


Note: Temperate Grasslands, Savannas & Shrublands [Temperate Grass], Temperate Conifer Forests [Temperate Conifer], Montane Grasslands & Shrublands [Montane Grass], Tropical & Subtropical Moist Broadleaf Forests [Moist Forests], Temperate Broadleaf & Mixed Forests [Mixed Forests], Mediterranean Forests, Woodlands & Scrub [Mediterranean], Tropical & Subtropical Dry Broadleaf Forests [Dry Forests], Deserts & Xeric Shrublands [Deserts Shrublands], Boreal Forests/Taiga [Boreal Forests]

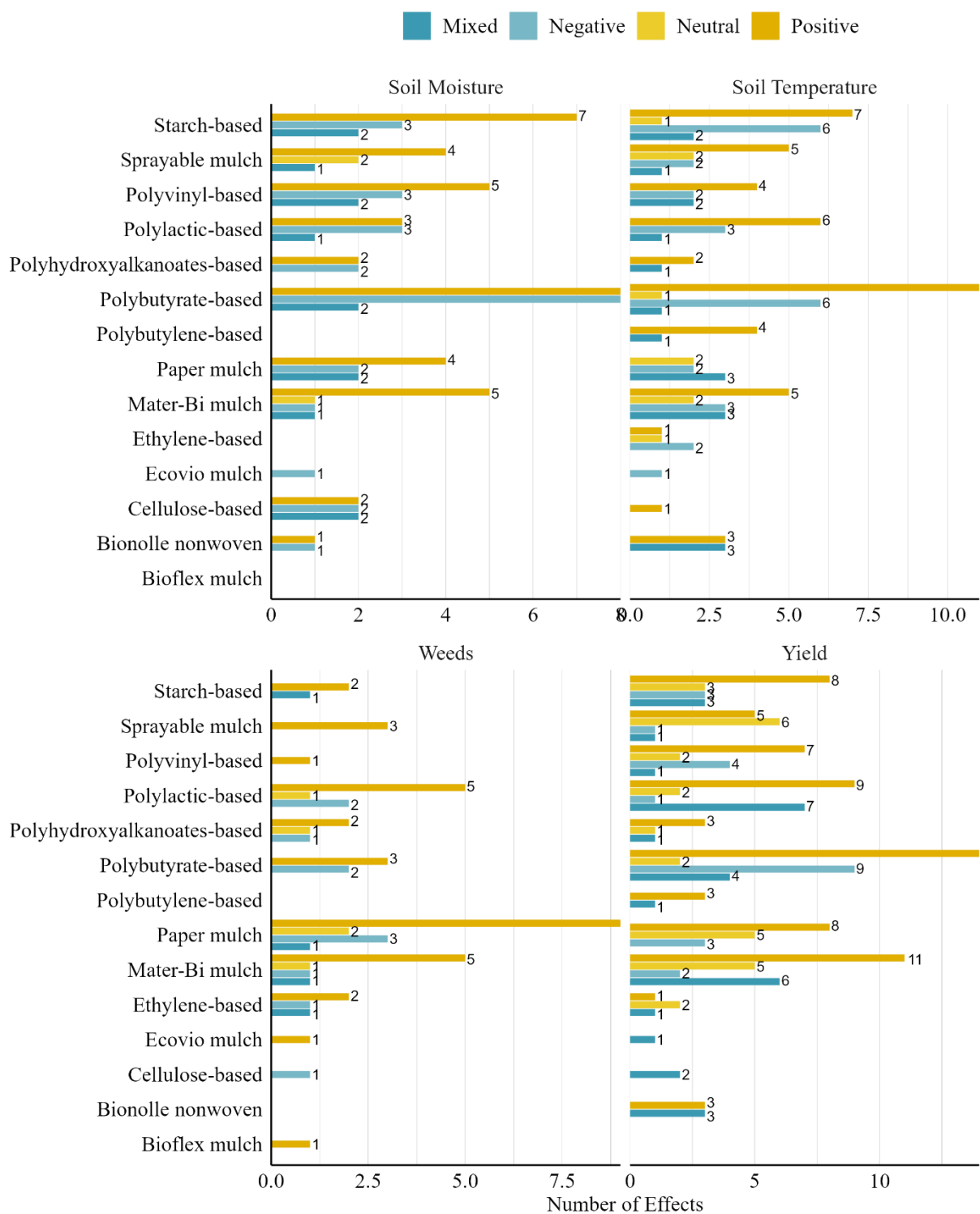
Appendix Figure 2.6. Effects of biodegradable mulch application by global biomes within studied area for the most studied agronomic factors



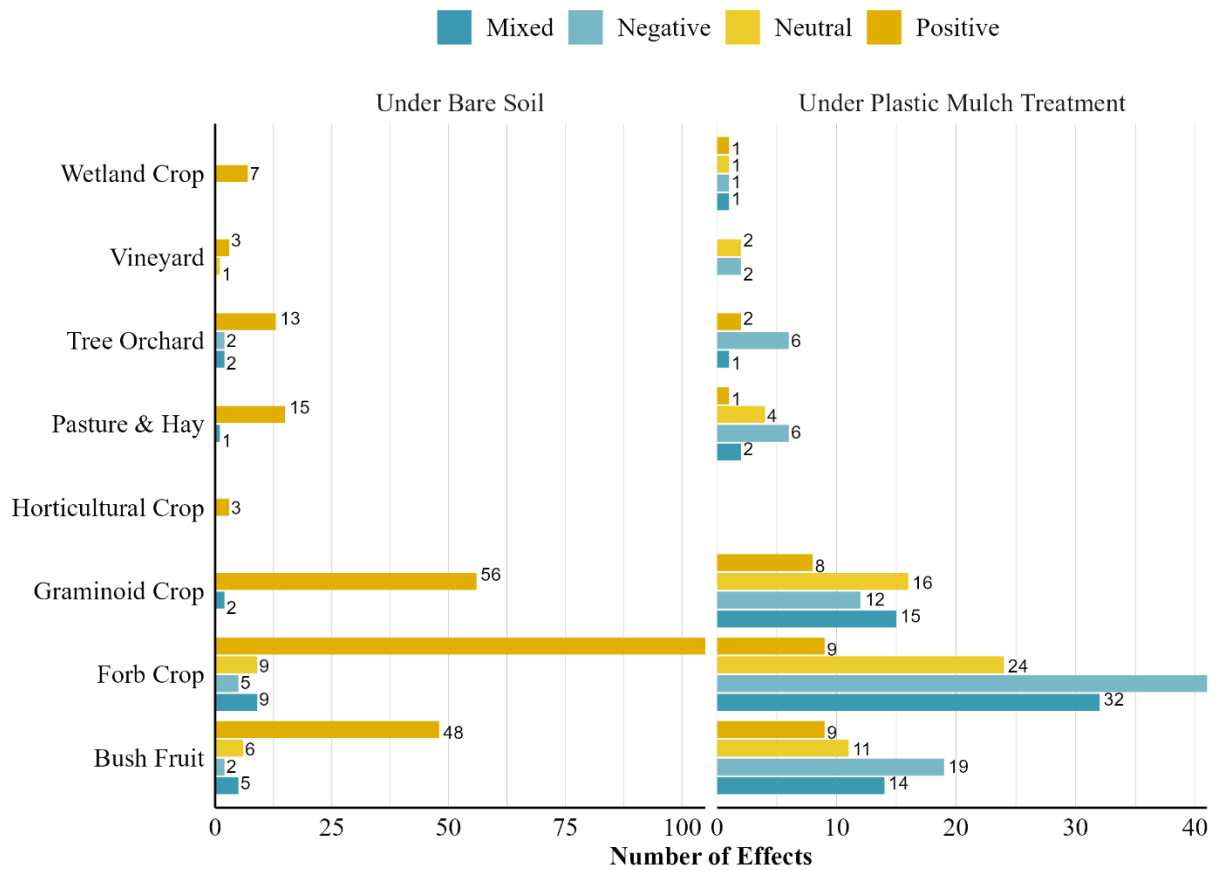
Appendix Figure 2.7. Effects of biodegradable mulch application by mulch type compared to no-mulch control and plastic mulch treatment



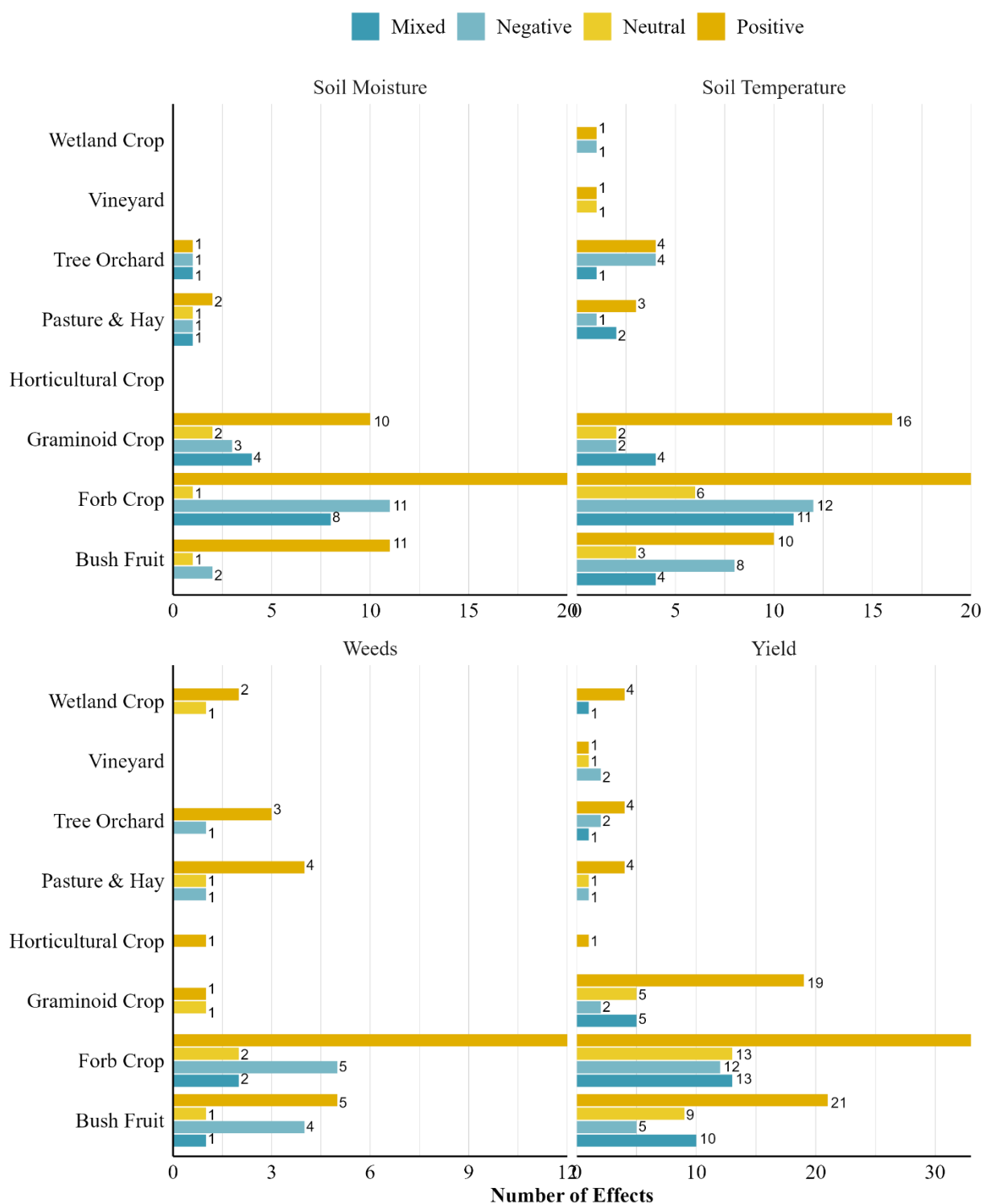
Appendix Figure 2.8. Effects of biodegradable mulch application by mulch type for the most studied agronomic factors



Appendix Figure 2.9. Effects of biodegradable mulch application by crop groups compared to no-mulch control and plastic mulch treatment



Appendix Figure 2.10. Effects of biodegradable mulch application by crop groups for the most studied agronomic factors



Appendix Table 2.1. Coded data extraction guide schema

Variable	Description	Label type
Include	Inclusion criteria to decide if the study should be included (Yes/No)	Categorical
Country of Study	The country in which the study/experiments took place	String
Year/s of Study	The year(s) in which the study took place	String
Detail Location	The GPS coordinates for where the experiments took place, if provided. Or name of study site if coordinates are not provided.	String
Research Setting	The research setting where the study was conducted	Categorical
Crop Type	The crop(s) studied	String
BioMulch Characteristics	The characteristics of the biodegradable mulches: films/sprays studied. Include relevant information on application type, chemical type, manufacturer, thickness, or quantity, etc... for only biodegradable mulch	String
Mechanical/Physical Properties Evaluated	Any properties of the biodegradable mulch examined by the study	Categorical
Agronomic Impacts Evaluated	Any agricultural impacts of biodegradable mulch use examined by the study. The options to choose are: effects on crop yield, effects on soil moisture, effects on soil temperature, effects on soil water use efficiency, effects on weed control, effects on nutrient used efficiency, effects on pest and disease control, and others	String
Other Agronomic Impacts Evaluated	Any other agricultural impacts of biodegradable mulch use examined by the study. Another agronomic impacts not in the above list was to be specified here.	Categorical
Factors that May Influence Suitability	Any contextual factors or biodegradable mulch properties that were examined and found to mediate its effectiveness on agronomic factors	Categorical
Reference/Comparison Group	Denote to what biodegradable mulch effectiveness was compared with	Categorical
Other Reference Group	Any other reference group not included in options for preceding question	String
Crop Yield Effects	The effectiveness of biodegradable mulch use in comparison to reference groups. Consistent or significant increases/decreases in yields (production of grain, fruit, or vegetable). The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and	Categorical

	conventional plastic were used as control (i.e., one option for each control).	
Crop Growth Effects	If biodegradable mulch use resulted in consistent or significant increases/decreases in growth (e.g. height, mass) or emergence (how many seed sprouted or survived) in comparison to reference groups. The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and conventional plastic were used as control (i.e., one option for each control).	Categorical
Water Efficiency Effects	If biodegradable mulch use resulted in consistent or significant increases/decreases in water use in comparison to reference groups. The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and conventional plastic were used as control (i.e., one option for each control).	Categorical

Soil Temperature Effects	If biodegradable mulch use resulted in consistent or significant increases/decreases in soil temperatures in comparison to reference groups. The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and conventional plastic were used as control (i.e., one option for each control).	Categorical
Soil Moisture Effects	If biodegradable mulch use resulted in consistent or significant increases/decreases in soil moisture in comparison to reference groups. The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and conventional plastic were used as control (i.e., one option for each control).	Categorical
Weed Control Effects	If biodegradable mulch use resulted in consistent or significant increases/decreases in weed control in comparison to reference groups. The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and conventional plastic were used as control (i.e., one option for each control).	Categorical

Pest/Disease Effects		If biodegradable mulch use resulted in consistent or significant increases/decreases in pests or disease in comparison to reference groups. The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and conventional plastic were used as control (i.e., one option for each control).	Categorical
Nutrient Effects	Efficiency	If biodegradable mulch use resulted in consistent or significant increases/decreases in nutrient use in comparison to reference groups. The options to choose are: positive/increased compared to bare ground, positive/increased compared to conventional materials, negative/decreased compared to bare ground, negative/decreased compared to conventional materials, neutral (No significant difference) compared to bare ground, neutral (No significant difference) compared to conventional materials, mixed (some positive and some negative) compared to bare ground, and mixed (some positive and some negative) compared to conventional materials. The coder would have to select at least one option if only biodegradable mulch effectiveness was assessed against only one control (i.e. either bare ground only or conventional plastic only). Or select at most two options if both bare ground and conventional plastic were used as control (i.e., one option for each control).	Categorical
Factor Influence on Biomulch Effects		If biodegradable mulch use effects varied across any other contextual factors or biodegradable mulch properties	String
Other things to consider		Any additional information that seems relevant	String

Appendix Table 2.2. Reference list of primary studies

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- Abduwaiti, A., Liu, X., Yan, C., Xue, Y., Jin, T., Wu, H., He, P., Bao, Z., & Liu, Q. (2021). Testing Biodegradable Films as Alternatives to Plastic-Film Mulching for Enhancing the Yield and Economic Benefits of Processed Tomato in Xinjiang Region. *Sustainability* 2021, Vol. 13, Page 3093, 13(6), 3093. <https://doi.org/10.3390/SU13063093>
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Appendix Table 2.3. Studied crops and their sub-groups

Crop	Frequency	Group (USNVC Sub-formation)
Maize/ Corn	28	Graminoid Row Crop
Tomatoes	23	Bush Fruit & Berry
Pie pumpkin	12	Forb Row Crop
Cotton	11	Forb Row Crop
Lettuce	10	Forb Row Crop
Strawberry	7	Bush Fruit & Berry
Raspberry	5	Bush Fruit & Berry
Watermelon	5	Forb Row Crop
Grass/ Weeds/ Folder	5	Cultivated Pasture & Hay
Pepper	4	Forb Row Crop
Potatoes	4	Forb Row Crop
Broccoli	4	Forb Row Crop
Rice	3	Herbaceous Wetland Crop
Grape/ Grapevine	3	Vineyard
Wheat	3	Graminoid Row Crop
Sorghum	2	Graminoid Row Crop
Peanut	2	Forb Row Crop
Garlic	2	Forb Row Crop
Cucumber	2	Forb Row Crop
Mandarin Orange	2	Tree Orchard
Radish	2	Forb Row Crop
Pak choi	2	Forb Row Crop
Apricot	1	Tree Orchard
Muskmelon	1	Forb Row Crop
Cantaloupe	1	Forb Row Crop
Sunflower	1	Forb Row Crop
Beans	1	Forb Row Crop
Gherkins	1	Forb Row Crop
Horens	1	Forb Row Crop
Java tea	1	Tree Orchard
Leek	1	Forb Row Crop
Lindens Trees	1	Tree Orchard
Oak	1	Tree Orchard
Ligustrum Ovalifolium	1	Tree Orchard
Miscanthus sinensis	1	Cultivated Pasture & Hay
Nutsedge	1	Cultivated Pasture & Hay
Onion	1	Forb Row Crop
Ornamental shrubs	1	Shrub Horticultural Crop

Peaches	1	Tree Orchard
Wall-rocket	1	Forb Row Crop
Pineapple	1	Forb Row Crop
Rapeseed	1	Forb Row Crop
Blueberry	1	Bush Fruit & Berry
Sainfoin	1	Cultivated Pasture & Hay
Taro	1	Forb Row Crop
Walnuts	1	Tree Orchard
Oilseed	1	Forb Row Crop
Zucchini	1	Forb Row Crop

Chapter 3 - A synthesis of factors influencing sustainable agriculture practices adoption among rural farmers: A scoping review

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Abstract

Rural regions are significant food producers, yet there are concerns about adoption of sustainable agriculture practices among rural farmers. Empirical studies show that a wide range of factors influence the adoption of sustainable practices. We reviewed 83 studies on this subject to analyze which climatic, economic, socio-cultural, and environmental factors significantly influence adoption of sustainable practices. Our analysis found that most of the selected studies (82%) considered socio-cultural and economic characteristics of farmers but neglected climatic and environmental factors. The influence of these factors on farmers' adoption likelihood varied by type of sustainable practice and study context. The results indicated that drought events, rising temperatures, higher income and wealth, perceived environmental friendliness or benefits, presence of disease, poor soil fertility, higher education, access to extension services, strong social networks, and positive psychological attitudes showed significant positive influence on farmers' uptake of most studied sustainable practices. In contrast, limited access to credit and markets consistently served as barriers to adoption. Characteristics such as gender and household size showed correlations to adoption of some studied practices, although these results were more mixed and affected by study context. While our findings are similar to the results of previous reviews, our focus on rural areas across the globe is distinct and suggests that the positive effects of education, adequate access to credit, and gender adoption may be stronger in more rural or less developed regions.

Keywords

Sustainable practices, adoption, rural farmers, decision factors, influence, agriculture

3.1 Introduction

Agricultural Agricultural extensification (i.e., the expansion of cultivated land) and longer fallow periods are rapidly becoming impractical, leading to intensive continuous cropping in many areas (Alexandratos & Bruinsma, 2012; Teklewold et al., 2013). This trend has been linked to land degradation, low productivity, food insecurity, and impoverishment in affected regions (Eswaran et al., 2019; Misiko & Ramisch, 2007; Pender et al., 2006). On the other hand, agriculture intensification—including reliance on agrochemical inputs such as fertilizers and pesticides, has played a critical role in boosting food production, enhancing crop yields, and reducing global hunger, especially in areas with nutrient-deficient soils or high pest pressure (Baweja et al., 2020). However, synthetic input misuse or overuse has resulted in human health risks (Bain et al., 2017), deleterious effects on ecosystem service providers (Vidau et al., 2011), soil fertility depletion, and emergence of invasive and herbicide resistant weed species (Bagavathiannan et al., 2019; Liebman et al., 2016).

While global food production has increased significantly over recent decades, evidence indicates that rural farmers in many regions continue to face declining production, particularly as climate change intensifies the vulnerability of local agricultural systems such as erratic rainfall, increased pest outbreaks, and soil degradation (IPCC, 2014; Madin et al., 2022; Raj et al., 2022). These localized impacts often offset broader global gains and disproportionately affect those with limited adaptive capacity. For instance, climate change is projected to reduce food production by up to about 35% in many regions, especially in tropical and subtropical areas, unless further adaptations are made to address increased heat stress, water scarcity, and pest and disease outbreaks (IPCC, 2023).

Sustainable agriculture practices offer solutions to these global challenges of growing food insecurity and the degradation of natural resources. The Food and Agricultural Organization (FAO) defines sustainable agriculture as practices that ensure sufficient food and nutrition production for all without compromising the economic, social, and environmental bases of agriculture for future generations (FAO, 2018, 2020). Some of the most reported practices in the literature include zero or minimum tillage, crop rotation, legume intercropping, improved seeds, biodegradable mulching, retention of crop residues, organic fertilizer application, and soil and water conservation practices (Begho et al., 2022; Foguesatto & Machado, 2022). These practices when adopted, contribute to increased yields, farm income, biodiversity, enhance soil moisture retention, improved soil fertility, or carbon sequestration (M. Madin et al., 2024; Piñeiro et al., 2020; Smith et al., 2020).

Despite the numerous benefits of sustainable practices and the substantial efforts made by governments and international organizations to encourage farmers to adopt them, adoption rates remain limited, particularly in rural areas (Kassie et al., 2013; Rodriguez et al., 2009; Somda et al., 2002). This limitation poses significant challenges to global agricultural sustainability because rural areas constitute a substantial proportion of productive arable land resources (FAO, 1989a; Mihai et al., 2021), and their populations face immediate risks from environmental degradation resulting from unsustainable practices (Barbier & Hochard, 2018; Chambers, 1988). For example, in the U.S., a majority of arable lands are located in rural Midwestern and Southwestern states, where 71% of the land is dedicated to agricultural-related purposes (Brown et al., 2005). Moreover, rural farmers often rely on family labor and face distinct socio-economic and institutional conditions compared to their urban or peri-urban counterparts (Cattaneo et al., 2022; Park & Deller, 2021). Recent empirical studies indicate that decision-making processes on

adopting sustainable agricultural practices are influenced by various contextual biophysical and socioeconomic factors. As such, there have been numerous review studies attempting to synthesize evidence on factors influencing farmers adoption decisions and patterns in general (Begho et al., 2022; Foguesatto et al., 2020; Piñeiro et al., 2020; Ruzzante et al., 2021).

While these reviews have provided important syntheses of information from empirical studies, the direction of effects of the factors that influence adoption of sustainable practices remain too general and lack connections across various practices. While enabling factors such as stronger social networks, higher educational attainment, and income are associated with higher likelihood of adoption, results of reviews studies are often reported without specificity regarding a particular practice like crop rotation or organic fertilizer (Begho et al., 2022; Foguesatto et al., 2020) or specific geographic contexts. For example, an excellent review by Prokopy and colleagues (2019) that provided information on the consistency, direction and strength of effects of a wide range of factors on adoption only examined studies on agricultural conservation practices in the United States and did not distinguish effects across specific practices. A subsequent meta-analysis by Lu and colleagues (2022) further examined breakdowns across types of conservation practices yet remained bound by the same limitations in scope as the Prokopy (2022) review. Similarly, a review by Begho and colleagues (2022) examined studies on factors of adoption of sustainable crop farming practices only in South Asia and did not distinguish effects across different types of practices.

In addition, the direction of effect of factors known to be related to sustainable practices uptake is frequently unreported in existing reviews (Rizzo et al., 2023; Yoder et al., 2019), making it challenging to incorporate this information into certain modeling exercises. For example, applied modeling methods— such as spatial adoption models or suitability mapping

often rely on expert-informed assumptions about whether a variable exerts a positive or negative influence on adoption behavior (Akpoti et al., 2022; Madin et al., 2025; Staala et al., 2002). A recent review by Rizzo and colleagues (2023) examined studies on the factors that influence adoption of sustainable innovations with a global scope, however while important factors were identified the direction and significance of effects were not identified. Consequently, it remains unclear whether the direction of influence of the enabling and barrier factors are consistent across all practices and regions. Moreover, previous reviews have not specifically examined sustainable agricultural practice adoption from a rural development perspective potentially masking unique considerations associated with adoption in more rural and remote farming communities, which faced unique contextual factors. Given these limitations, this review contributes to the body of knowledge on sustainable agricultural practice adoption by compiling evidence from the literature on:

1. factors influencing the adoption of sustainable practices among rural farmers, and
2. consistency and the direction of factors influence specific sustainable practices.

This synthesis aims to identify the factors influencing sustainable agricultural practice adoption decisions in rural areas and provide information on their direction and context-specific details to aid in modeling adoption in rural agricultural systems. It will further highlight areas for future improvement in modeling adoption decisions, benefiting the broader research community in guiding the upscaling of sustainable agriculture practices adoption among rural farmers.

3.2 Methods

This This paper adopted the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) extension for scoping reviews (Moher et al., 2009, 2010). Although preliminary article screening by two or more people is ideal, the current

guidelines for scoping reviews provide that screening by a single person, subject to a check of screener reliability is acceptable (Collaboration for Environmental Evidence, 2022; Piñeiro et al., 2020). Scoping reviews aim to summarize studies with diverse methodological designs, emphasizing key areas for future research and engagement (Arksey & O'Malley, 2005). A scoping review was selected because our primary objective was to explore the consistency and the direction of factors influencing the adoption of sustainable practices rather than to assess effect sizes or intervention outcomes. This approach is especially appropriate for topics with diverse study designs, varied outcome measures, and evolving conceptual frameworks similar to the case with sustainable practice adoption literature (Moher et al., 2010). The strengths of the scoping review include its flexibility in capturing diverse evidence types (both qualitative and quantitative), its ability to identify thematic gaps, and its usefulness for informing future research directions and modeling inputs (Arksey & O'Malley, 2005; Piñeiro et al., 2020). However, this method has limitations, including the lack of statistical synthesis (e.g., effect sizes) and potential variation in study quality (Moher et al., 2010). To mitigate these limitations, we applied transparent inclusion criteria, categorized influencing factors using clearly defined thematic domains (e.g., climatic, economic), and focused on the directionality of relationships, an approach particularly relevant for informing qualitative or spatial models of adoption behavior.

Our review was guided by the research question: “What factors influence the adoption and utilization of sustainable agriculture practices or innovations among rural farmers and what are the effects of these factors?” This scoping review included studies from both developed and developing world contexts to characterize barriers and enabling factors to adoption and identify areas for potential future research. In the following sections, we outline our study inclusion criteria, describe the literature search methodology, explain the selection process for studies

meeting our criteria, and clarify the coding procedure for collected reports. Throughout, studies meeting all eligibility criteria are referred to as selected studies.

3.2.1 Literature search

The relevant studies needed to answer the stated research question were obtained from academic databases (i.e., google scholar, Scopus, Web of Science) using keywords and search terms (Table 1). One-hundred and fifty-six articles were retrieved from the Scopus database using the search terms “sustainable AND agriculture AND practices AND adoption AND rural”. The search string used in Google Scholar and the Web of Science database was “sustainable agriculture practices adoption in rural”. The Google Scholar database returned 5,432 articles while Web of Science returned 452 articles. As Google Scholar limits the number of retrievable articles to 999 we retrieved all 5,432 by iteratively restricting the search by year and examining each temporal subset. While we did not restrict publication date during our search, we did confine our inquiry to encompass studies explicitly conducted in rural settings and only full-text studies presented in the English language. The majority of studies were excluded mainly because they were not focused on rural areas or farmers. Our designated search process ended on April 06, 2023.

Table 3.1. Number of Articles Identified by Database

Database	Results
Scopus	156
Web of science	452
Google scholar	5,432
Total	6040

We note that certain potential limitations should be acknowledged. Though the iterative procedure for search term development enhances comprehensiveness, it might still miss some relevant terms or concepts. The search strings, although designed to capture a wide spectrum of relevant studies, might still introduce bias due to the specificity of terms used. Furthermore,

confining the search to studies available in English could introduce language bias, excluding relevant non-English literature. Lastly, while the exclusion of studies not specifically focused on rural farmers might introduce bias, we note that though often treated as such, rurality and farming are not synonymous (Nelson et al., 2021). Focusing on rural studies offers an additional contribution to knowledge of adoption gaps by highlighting adoption issues specific to rural farming and smallholder contexts and communities that can be contrasted to adoption issues relevant to farming and agriculture more broadly (Zulauf & Wagner, 2021). Although these limitations do not inherently detract from the significance or practical implications of our findings, they do restrict the scope of our study and limit the extent to which our results can be generalized.

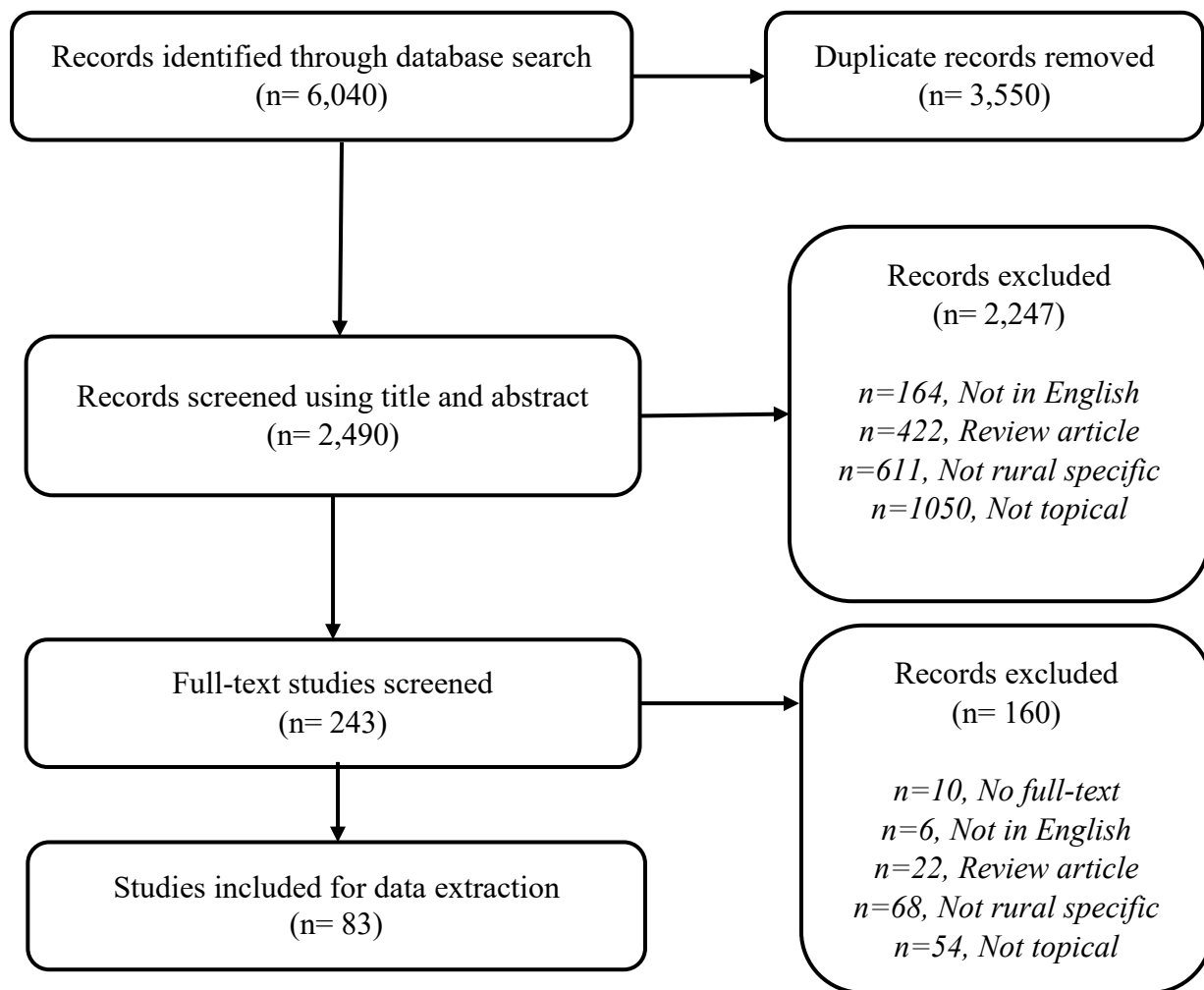
3.2.2 Inclusion criteria and studies meeting eligibility criteria

Our scoping review seeks to assess all searchable literature on sustainable agriculture innovation or practices adoption among rural farmers, with the objective of offering a concise summary and synthesis of factors influencing rural farmers' adoption decisions. It will further provide information on the magnitude, direction of influence, and heterogeneity of the effects of the identified factors. As such, for a publication to be selected, it must meet the following criteria: 1) full text available, 2) text written in English, 3) studied sustainable agriculture practices adoption, 4) an empirical study and not a review article, and 5) focus on rural farmers. See Fig. 1 for counts of reasons for exclusion.

For an article to be relevant and be included in the analysis, the authors must clearly state or illustrate that it is focused on rural farmers' adoption of sustainable agriculture innovations or practices. We attempt to capture adoption studies specific to rural spaces as sustainable innovation adoption decisions in rural areas are substantially different from urban areas (Zulauf

& Wagner, 2021). Included studies must also include an effort to explain the likely or unlikely adoption of sustainable innovation among farmers using factors such as climate, environment, economic, and socio-cultural factors. We considered sustainable agriculture innovations as practices that produce food and nutrition for all in such a way that the economic, social, and environmental bases of agriculture production for future generations are not compromised (FAO, 1989b). This includes innovations that are embodied in capital goods or products (biodegradable mulch films, tractors, fertilizers, irrigation, pesticides, and improved seeds, etc.) and those that are disembodied and associated with management (integrated pest management, no-tillage, crop rotation, mixed cropping, and soil and water conservation practices, etc.) (Sunding & Zilberman, 2001).

Figure 3.1. Flow chart of the scoping review process with study counts



To ensure that the quality of the studies included in the review met the set eligibility criteria for inclusion (Fig. 1), we used a three-step process to screen and code selected studies that met all the eligibility criteria (Fig. 1). In step one, unique studies identified in the database search were screened using title and abstract in the ‘revtools’ R package (Westgate, 2019). One team member screened and determined if the title and abstract of each study met the inclusion criteria. A total of 2,490 unique publication records were screened using title and abstract for eligibility. In step two, 243 studies were evaluated for inclusion using a full text reading. The PDF files of the 243 studies were downloaded for full text screening using the exclusion criteria (Fig. 1). Research team members then read and assessed whether each study met the eligibility

criteria. Most of the excluded studies did not focus on adoption among rural farmers (Alotaibi & Kassem, 2021; Rodriguez et al., 2009; B. Thompson et al., 2022), or did not cover factors influencing sustainable practice adoption in agriculture production (Baig & Straquadine, 2014; Castelli et al., 2021; Sulifoa & Cox, 2020). About 160 studies were excluded through the full text review under step two. Thus, 83 studies were selected for data extraction after the full-text screening (See Appendix Table 3.1).

3.2.3 Data extraction and coding report

In step three, data were extracted from the selected studies using SysRev (Bozada et al., 2021). We coded the questions in the form of labels to help guide in the data extraction. The labels included open ended questions (string labels) and closed ended questions (categorical labels). Coding (data extraction) instructions and help guides (for reviewer's reference) were provided for each label as well as in the SysRev project description. For data extraction, four (4) graduate students were recruited and trained. The coder training session was held before conducting a pilot extraction of ten selected studies. All coders were trained on how and what data to extract from the studies. Labels were created in a demonstration project and a pilot screening exercise was conducted. Pairs of coders independently extracted relevant information from each of the remaining 83 studies using the created labels schema (See S Appendix Table 3.2). The SysRev project was set to randomly assign every study to two coders with each blinded from seeing the extracted data from the other pair. This allowed the SysRev system to mark a study as completed if there was no conflicting label or as conflict if the two coders' labels lacked consensus. A third reviewer resolved conflicts between labels of paired reviewers.

Some of the key information extracted includes the country of study, type of sustainable innovation or practice, focus of study (i.e., adoption or adoption intensity), study method (i.e.,

qualitative, or quantitative; logit, probit, etc.), and the thematic factors (i.e., climate, socio-cultural, economic, environment) considered in the study. Others include specific factors under each of the thematic areas considered in the study, and the influence (i.e., likely adopt, unlikely adopt, or mixed) of each of the studied factors on adoption of sustainable agriculture practices among farmers. For more information, see Appendix Table 3.2.

3.2.4 Data cleaning and analysis

The extracted data in the SysRev project was downloaded in .CSV file format and then imported, cleaned, and processed in RStudio. Note that to examine the direction of influence across all practices, the influence of each factor on adoption decisions extracted from the selected studies was not recorded individually for multiple practices described in a study unless there was mixed influence within the study. Therefore, a factor was deemed to contribute to farmers being more likely or unlikely to adopt sustainable practices if it consistently showed a positive or negative relationship with the adoption of all practices considered in the study, respectively. Conversely, a factor was considered to have mixed effects on adoption likelihood if it exhibited a positive association with certain practices and a negative relationship with other practices within the same study. We used both the statistical significance and the signs of the estimated regression coefficients to determine whether the influence was positive or negative. A regression coefficient was considered statistically significant if the p-value was less than 0.1.

Thus, the category *likely* influences farmers to adopt was assigned only if the sustainable practice(s) considered in the study were reported to have a statistically significant positive association with a given factor. The category *unlikely* influences farmers to adopt was designated only if the sustainable practice(s) considered in the study were reported to have a statistically significant negative association with a given factor. The *mixed* category was applied if the study

reported a statistically significant positive coefficient for some practices and a statistically significant negative coefficient for other practices within the same study. In addition, we separately recorded all the individual adoption factors with significant negative or positive associations by studied practices within studies. The category *insignificant* was chosen in cases where the study reported non-statistically significant coefficients for all sustainable practices considered under a given factor. Data extracted as unique text strings were recategorized using common themes and terms.

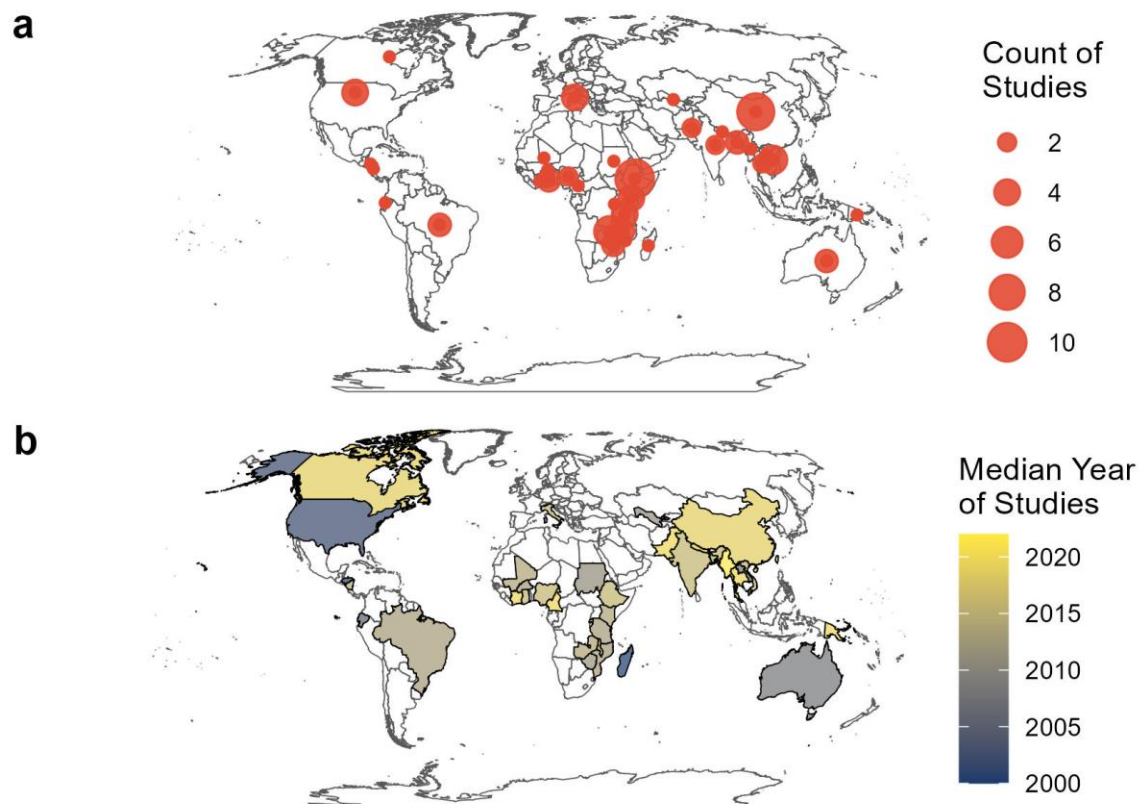
3.3 Results and Discussion

3.3.1 Study area and publication statistics

The data comprises studies conducted in 35 countries across different agriculture production regions in the world. The countries with most selected studies were Ethiopia (10 studies) and China (9 studies) [Fig. 2a]. The global growth in studies assessing sustainable agriculture practices adoption is associated with a surge in the development policy agenda, especially to tackle climate change and global environmental degradation in rural areas. These innovative practices are expected to broadly contribute to the reduction and reversal of the processes of environmental degradation (FAO, 1989a; Smith et al., 2020). Moreover, the adoption of sustainable practices in agriculture is intended to achieve food security and soil health through maintaining fertile and functioning soil biodiversity (Kassie et al., 2013; Piñeiro et al., 2020). As such, a greater proportion of the studies were conducted in global regions noted for frequent droughts, floods, and food insecurity (Douglas, 2009; Sasson, 2012) [Fig. 2a]. For instance, about 30.1% (10 in Ethiopia, 3 in Malawi, 5 in Vietnam, 4 in Tanzania, and 3 Bangladesh) of the selected studies were conducted in locations within these regions with publication dates between 2010 and 2022 (Fig. 2). In contrast, studies based in the United States,

Australia, and Brazil were early leaders in rural sustainable agriculture adoption studies starting in 1990 through 2007, but account for only 12.0% of the selected studies (Fig. 2b). The most recent studies come from China and Canada with median publication years of 2020 and 2015, respectively (Fig. 2b). Since 2000, there has also been growth in rural sustainable agriculture adoption studies in Central and South America, with six (6) studies conducted in Brazil, Nicaragua, Honduras, and Ecuador (Fig. 2a). The selected studies included four (4) from Italy; and the absence of additional studies from Europe was driven partly by a lack of comparable studies in some countries, and by lack of studies in English in other cases. Follow-up reviews of literature published in other languages would be beneficial to a more global understanding of adoption influences.

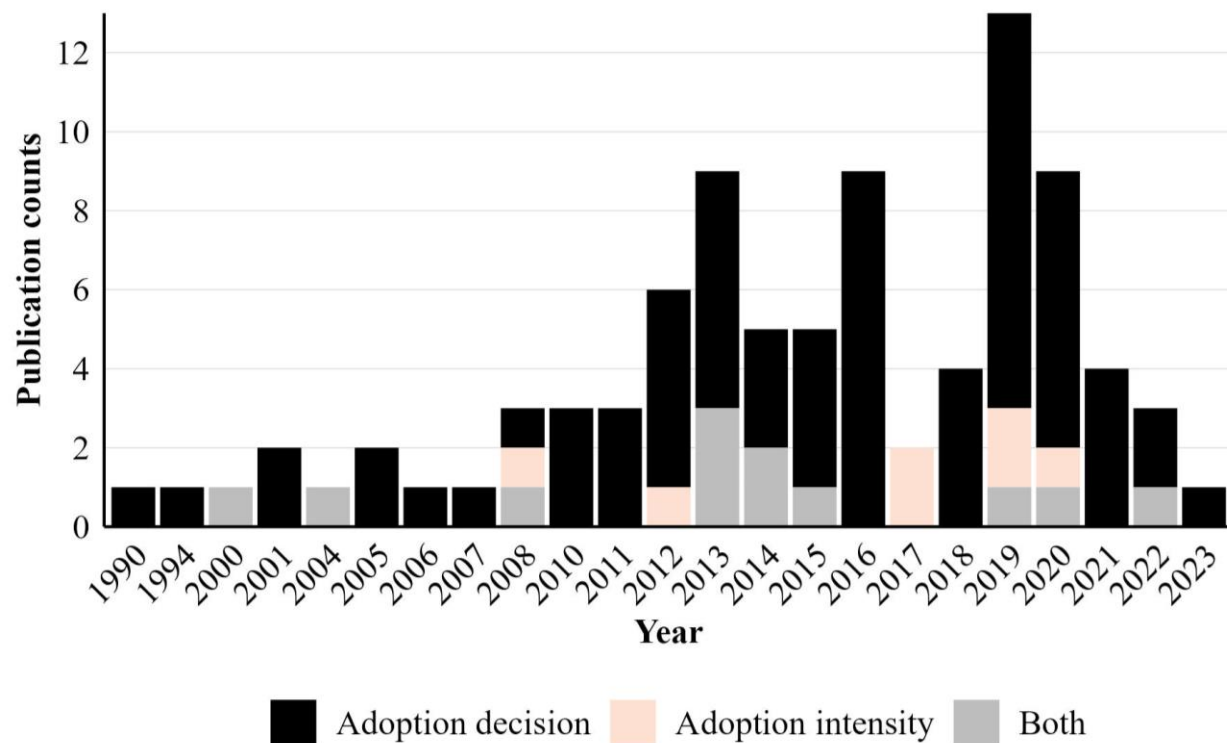
Figure 3.2. Spatial distribution of publication counts (a) by country of study (b) and median publication year



3.3.2 Studies' focus and practices examined

We found that the selected studies used either adoption decision, adoption intensity, or both as an outcome (dependent) variable in understanding and modeling adoption decision-making processes and outcomes (i.e., adopted or not adopted) among farmers (Fig. 3). The majority (84.3%) of the studies focused primarily on farmers' adoption decision. Studies focused on adoption decisions assess farmers' choices whether to adopt or not to adopt (Curry et al., 2021; Manda et al., 2016) or the likelihood of farmers adopting a specific sustainable practice (De Souza et al., 1998; Thi et al., 2021). While those focused on adoption intensity (just seven studies) measure farmers' adoption based on the ratio of adopted area to total cultivated land area, investment amount, labor input, adoption time (Lestrelin et al., 2012; Rodthong et al., 2020) or the number of unique sustainable practices adopted by each farmer (Teklewold et al., 2013). About twelve studies used both adoption decision and adoption intensity as dependent variables in the analysis (Moser & Barrett, 2003; Munasib & Jordan, 2011). In terms of the temporal nature, the research on sustainable agriculture practices adoption among rural farmers has somewhat increased since 2011 (Fig. 3). A key part of the increase is due to the emergence of studies that examine adoption intensity. The earlier studies have mainly focused on farmers adoption decisions until 2008 when Lestrelin et al. (2012) assessed adoption intensity. The growth in total studies likely coincides with increased awareness and incorporation of climate change and environmental risks reduction into the popular goals of sustainable development between 2005 to 2015 (Füssel, 2007; Gallopín, 2006; Nelson et al., 2023).

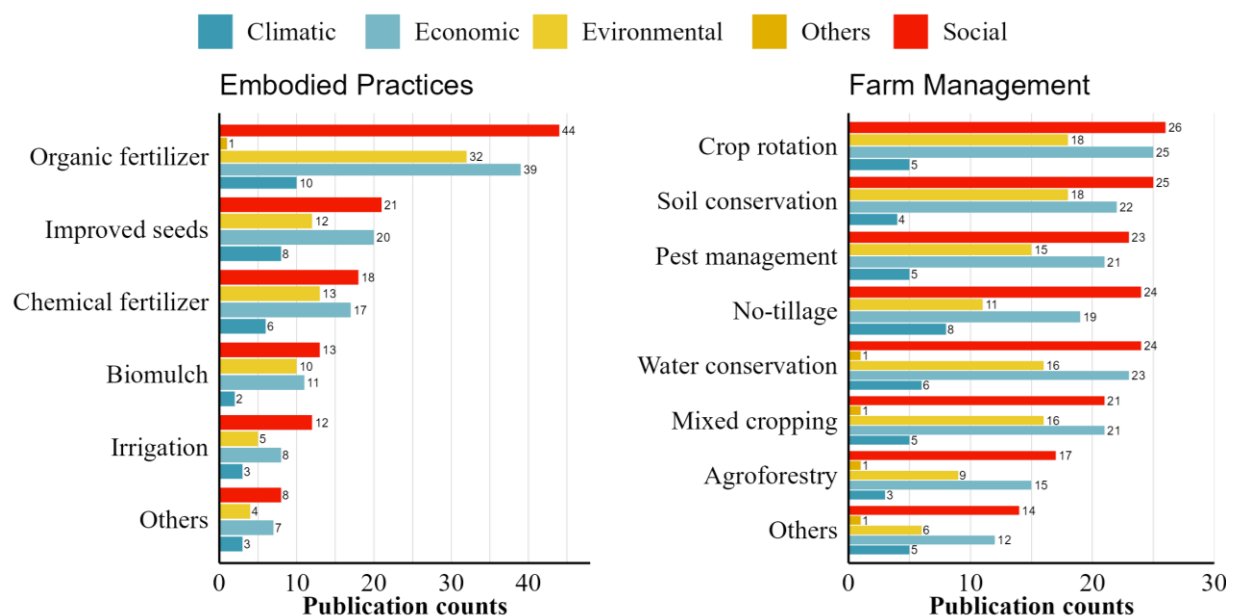
Figure 3.3. Count of selected studies by publication year and focus of analysis



The studied sustainable agriculture practices are conceptualized in line with the FAO definition— innovative practices ensuring agriculture production without compromising economic, social, and environmental bases for future generations (FAO, 1989b). The practices involve farming based on ecological principles and fostering long-term environmental benefits while sustaining productivity (Blesh & Wolf, 2014; Brodt et al., 2011). These practices include innovations embodied in capital goods (e.g., biodegradable mulch, tractors, fertilizers) requiring farmers to purchase them and those disembodied from capital goods and instead involving farm-level management activities like integrated pest management, no-tillage, and crop rotation (Sunding & Zilberman, 2001). A majority of 59.01% of the selected studies considered at least farm management (Fig. 4). The most studied farm management methods were crop rotation and soil conservation practices. For example, Fantappiè et al. (2020) and Yifru & Miheretu (2022) assessed farmers’ adoption of sustainable farm-level management practices such as soil

conservation, while Kotu et al. (2017) examined the adoption and impacts of crop rotation as a sustainable intensification practice. These (sustainable) farm management are mostly adaptation strategies by rural farmers in response to land degradation and poor soil fertility (Piñeiro et al., 2020a; Shiferaw et al., 2009; Smith et al., 2020). The frequently studied embodied practices were organic fertilizer, improved seeds, and chemical fertilizer (Fig. 4). For instance, Oyetunde-Usman et al. (2021), Kassie et al. (2012), and Zeweld et al. (2020) studied the adoption of embodied practices such as organic fertilizer (animal manure), improved seeds, and chemical fertilizer among farmers. Embodied practices are notably capital-intensive with farmers adopting them primarily to enhance on-farm productivity and profitability. See Appendix Table 3.3 for other sustainable practices studied.

Figure 3.4. Studied sustainable practices and thematic areas of factors considered



Note: Biomulch refers to biodegradable mulches including synthetic films, sprayable mulches, feathers, crop residues, and straws. No-tillage includes conservation tillage such as zero tillage, strip, or minimal tillage. Organic fertilizer includes animal manure and compost.

Nearly all (98.8%) of the selected studies considered farmers' or household socio-cultural factors in the analysis of sustainable practices adoption (Fig. 4). This underscores the importance

and researchers' preference for cultural and social factors in understanding farmers' decisions. Economic factors are also widely considered, with 85.5% of the studies incorporating resources availability and financial indicators into their analyses. Additionally, environmental factors were only considered in half of the studies, reflecting a noteworthy but somewhat less emphasized aspect of studying sustainable agriculture practices adoption. Overall, the comprehensive inclusion of socio-cultural and economic factors underscores their perceived role in shaping farmers' decisions. Climate factors, despite their critical role in agriculture, were considered in just a quarter of the studies, possibly indicating an area where more attention is needed in understanding the interplay between climate variability and adoption patterns. Moreover, whereas broader landscape scale climate factor interactions could shape farmers adoption decisions, most of the studies scale of analysis, were at the household or field level. For instance, climate variables included in the models were mostly plot level incidence of floods or droughts and amount of precipitation (Amadu, 2022; Ochieng et al., 2022). This approach largely neglects the multi-scalar nature of climate change and innovation adoption processes, spanning from the micro-scale of the farm operator to the broader scale of shifting climate regimes (Argent, 2019; Lyle, 2015).

3.3.3 Factors influencing sustainable agriculture adoption

While all the selected studies provide empirical analyses of factors influencing sustainable agriculture adoption among farmers, we were most interested in the coefficients of effects (indicating likelihood or unlikelihood of adoption) and their statistical significance. Consequently, the results presented in Table 2 are only from quantitative studies that utilized modeling. Despite the exclusion of qualitative studies, we find them valuable for explaining the presented results and offering nuances to the synthesis. The findings reveal a slow and limited

adoption of sustainable agriculture practices among rural farmers. For instance, Manson et al., (2016) reported a 7-26% adoption rate for rotational grazing in the United States. In Zimbabwe, Murendo et al. (2016) noted that although 98% of sampled farmers had knowledge of sustainable conservation practices, only about 28% adopted them. In terms of adoption intensity, Kpadonou et al. (2017) observed that over 70% of farmers adopted up to three practices, while less than 30% adopted four or more practices. Due to the limited amount of research on adoption intensity many of the factors and practices in Table 2 were not considered in studies specifically assessing adoption intensity. As such, adoption intensity findings are only discussed narratively where relevant. The factors influencing adoption (as a binary decision) across all practices are detailed in Table 2 while a complete table documenting factors influencing adoption of specific practices is provided in Appendix Table 3.5. Subsequent subsections discuss the results of these identified factors under their respective thematic areas.

Table 3.2. Factors influencing sustainable innovation adoption among rural farmers (n= 63)

Thematic Area	Factor	Insignificant	Likely adopt	Unlikely adopt	Mixed
Climatic	Drought present	2	5	1	2
	Floods present	5	1	2	-
	Higher temperatures	1	2	-	-
	Precipitations (higher)	3	5	2	-
Economic	Higher Profit	-	2	-	-
	Higher income	7	18	4	3
	Higher price	-	3	2	-
	Higher wealth	8	18	2	8
	Limited credit	7	3	14	2
	Limited market	7	4	10	3
Environmental	Environment benefits	4	8	-	2
	Environment friendly	1	2	-	-
	Pest present	1	5	2	2
	Saline soil	-	1	-	-
	Sloped land	2	5	5	3
	Soil fertility (poor)	8	8	3	6
Socio-cultural	Age (Older)	24	13	12	3
	Education (higher)	24	25	7	3

	Extension (accessible)	11	27	3	3
	Gender (male)	15	21	5	2
	Household size (larger)	13	14	14	1
	Land-tenure (tenant)	5	9	8	5
	Networks (stronger)	6	32	1	5
	Positive attitudes	3	8	-	3

3.3.3.1 Socio-cultural factors

Almost all the selected studies included some socio-cultural factors in the analysis of sustainable practices adoption among farmers. Twenty-five out of 59 studies on farmer education and adoption reported that more educated farmers had higher likelihood of adopting sustainable practices with statistical significance (Table 2). Three (3) studies reported mixed effects across multiple practices evaluated, seven (7) reported that more educated farmers were less likely to adopt, and twenty-four observed non-significant relationships. Overall, the findings suggest a positive effect of education on the likelihood of adoption. While just 42% of the studies reported significant positive results, this represents 71% of the studies that reported statistically significant associations (Table 2). We find these positive effects of education are relatively consistent across practices.

For example, farmer education level had a positive effect on adopting improved seeds and integrated pest management technologies, implying that educated farmers tend to adopt these practices than their less educated counterparts (Manda et al., 2016; Muriithi et al., 2018). Kpadonou et al., (2017) found a significant positive effect of formal education on farmers' likelihood of adopting compost applications, which suggest limited education as a barrier to farmers adopting knowledge intensive practices like compost use. Likewise, Adjei et al. (2017) found that most rural farmers show a desire to adopt sustainable practices but feel they possess insufficient knowledge. Education was also found to have a positive interactive effect on other social factors. For instance, Jin et al. (2015) found educated female farmers to be more likely to

adopt sustainable practices compared to their counterparts, while more educated male farmers had a higher probability of investing in capital-intensive innovations. Other studies found educated farmers to be associated with greater access to extension services and higher likelihood of adoption relative to their counterparts (Amadu, 2022; Kassie et al., 2013). On the other hand, more educated farmers were reported to be unlikely to adopt maize-legume intercropping (Kassie et al., 2012; Ndiritu et al., 2014) and planting basin practices (Nkomoki et al., 2018) compared to their less educated counterparts.

From Table 2, thirteen (13) studies found a positive significant relationship between farmer's age and likelihood of adoption, twelve (12) found observed a negative relationship, while three studies reported mixed effects of age on adoption (Table 2). This result, which is similar to the findings of Begho et al. (2022), suggests the direction of effect of farmers' age on adoption of sustainable practices is not clear. Age as an individual attribute of farmers had almost equally split positive and negative reported influence on sustainable practices adoption likelihood among selected studies. While the age of the farmer did not present clear direction of influence in the overall adoption, we observed that older farmers were more likely to intensify compared to their younger counterparts when adoption intensity alone was considered (Bekele et al., 2021; Rodthong et al., 2020). Among studies reporting positive influence of age, authors noted that older farmers often have more experience and are more likely to adopt sustainable practices requiring indigenous knowledge and expertise such as organic fertilizer and water conservation practices (Appendix Table 3.5). For example, Manda et al. (2016) found that older farmers were more likely to adopt residue retention and maize-legume rotation practices relative to their younger counterparts. Older farmers were also associated with higher likelihood of adopting compost application (Kpadonou et al., 2017), and conservation agriculture practices

(Murendo et al., 2016), compared to their younger counterparts. By contrast, others reported that older farmers were less likely to adopt agricultural innovations like chemical fertilizer and power tiller practices (Ahmed et al., 2022). Similarly, Ndiritu et al. (2014) also found that older farmers were less likely to adopt improved seeds and chemical fertilizer relative to their younger counterparts.

Among the studies that included gender as a variable, 21 reported that male farmers were significantly more likely to adopt compared to their female counterparts while five (5) found male farmers to be less likely to adopt compared with female farmers (Table 2). This suggests that male rural farmers were more likely to adopt sustainable practices in ~49% of the relevant included studies. Despite the relatively high level of consistency in the positive effect of male gender on adoption, some nuances across practices emerge. Thus, while Si et al. (2021) described the likelihood of adopting sustainable practices as 6.65% higher in male-headed households compared with female-headed households, Amadu (2022) observed female-headed households to be less likely to adopt resource intensive sustainable practices such as non-woody agroforestry relative to their male counterparts, but also found male farmers to be less likely to apply animal manure compared to their female counterparts. Although most authors adjusted for levels of wealth and size of land holdings in making gender comparisons, most did not account for differences in ownership status or length of tenure.

More importantly, the studies consistently employed a categorization that compared single female heads of household against all other households, rather than comparing single females with single males. A heterosexual married couple, for example, was automatically counted as “male” in these studies. Research focused on gender in sustainable agriculture has indicated that, particularly in the West, women farmers are significantly more likely to be

engaged in sustainable agricultural models than in traditional production-focused models (Trauger, 2007). Related work has found that women farmers may be subject to additional risks, less able to access direct land ownership, or less likely to be included in social and information networks (Azumah, et al., 2023; Pilgeram and Amos, 2015; Leckie, 1996). The gender correlation that emerged in our review is worth noting because it indicates that men and women farmers, as well as married and single farmers, may be influenced by different factors in their decisions to adopt sustainable practices, and highlights the need for additional research and analysis.

Land tenure arrangement was found to have split influence on farmers' adoption decisions across diverse sustainable practices considered. Nine (9) studies reported significant positive effects of secured or stable land tenure on farmers' adoption likelihood, eight (8) observed negative effects, and five (5) found mixed effects (Table 2). This large degree of variability is explained in part by variations across practices (Appendix Table 3.5). Kassie et al. (2013) and Teklewold et al. (2013) noted that because long-term investments in innovations accrue over time, the level of access to land or tenure security influences adoption decisions. Thus, farmers turn to using long-term and conservation practices leading to improved soil health and fertility enrichments on their own lands, while applying short-term and higher yield-return practices on rented plots. Kassie et al. (2013) reported that farmers cultivating on own farmlands were more likely to adopt sustainable practices (i.e., soil and water conservation, zero-tillage, and animal manure) compared to their counterparts cultivating on rented lands.

Moreover, farmers cultivating on owned lands were more likely to adopt mulching and tree planting than tenant farmers or those with limited land access (Brüssow et al., 2017). In terms of adoption intensity, farmers with stable tenure security were found to be associated with

about a 30.55% increase in adoption intensity (Q. Yang et al., 2022b). On the other hand, households with customary land ownership arrangements were noted to have a 9.1 -17.4% lower probability of adopting crop diversification, agroforestry, and planting basins compared to their counterparts with statutory tenure (Nkomoki et al., 2018). These findings confirmed earlier call for consideration of land tenure arrangements to moderate implications on the sustainability of rural farming systems (Fairbairn, 2014).

In general, stronger social networks were reported to have largely positive influence on adoption likelihood and intensity. Thirty-two studies reported positive effects, while only one study observed a negative relationship between strong farmer networks and the likelihood of adoption (Table 2). In general, this finding is robust to variations in practice examined (Appendix Table 3.5). For example, Teklewold et al. (2013) found that both the probability and the intensity of adoption of sustainable practices are positively related to the robustness of farmers' social capital, connection, and networks. Farmers with cooperative membership were more likely to adopt water conservation practices and improved seeds along with higher adoption intensity compared to their counterparts without membership (Bro et al., 2019). Similarly, farmers' membership in producer groups and associations were found to positively influence their odds of adopting two or more sustainable practices by 6.8%. However, Si et al. (2021) indicated that while strong social networks largely enable farmers' adoption, their effects are contingent on social and spatial context. Thus, Manson et al., (2016) noted that adoption of rotational grazing among farmers was influenced by the probability of the neighboring farmers sharing strong ties and how those networks are formed in space. Increases in farm profitability and environmental sustainability serving as motivation for adoption were also more likely to be realized in areas where social networks were strong and supportive of sustainable agriculture

systems (Manson et al., 2016). On the contrary, Kassie et al. (2013) indicated that households with a smaller number of relatives and fewer interactions with traders were more likely to adopt zero (conservation) tillage compared to their counterparts with larger households.

Farmer psychological attributes such as positive attitudes were also included as possible explanatory variables to farmers' adoption decision-making. Studies considering this variable conceptualized psychological attitude as farmers' perceptions and beliefs on climate change, environmental concerns, perceived behavioral control, and/or risk aversion. Eight (8) of the studies (57%) found significant positive effects of positive psychological attitude on farmers adoption likelihood while three (3) papers reported mixed effects on adoption likelihood (Table 2). There was no reported unlikely adoption among farmers with a positive psychological attitude. Zeweld et al. (2017) indicated that psychological attitudes serve as positive drivers in farmers' adoption behavior and decision-making processes. Si et al. (2021) found that psychological confidence among farmers significantly and positively influences climate risk aversion and adoption of biodegradable mulches for its environmental friendliness. Moreover, farmers tend to assign socio-psychological value to symbols of productivist farming— such as tidiness, neatness, and weed-free fields. As such, sustainable practices that do not conform to these symbols can present barriers and limit adoption (Dentzman & Goldberger, 2020b).

Fourteen (14) studies each reported positive and negative effects of household size on farmers' adoption likelihood (Table 2). The key reason is that adopting certain sustainable practices requires additional manual labor. Therefore, larger households with sufficient family labor are more likely to adopt labor-intensive practices compared to smaller households. For instance, larger farmer households were more likely to adopt animal manure applications compared to smaller size households (Kassie et al., 2013). In contrast, Brüssow et al. (2017)

found that larger farmer households were less likely to adopt agroforestry (tree planting) compared to their counterparts. Farmers with larger households were also less likely to adopt chemical fertilizer and soil conservation (Zai) practices compared to their counterparts (Kpadonou et al., 2017), which require fewer people but can present higher costs.

Notably, mixed effects within studies were more prevalent for socio-cultural factors than any other theme. All eight widely used socio-cultural factors exhibited at least one mixed influence where the factor had a positive influence on adoption of some practices and a negative influence on adoption of other practices in the same study (Table 2). For example, Kassie et al. (2013) observed that older farmers were more likely to adopt soil and water conservation practices but less likely to adopt improved seeds and legume intercropping practices compared to their younger counterparts. Regarding education, Ehiakpor et al. (2021) found that more educated farmers were likely to adopt integrated pest management and chemical fertilizer but less likely to adopt maize-legume rotation practices compared to less educated counterparts. In terms of adoption intensity, highly educated farmers were less likely to adopt animal manure as a single practice but more likely to jointly adopt crop residue retention and contour plowing along with animal manure (Zeweld et al., 2020). Farmers cultivating their own lands were more likely to apply organic fertilizer and less likely to use chemical fertilizer and improved seeds compared to tenant farmers (Kotu et al., 2017). Similarly, Ndiritu et al. (2014) found that farmers cultivating their own farmlands were more likely to adopt sustainable practices such as soil conservation and animal manure application but less likely to adopt improved seeds compared to their counterparts. Farmers with stronger social networks were more likely to adopt sustainable practices such as improved seeds and integrated pest control but less likely to adopt maize-legume intercropping compared to those with weaker networks (Muriithi et al., 2018).

While the inconsistency we observe in effects across studies may in part be a result of varying study contexts and the specific practices examined, this inconsistency can also be partially attributed to the lack of consistency and coherent conceptualization of the variables used in the modeling. We found differences in how farmers' education is conceptualized between studies conducted in the global south and those in the global north. For instance, Teklewold et al. (2013) measured farmers educational level in Ethiopia by using years of schooling and Kpadonou et al. (2017) used binary yes or no for if respondent attended formal school among farmers in West African Sahel. On the other hand, Scaringelli et al. (2016) measured educational level using the level of education attainment such as none, primary education, secondary education, etc. among farmers in Italy. Similarly, Saltiel et al. (1994) considered farmers education in USA using a coded six-point scale ranging from grade school to post-graduate. Employing age as an explanatory variable of farmers' adoption, Ahmed et al. (2022) categorized farmers aged ≤ 35 years as young, 36 to 50 years as middle, and ≥ 51 years as older whereas Si et al. (2021) categorized farmers aged 18 to 40 years as young, 41 to 60 years as middle and ≥ 61 years as older. Moreover, while Kassie et al. (2013) considered the number of relatives of farmers or the number of relations with traders as a measure of social networks or capital, Bro et al. (2019) used corporation membership as an indicator of social capital. The current fluidity of the socio-cultural factors makes it difficult to synthesize evidence across studies.

3.3.3.2 Economic factors

We found that farmers' income was the most common economic factor used as an explanatory variable in the selected studies. Income, derived from the utilization of sustainable practices or the total annual earnings of farmers, was mostly reported as a significant and

positive driver of farmers' adoption decisions (Table 2). 72% of studies reporting statistically significant on income (18) indicated that higher-income earning farmers were more likely to adopt sustainable practices compared to their counterparts (Table 2). This trend is consistent across the variety of sustainable practices considered in this systematic review (Appendix Table 3.5). For example, Saltiel et al. (1994) found that higher gross crop sales and the percentage of crop revenue had a positive influence on farmers' likelihood of adopting cover cropping, crop rotation, animal manure, and no-tillage. Farmers with higher off-farm income were also more likely to adopt soil and water conservation, legume crop rotation, no-tillage, improved seeds (Mutyasira et al., 2018), and integrated pest management practices (Ochieng et al., 2022) compared to their counterparts. Likewise, Kotu et al. (2017) observed that higher off-farm income earners were more likely to adopt chemical fertilizer and crop rotation practices compared to their counterparts. About four (4) studies and three (3) studies reported negative effects and mixed effects of higher income earning on farmer's adoption likelihood, respectively (Table 2). For instance, higher-income earning farmers were found to be unlikely to adopt sustainable practices such as crop residue retention and conservation tillage (Kassie et al., 2013; Manda et al., 2016).

Variables such as household wealth and farm assets were used interchangeably with income in some studies. Eighteen (18) studies representing 50% of the studies that included wealth found a positive influence, two (2) reported negative effects, while eight (8) indicated mixed effects on farmer's adoption likelihood (Table 2). For example, wealthier farmers are found to be more likely to adopt soil and water conservation, chemical fertilizer, mulching, and agroforestry (Akter et al., 2021; Huan et al., 2022; Makate et al., 2017; Saltiel et al., 1994). While using assets, Kassie et al. (2013) noted that households with more assets are able to bear

the potential risks associated with the adoption of innovations and are more likely to afford embodied practices such as chemical fertilizer and improved seeds. The influence of higher cost or price of the practices to be adopted appeared split with three (3) studies reporting positive effects and two (2) studies reporting negative effects on adoption likelihood. Price or cost of innovation was reported to significantly influence the likelihood of farmers' adoption in studies using sustainable practices (chemical fertilizer and biodegradable mulch) embodied in capital goods. The price of biodegradable mulch is currently higher than conventional mulch, hence wealthier farmers are more likely to afford biodegradable mulch compared to their counterparts (Si et al., 2021). Goldberger & Lyons (2017) observed that about 54% of the respondents were likely to adopt biodegradable mulch if the price dropped. Conversely, higher cost limited farmers' ability to adopt improved technologies such as chemical fertilizer and power tillers (Ahmed et al., 2022).

Access to credit among rural farmers served as a major determinant of the likelihood of adopting sustainable practices in studies reporting statistical significance. This was particularly evident when credit is the primary means of acquiring sustainable practices embodied in capital goods, making farmers with credit constrained less likely to adopt (Jin et al., 2015). Fourteen (14) studies representing 53.8% of the articles that examined access to credit found that limited access to credit among farmers is a barrier to adoption, three studies reported that it enabled adoption, and two noted mixed effects on adoption likelihood (Table 2). Credit constraints act as barrier to investing in agricultural, as farmers with limited liquidity are unlikely to adopt sustainable practices that require cash outlays (Adjei et al., 2017; Jin et al., 2015). Both the intensity and likelihood of adopting sustainable practices among farmers are impeded by limited access to credit (Teklewold et al., 2013). Farmers with access to credit were more likely to adopt

chemical fertilizer and integrated pest management compared to those with limited access to credit (Ehiakpor et al., 2021; Ochieng et al., 2022). Farmers who reported as having accessed credit were associated with a higher likelihood of investing in and adopting irrigation, improved seeds, and conservation practices (Appendix Table 3.5). In terms of intensity, Abeje et al. (2019) noted that farmers without credit constraints were more likely to adopt at least four sustainable practices compared to their counterparts. However, Muriithi et al. (2018) found that credit-constrained farmers were more likely to adopt practices such as crop rotation and animal manure application, which require fewer or no capital.

The influence of farmers' access to markets on the adoption of sustainable practices was examined in 24 studies (Table 2). About 58.3% (10) of these studies observed that farmers with limited access to input and produce markets are unlikely to adopt sustainable practices, four found those farmers to be more likely to adopt, while three reported mixed effects on adoption likelihood (Table 2). For example, an increase in the distance of a farmer's location from the market was found to reduce the probability and intensity of adopting practices such as improved seeds and legume intercropping (Kassie et al., 2013; Ochieng et al., 2022). This is attributed to the increased costs associated with longer distances, which disincentivize farmers and lead to a higher tendency to adopt alternative practices that do not require external input but may not be sustainable. For instance, Teklewold et al. (2013) found that longer distance to input market reduced the likelihood of adopting improved seeds due to increased transaction and access costs but positively influenced the adoption of conservation tillage practices. Similarly, Lovell et al. (2021) observed that closer distance to market was associated with an increased likelihood of adopting water conservation practices. These findings provide consistent indication that limited

access to markets is a barrier to farmers adoption of innovations, particularly sustainable practices that are embodied in capital goods.

In terms of economic factors, farmers' wealth and access to markets had the most reported mixed influence on adoption likelihood. We observed differences in how farmers' wealth or assets were measured between studies conducted in the global south and global north, which in turn led to differences in the reported influence on adoption. Thus, studies conducted in the global south most often conceptualized farmers' assets in terms of livestock ownership and farm size, while studies from global north often used farm equipment ownership, investment amount, and farm size. Inherently, studies using livestock ownership were more likely to report higher likelihood of organic fertilizer (manure) and zero tillage adoption compared to chemical fertilizer (Appendix Table 3.5). For example, Muriithi et al. (2018) noted that wealthier farmers in Kenya (in terms of livestock ownership) were likely to adopt animal manure practices but unlikely to adopt integrated pest management practices compared to their counterparts with fewer livestock. Wealthier farmers in Ghana were also associated with a higher likelihood of adopting crop rotation, soil and water conservation, and organic fertilizer application but were less likely to adopt chemical fertilizer compared to their counterparts (Kotu et al., 2017). Likewise, livestock owners were more likely to adopt low-intensity practices but unlikely to adopt high-intensity practices compared to their counterparts (Amadu, 2022). Besides, Ndiritu et al. (2014) found that farmers with a shorter distance to the market were more likely to adopt maize-legume intercropping and maize-legume rotation practices but less likely to adopt animal manure applications.

3.3.3.3 Climatic factors

Only 21 studies considered at least one climate variable in the analysis of farmers' adoption of sustainable practices (Table 2). Among the climatic factors, the most widely used variables were precipitation (47.6%), droughts (47.6%), and floods (38.1%). In some cases, precipitation was used interchangeably with either rainfall, droughts, or floods (Kassie et al., 2013; Teklewold et al., 2013). From Table 2, five studies found higher precipitation to positively influence farmers to adopt sustainable practices while two studies reported otherwise. Farmers operating in rain-fed or dryland systems were found to be more likely to adopt zero tillage, minimum tillage, and strip tillage compared to their counterparts in irrigated systems (Akter et al., 2021). Kassie et al. (2013) found that the likelihood of jointly adopting conservation tillage along soil and water conservation practices was higher in years where rainfall was unreliable, in terms of timing, amount, and distribution. Moreover, Teklewold et al. (2013) found that while there was heterogeneity concerning factors influencing farmers' decisions to adopt, the importance of limited rainfall was underscored by the model results. In contrast, Jera & Ajayi (2008) observed that the likelihood of adopting agroforestry practices (i.e., fodder trees) decreased by 0.638 odds from high rainfall areas to drier regions.

On the other hand, five studies found drought events to positively influence farmers likelihood of adopting sustainable practices while only one study reported otherwise (Table 2). Broadly, the evidence suggests that farmers experiencing lower precipitation, including occurrences that lead to drought, were more likely to adopt sustainable practices aimed at reducing the impacts. For example, farmers in regions with lower rainfall were associated with a greater likelihood of adopting soil and water conservation practices relative to their counterparts experiencing higher rainfall (Kassie et al., 2013). Shulman et al. (2000) observed that the adoption of improved seeds—tolerant to drought, was often influenced by the timing of planting

in relation to rainfall at the start of the growing season. Farmers with higher risk perceptions on droughts were also associated with a greater likelihood of adopting integrated pest management and power tillers relative to their counterparts (Ahmed et al., 2022). Also, farmers' adoption intensity increased by 13.85% as droughts index increased by one unit (Ahmed et al., 2022).

Two studies found farmers experiencing floods to be unlikely to adopt sustainable practices while only one study reported otherwise (Table 2). Thus, Hinton et al. (2021) found that farmers in areas with frequent flooding were less likely to adopt water conservation practices, where wastewater accumulating around rural water points is used to irrigate community gardens. Likewise, Ochieng et al. (2022) observed that in areas with higher flood rate, farmers were less likely to adopt animal manure applications as it could be washed away by floodwaters. Ochieng et al. (2022) explained that floods can destroy crops and soils, causing farmers to limit or avoid adopting sustainable practices in efforts to minimize risks. Conversely, Si et al. (2021) found that natural disaster shocks such as floods, together with risk-averse attitudes, significantly and positively influenced farmers' adoption of biodegradable mulch. Lastly, out of the three studies that examine the influence of temperature variability on adoption decision, two found a significant positive influence on likelihood of adoption while one reported insignificant result. Jin et al. (2015) noted that farmers' awareness of changes in temperature had a positive influence on the adoption of improved seeds and their willingness to invest in sustainable innovations. Relatedly, the need for agronomic benefits such as moderating soil temperature was found to positively influence farmers' likelihood of adopting biodegradable mulch (Scaringelli et al., 2016).

Overall, there were relatively fewer reported mixed influences of climatic factors on the adoption of sustainable practices. Nonetheless, Ochieng et al. (2022) observed that farmers

experiencing droughts were more likely to adopt chemical fertilizer but less likely to adopt integrated pest management compared to their counterparts. While there is relatively consistent influence of climate variables on farmers' adoption of sustainable practices, there remains a lack of consistency in how these variables are conceptualized and incorporated in analysis. For example, whereas Hinton et al. (2021) constructed a flood vulnerability index, Ochieng et al. (2022) used a binary measure of whether a given household experienced floods in the past five years or not. Jin et al. (2015) used a binary measure of climate change based on whether farmers agreed to stated climate change effects on crop yield (1) or disagreed (0). Similarly, Foguesatto & Machado (2022) measured variables through farmers' beliefs about climate change using a Likert scale for disagreement. While Jera & Ajayi (2008) used natural agro-climate regions to represent rainfall levels.

3.3.3.4 Environmental factors

The influence of environmental factors such as soil fertility, perceived environmental benefits, the friendliness of practices, and the incidence of pests and diseases on farmers' likelihood of adopting of sustainable practices was considered in some studies (Table 2). Soil fertility was the most frequently considered environmental factor in assessing farmers' adoption. Eight (8) of the studies found that farmers cultivating on land with poor soil fertility were more likely to adopt, three (3) studies observed otherwise, while six (6) reported mixed effects on adoption likelihood (Table 2). For example, rural farmers facing soil fertility challenges were more likely to adopt sustainable practices such as crop rotation and legume intercropping, which contribute to improving soil quality (Saltiel et al., 1994). Results of Kpadonou et al. (2017) indicate that farmers experiencing poor soil fertility are more likely to adopt organic fertilizer and mulching compared to their counterparts with better soil fertility.

Farmers awareness on the effects of poor soil fertility and erosion lead to higher likelihood of adopting animal manure application, crop residue retention, and integrated pest management (Foguesatto et al., 2020; Ochieng et al., 2022a; Zeweld et al., 2020). Farmers were also found to be more likely to adopt biodegradable mulching for its agronomic benefits, such as enabling crops to efficiently use nutrients in poor soil (Scaringelli et al., 2016). However, Ndiritu et al. (2014) found that farmers cultivating fertile soil were more likely to adopt improved seeds compared to their counterparts farming on poor soils. Farmers cultivating fertile soil were also more likely to adopt chemical fertilizer compared to their counterparts farming on poor soils (Ehiakpor et al., 2021). Pham et al. (2021) observed that farmers operating on plots with soil fertility problems were less likely to adopt intercropping.

Moreover, five studies reported a higher likelihood of adoption among farmers experiencing pest and diseases infestation, two studies found otherwise, while two others reported mixed effects on adoption (Table 2). The synthesized evidence suggests that farmers experiencing pests and diseases are likely to adopt practices that involve smaller cash outlays and lower risk to reduce the impact of such shocks. For instance, sustainable practices including conservation tillage, soil and water conservation, legume intercropping, and animal manure were more likely to be adopted on farms experiencing pest and disease infestations (Kassie et al., 2013). Farmers facing soil-borne diseases and plant parasitic nematodes were also more likely to adopt biodegradable mulch to improve fumigation efficacy and reduce buffer zones around application sites (Goldberger, 2008; Goldberger et al., 2019).

The influence of farmland slope was uncertain among the selected studies, with five studies reporting a likely adoption and five reporting an unlikely adoption among farmers cultivating on sloped land (Table 2). Farmers cultivating steeper-slope farmlands were more

likely to adopt water and soil conservation practices to reduce excess water runoff and soil erosion (Kotu et al., 2017). Similarly, farmers on sloping terrain were more likely to adopt agroforestry (tree planting) to mitigate soil erosion and degradation (Brüssow et al., 2017). The likelihood of adopting fertilizer and improved seed (Teklewold et al., 2013), and maize-legume intercropping (Manda et al., 2016) was also higher among farmers cultivating steeper slope farmlands compared to their other counterparts. In contrast, farmers cultivating steeper slope land were unlikely to adopt organic fertilizer (Kotu et al., 2017) and manure along with contour terracing compared to their other counterparts (Zeweld et al., 2020).

The synthesized results largely suggest that the environmental friendliness and benefits of adopted practices increased farmers' likelihood of adoption, as found in eight studies, with no study reporting contrary findings (Table 2). Sustainable practices such as agroforestry was more likely to be adopted by farmers with the intention of promoting biodiversity and related environmental benefits (Foguesatto & Machado, 2022; Noeldeke et al., 2022). This was evident in situations where farmers made decisions and choices between alternative innovations. In the case of biodegradable mulch versus plastic mulch, adoption decisions were influenced by farmers' preferences for mulch attributes such as degradation elimination of microplastics in soil (Si et al., 2021; Yang et al., 2023). Positive attitude toward the environment significantly predicted the intention to adopt conservation practices (Hayat et al., 2020). Thus, farmers with positive environmental attitudes were more likely to adopt low-input sustainable practices such as organic fertilizer, conservation tillage, crop rotation, and delayed herbicide spraying (Saltiel et al., 1994). Moreover, farmers with concerns about environmental friendliness were more likely to adopt integrated pest management practices, organic fertilizer, and water-saving irrigation systems compared to their counterparts (Zhao et al., 2022). Similarly, farmers who believe that

agricultural production should ensure environmental protection were more likely to adopt improved seeds, efficient irrigation systems, and integrated pest management (Ma & Wang, 2020).

3.4 Limitations

We noted that the term “sustainable agriculture practices” is used as an umbrella term encompassing practices aimed at enhancing environmental, economic, and social sustainability in agriculture by most of the studies. However, we acknowledge that in certain geographic or institutional contexts, alternative terms such as “agri-environmental measures” (common in European policy contexts), “organic farming,” “climate-smart agriculture,” or “ecological farming” may be used to describe similar or overlapping practices. While our review may not have captured all such studies due to terminology variation, our keyword choice aligns with commonly used language in global sustainability and rural development discourse, ensuring relevance to the core research focus. Future reviews may expand on this work by incorporating a broader set of regionally or policy-specific terms to capture additional dimensions of sustainable practice adoption.

While this review illustrates a range of factors influencing the adoption of sustainable agricultural practices, it also reveals several methodological and conceptual limitations within the existing literature. A key limitation is methodological heterogeneity in how variables are defined and measured across studies, which complicates cross-study comparisons and weakens the potential for evidence synthesis. For instance, factors such as climate risk, social capital, and the farmer age are often operationalized inconsistently ranging from subjective self-reports to objective indices. Additionally, many studies overly rely on binary models of adoption (i.e., adopter vs. non-adopter), which may obscure more nuanced patterns such as partial,

discontinued, or repeat adoption behaviors. This limited modeling approach could constrain our understanding of adoption as a dynamic, multi-stage process. Recognizing and addressing these limitations is essential for refining future research designs and enhancing the explanatory robustness of adoption studies.

3.4 Conclusion

This paper provides a scoping review of the factors influencing farmers' adoption of sustainable agriculture practices using eighty-three studies from diverse rural farming regions across the world. Unlike most meta-analysis and reviews, this review included both qualitative and quantitative studies to provide in-depth analysis. Our findings show that the adoption of sustainable practices among rural farmers is limited and slow due to several factors influencing adoption. We broadly categorized these factors into climatic, economic, socio-cultural, and environmental variables. Most of the selected studies (82%) considered both socio-cultural and economic characteristics of the farmers or their households in the analysis, with limited consideration of climatic and environmental factors. Similar to prior reviews (e.g. Prokopy et al 2019; Foguesatto et al. 2020; Lu et al 2022; Begho et al., 2022) results indicate that the influence of the factors on farmers adoption likelihood varies according to the type of sustainable practice and study context.

We found that more often than not drought events, rising temperatures, higher income and wealth, perceived environmental friendliness or benefits, presence of pest and diseases, poor soil fertility, higher education, access to extension services, strong social networks, and positive psychological attitudes positively and significantly influence farmers to adopt most sustainable practices. While there are some notable variations across types of practices (for example, the uptake of farm management-based sustainable practices was found to be mostly positively

correlated with education whereas capital embodied practices were not) more often than not, these factors appear to support adoption of sustainable practices on rural farms. The extent to which these factors show positive effects on adoption, in our sample of studies with a rural focus, is sometimes consistent with prior reviews and in others varies notably. For example, the 42% positive effect rate for higher education is more than double that found for adoption of conservation practices in the U.S. (Prokopy et al., 2019) although slightly lower than the 57% positive effect rate found for adoption of sustainable cropping practices in South Asia (Begho et al., 2022).

However, we noted that the effect of higher education on management practices that are managerially complex (agroforestry, crop rotation, inter-cropping/mixed cropping, soil conservation) are more likely to be mixed or negative (Appendix Table 3.5). Although formal education is generally considered important for adoption, recent evidence suggests that knowledge gained through experiential learning, both individually and with other farmers are equally important (Jabbour et al., 2014). The general use of formal education as a measure of farmers education status in adoption literature might largely explain the mixed or negative effects associated with managerially complex practices in rural regions.

In addition, we noted a correlation between adoption of some practices and an identified male head of household (positive effect in 49% of cases), suggesting that men and women farmers may be subject to and influenced by different factors in adoption decisions, and further study would likely be instructive. This level of gender influence is significantly higher than other studies have reported (e.g. 18% by Begho et al., (2022) and ~5% by Prokopy et al. (2019)) and may point to specific gendered processes in rural smallholder farming systems that are less apparent in other agricultural settings. We also observed that limited access to credit and limited

access to (input and produce) markets among farmers consistently serve as barriers to adoption of most sustainable practices. Our observed 53.8% rate of unlikely adoption among rural farmers facing limited access to credit is higher than 12.1% reported by Prokopy et al. (2019) in the U.S. but similar to 53.2% reported by Begho et al., (2022) in South Asia. This finding underscores the influence of access to credit on the uptake of sustainable practices among farmers in developing regions.

However, a couple of the factors such as cost or price of the practice, slope of farmland, farmer age, size of households, and land-tenure arrangements were frequently associated with mixed effects on adoption likelihood across sustainable practice types and study. Depending on the study and the type of sustainable practice considered, these factors were either significantly and positively correlated with adoption or negatively correlated with adoption of innovations (Appendix Table 3.5). For example, farmers tend to use long-term and conservation practices on their own lands to enhance soil health and fertility, while adopting short-term, high-yield sustainable practices on rented plots. In general, most of the factors frequently associated with mixed effects on adoption likelihood were socio-cultural variables, due in part to differences in sustainable practices considered, study context, and inconsistency in conceptualization of variables into models and analysis. Often, these variables are measured based on farmers' perceptions through a unique statement, but as perception is latent, this type of variable needs to be analyzed through a set of statements. For instance, Ruzzante et al. (2021) noted that studies that use a credit constraint statement generally find that credit plays a larger role in adoption than studies that use a simpler access to credit definition. This is an important finding that deserves further consideration in future studies. The development of frameworks and establishment of

coherent methodologies in adoption studies would ensure robust synthesis of evidence across studies and modeling approaches. .

Overall, we find that conclusions regarding the factors that influence adoption of sustainable agricultural practices in rural farming communities are mostly consistent with the findings of prior reviews. However, we find that several factors (e.g. higher education, strong social networks, droughts, and access to extension services) have notably more or less consistent effects on adoption in our rural farming sample. These variations may point to differences in the importance of these factors in specifically rural contexts or may simply point to the strong influence of sample selection criteria on synthesis results. In addition, we document significant variability in effects across a suite of twelve (12) practices. While we provide a synthesis of effects on a more comprehensive set of practices than previously examined, the small number of studies examining any one factor-practice pair impair our ability to draw concrete practice-specific conclusions. Further information on adoption factors and their influence on specific adoption decisions would be helpful in formulating context-specific interventions to promote sustainable practices uptake among rural farmers.

Lastly, we found that most of the models used in the adoption studies assumed a discrete binary approach, where adoption decisions were assessed in terms of whether farmers adopted or did not adopt. Adoption decision-making is inherently continuous and multivariate, attempting univariate or binary analysis of adopters and non-adopters likely excludes useful information required to adequately understand farmers' sustainable practices uptake decisions (Rogers, 2003). Binary models may exclude the ability to capture conditions and context under which farmers choose to discontinue adoption and or readopt. Therefore, adoption literature will benefit from alternative approaches such as continuous and multivariate path-dependent-analysis, which

is rarely considered in farmers adoption decision-making studies. Using path-dependent analysis would be particularly important for socio-cultural factors noted for interactive relationships (Ervin & Jussaume, 2014). Farmers make adoption decisions based on technological constraints, economic constraints, personal attributes, and profitability, but a key part of the technological constraints is biophysical suitability of local context (Moxey et al., 2010). Hence, employing path-dependent analysis will help untangle this interdependent relationship.

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Appendix B - Chapter 3 Supplementary Information

Appendix Table 3.1. Selected Primary Studies

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- [1] Abeje MT, Tsunekawa A, Adgo E, Haregeweyn N, Nigussie Z, Ayalew Z, et al. Exploring drivers of livelihood diversification and its effect on adoption of sustainable land management practices in the upper Blue Nile basin, Ethiopia. *Sustainability (Switzerland)* 2019;11. <https://doi.org/10.3390/su11102991>.
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Appendix Table 3.2. Coded data extraction guide schema

Variable	Description	Label type
Include	Inclusion criteria to decide if the study should be included (Yes/No)	Categorical
Country of Study	The country in which the study/experiments took place	String
Year/s of Study	The year(s) in which the study was conducted	String
Innovative practices	The field to hold the types of innovative practices considered in the study.	Categorical
Focus of Study	The field to hold the research focus of the study	Categorical
Study Theory	The field to hold the theory adopted by the study to assess innovation adoption.	Categorical
Study Method	The field to hold the method used to study innovation adoption.	Categorical
Thematic Factors	Field to hold the broader factors or thematic areas considered in the study e.g., sociocultural, economic, environmental.	Categorical
Climate Factors	A field on the climatic factors that influence innovation adoption.	Categorical
Environmental Factors	A field on the environmental factors influence innovation adoption	Categorical
Socio- cultural Factors	A field on the Socio- cultural factors that influence innovation adoption	Categorical
Economic Factors	A field on the economic factors that influence innovation adoption.	Categorical
Influence of precipitation/ rainfall	The field to hold the influence of Precipitation/ Rainfall on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of droughts	The field to hold the influence of Droughts on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of floods	The field to hold the influence of Floods on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of temperature	The field to hold the influence of Temperature on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of land suitability	The field to hold the influence of Land Suitability on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical

Influence of slope	The field to hold the influence of Slope on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of soil salinity	The field to hold the influence of soil salinity on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of pest/ diseases	The field to hold the influence of Pest/ Diseases on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of soil fertility	The field to hold the influence of Soil Fertility on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of education	The field to hold the influence of Educational Level on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of household size	The field to hold the influence of Household Size on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of land tenure	The field to hold the influence of Land Tenure on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of psychological attitudes	The field to hold the influence of Psychological Attitudes on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of social capital/ networks	The field to hold the influence of Social Capital/ Networks on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of age of farmers	The field to hold the influence of age of farmers on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of gender of farmers	The field to hold the influence of gender of farmers on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of access to credit	The field to hold the influence of access to credit on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of access to market	The field to hold the influence of access to market [both commodity and input market] on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of income	The field to hold the influence of Income on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of wealth/ assets	The field to hold the influence of Wealth/ Assets on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of profit margins	The field to hold the influence of profit margins on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of price/ cost	The field to hold the influence of Price/ Cost on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
Influence of environmental benefits	The field to hold the influence of Environmental Benefits on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical

Influence of environmentally friendly	The field to hold the influence of Environmentally Friendly on sustainable agriculture adoption. Options to select are; 1. Insignificant, 2. Likely adopt, 3. Mixed, and 4. Unlikely adopt.	Categorical
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Appendix Table 3.3. Other studied sustainable agriculture practices

Other innovative practices	No. of studies
Agricultural economic efficiency	1
Borehole-garden permaculture (BGP	1
Compost, Fallow	1
Contour planting	1
Contour ploughing	1
Contour plowing, fallowing	1
Contour terracing, crop residues	1
Contour trench	1
Crop diversification	1
Crop residue retention	3
Crop residue retention, Soil conditioner	1
Crop-livestock integration	1
Digital extension service; soil testing and formular fertilization	1
Direct seedling	1
Drip fertigation	1
Fallowing	1
Fodder bank technology	1
Integrated soil fertility management	1
Integrated Soil Fertility Management	1
Integrated Striga Management technologies	1
Land fallow	1
Land Preparation	1
Lime application	1
Mixed farming	1
Nutrient management	1
Plant-derived pesticides, Trap and decoy crop	1
Planting Basin	1
Precision agriculture technologies	1
Residue management	1
Residue retention	1
Rotational grazing	1
Row planting	1
Shade management	1
Staggered planting	1
Sustainable grazing	1
Sustainable land management practices	1
System of Rice Intensification (early transplanting, the planting of single seedlings, wide spacing, intermittent irrigation and good water control, and frequent weeding)	1
Zero grazing	1

Appendix Table 3.4. Adoption theories and factors of studies

Factor	PBT	IDT	EC	None	Others	RAT	UT
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Age (Older)	4	8	12	20	1	5	5
Education (higher)	4	9	13	24	3	5	6
Extension (accessible)	2	7	12	13	1	5	5
Gender (male)	1	6	10	17	1	3	6
Household size (larger)	4	6	12	17	2	3	3
Land-tenure (Limited)	1	1	10	10		4	2
Networks (stronger)	4	8	12	11	1	4	5
Positive attitudes	5	3	2	3			2
Environ. benefits	3	2	3	2	2	3	1
Environ. friendly			1	1			1
Pest present			5	3	1		
Saline soil				1			
Slopy land			6	4	1	2	2
Soil fertility (poor)	2	3	10	5		3	3
Higher Profit		1		1			
Higher income	3	3	10	10	1	3	3
Higher price	1		1	1	2		
Higher wealth	3	7	9	11	1	4	5
Limited credit	2	3	6	9		1	5
Limited market		4	9	8	1	1	2
Drought present		1	2	4	1	1	1
Floods present	1	1	2	2	1	2	1
Higher temperatures				2		1	
Precipitations (higher)			3	4		2	

Note: *PBT= Planned Behavior Theory, IDT= Innovation Diffusion Theory, EC= Economic Constraint, RAT= Rationale or Reasoned Action Theory, UT= Utility Theory.*

Appendix Table 3.5. Adoption factors with significant negative or positive associations by studied practices

Factor	Agroforestry		Biomulch		Chemical fertilizer		Crop rotation	
	Likely	Unlikely	Likely	Unlikely	Likely	Unlikely	Likely	Unlikely
Droughts present	0	0	4	0	9	0	8	4
Floods present	0	0	4	0	0	4	0	0
Higher temperatures	0	0	0	0	0	0	0	0
Precipitations (higher)	0	0	0	0	0	4	4	4
Higher Profit	0	0	0	0	0	0	8	0
Higher income	5	0	10	0	6	8	20	8
Higher price	0	0	4	4	0	0	0	0
Higher wealth	23	1	9	0	28	3	46	0
Limited credit	1	11	3	5	10	11	7	21
Limited market	0	2	0	0	6	8	1	20
Environ. benefits	18	0	3	0	0	0	6	0
Environ. friendly	0	0	0	0	0	0	3	0
Pest present	0	0	4	0	12	0	9	4
Saline soil	0	0	0	0	4	0	0	0
Slopy land	3	8	3	4	3	2	10	7
Soil fertility (poor)	1	16	1	0	13	1	18	8
Age (Older)	2	15	5	8	19	7	17	24
Education (higher)	4	11	11	1	13	8	21	19
Extension (accessible)	10	14	9	0	24	2	39	9

Gender (male)	20	0	5	3	21	0	20	11
Household size (larger)	24	3	0	0	15	22	23	15
Land-tenure (Limited)	4	15	4	3	8	6	7	14
Networks (stronger)	15	9	2	0	31	0	42	9
Positive attitudes	0	1	3	0	3	0	12	0

Appendix Table 3.6. Continued

Factor	Improved seeds		Irrigation		Mixed cropping		No-tillage	
	<i>Likely</i>	<i>Unlikely</i>	<i>Likely</i>	<i>Unlikely</i>	<i>Likely</i>	<i>Unlikely</i>	<i>Likely</i>	<i>Unlikely</i>
Droughts present	6	4	0	0	0	0	6	4
Floods present	0	4	0	0	0	0	0	0
Higher temperatures	2	0	0	0	0	0	2	0
Precipitations (higher)	6	4	4	0	4	4	10	4
Higher Profit	0	0	0	0	6	1	3	1
Higher income	25	8	6	2	11	6	12	8
Higher price	0	0	4	0	4	0	0	0
Higher wealth	28	3	4	4	34	4	20	3
Limited credit	7	19	0	10	8	15	4	13
Limited market	2	26	0	1	2	12	3	8
Environ. benefits	0	0	0	0	11	1	7	0
Environ. friendly	3	0	3	0	3	0	3	0
Pest present	4	5	0	4	5	4	13	0
Saline soil	0	0	0	0	0	0	4	0
Slopy land	10	5	0	0	8	8	0	4
Soil fertility (poor)	16	4	0	0	18	1	11	0
Age (Older)	14	12	3	4	10	21	9	17
Education (higher)	25	7	17	0	12	18	11	9
Extension (accessible)	36	2	4	0	30	14	27	2
Gender (male)	14	14	11	3	22	3	11	7
Household size (larger)	22	18	0	6	16	24	16	13
Land-tenure (Limited)	7	7	5	4	8	7	9	1
Networks (stronger)	41	0	10	0	33	10	29	0
Positive attitudes	2	0	3	0	7	1	6	0

Appendix Table 3.7. Continued

Factor	Organic fertilizer		Pest management		Soil conservation		Water conservation	
	<i>Likely</i>	<i>Unlikely</i>	<i>Likely</i>	<i>Unlikely</i>	<i>Likely</i>	<i>Unlikely</i>	<i>Likely</i>	<i>Unlikely</i>
Droughts present	4	4	1	1	8	0	8	0
Floods present	0	4	0	4	0	0	0	4
Higher temperatures	0	0	0	0	0	0	4	0
Precipitations (higher)	8	4	0	0	4	4	4	4
Higher Profit	7	1	3	1	3	1	3	1
Higher income	34	6	18	4	11	4	17	4
Higher price	6	0	0	3	4	0	0	0
Higher wealth	53	6	18	3	36	6	28	4
Limited credit	11	25	7	11	6	15	6	23

Limited market	6	20	2	7	7	7	13	6
Environ. benefits	14	0	10	0	4	0	11	0
Environ. friendly	6	0	6	0	3	0	6	0
Pest present	4	5	5	0	8	4	8	0
Saline soil	0	0	4	0	0	0	0	0
Slopy land	9	14	3	0	7	7	7	12
Soil fertility (poor)	28	4	8	0	12	3	11	3
Age (Older)	26	20	12	20	14	16	14	6
Education (higher)	42	21	23	9	17	20	24	11
Extension (accessible)	54	16	21	11	23	11	27	9
Gender (male)	35	12	15	3	21	3	32	6
Household size (larger)	31	29	22	24	25	18	19	13
Land-tenure (Limited)	15	15	1	4	15	4	10	4
Networks (stronger)	62	10	32	9	26	9	31	1
Positive attitudes	21	1	6	0	8	0	11	0

* *Organic fertilizer= organic fertilizer, manure, compost; Chemical fertilizer = mineral/ inorganic fertilizer; BioMulch= Biodegradable mulch; Pest control= Integrated pest management, No tillage= zero/ minimal tillage; Mixed cropping = legume/ inter cropping.*

Chapter 4 - Projecting biodegradable mulch suitability: A GIS multicriteria analysis

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Abstract

The adoption of sustainable agriculture innovations to address environmental degradation has received growing attention recently. However, most research remains focused on present and past conditions with little consideration of future scenarios. Moreover, while a key component of adopting many innovations is suitability within a given biophysical context, there exist limited studies on how suitability varies across spatial and temporal extent. This study contributes to the literature on sustainable agriculture innovation adoption by assessing the biophysical suitability of biodegradable mulch (BDM) application under recent and future scenarios. We use fuzzy multicriteria decision analysis in a GIS-based model to characterize the ability of BDM products to provide agronomic benefits and degrade within desired time limits across the conterminous U.S. We find that about 62% (3.35 million square kilometers) of arable land is moderately to highly suitable for BDM application under recent past conditions. Suitable areas are reduced to ~59% by 2100 under a more sustainable scenario (SSP126) and increased to ~75% under a fossil-fuel driven development scenario (SSP585). Overall, the results suggest that if the world takes the path of SSP585 representing higher emissions with limited mitigation, BDM will have increased relevance as an adaptation with potential to replace plastic mulch and enhance crop production in many areas of the U.S. The Corn Belt, Delta, Southeast, Southern Plains, and Pacific regions are projected to experience the highest increase in suitable areas by 2100. This suggests a need for regional agricultural sustainability planning and future BDM development to meet context specific needs.

Keywords

Sustainable agriculture, plastic mulch, biodegradable mulch, adoption, suitability, future scenarios modeling

4.1 Introduction

The adoption and utilization of sustainable agriculture innovations have become an important issue in policy development agendas, especially in efforts to mitigate and adapt to climate change and global environmental degradation. Sustainable innovations have long been expected to broadly contribute to the reduction and reversal of the processes of global environmental change and degradation (FAO, 1989). The potential benefits of adopting sustainable innovations are diverse, including efficient resource use, improved crop resilience, and enhanced ecosystem services (Piñeiro et al., 2020). Among these benefits, one critical focus is improving soil health, which contributes to increasing soil fertility and carbon sequestration without sacrificing yield levels (Kassie et al., 2013). Practices that enhance soil health also have positive impacts on food security and soil biodiversity by maintaining fertile and functioning soils, addressing soil fertility depletion—a major biophysical limiting factor for increasing per capita food production (Kassie et al., 2013; Piñeiro et al., 2020).

While agricultural sustainability will require a wide array of approaches such as water conservation, integrated pest management, and agroforestry, we focused on soil health as it helps in achieving food security while mitigating and adapting to climate change and global environmental degradation. Thus, adopting sustainable innovations that help to improve soil health can directly contribute to achieving several United Nations Sustainable Development Goals [SDGs], including No poverty (SDG 1), Zero hunger (SDG 2), Decent work and economic growth (SDG 8), Reducing inequalities (SDG 10), Responsible consumption and production (SDG 12), Climate action (SDG 13), Life below water (SDG 14), Life on land (SDG 15), and Peace, justice, and strong institutions (SDG16). Hence, sustainable and innovative farming

practices that promote better soil health and water retention for crop usage are considered crucial to maintaining agricultural productivity and global sustainability.

For instance, mulching as an innovative practice serves a vital role in maintaining soil moisture by slowing soil water leaching and evaporation, which is crucial to agriculture production in dwindling precipitation and water-stressed areas (Cook et al., 2015; E. Liu et al., 2021; Madin et al., 2024; Ni et al., 2016). Mulch application also serves as a means of controlling weeds and moderating soil temperature in marginal lands prone to weed invasion and freezing (Eswaran et al., 2019; Schettini et al., 2004). Thus, mulching practices could help extend farming to areas previously not productive for agriculture activities. Mulching also provides valuable services that reduce irrigation requirements, decrease the use of inorganic herbicide inputs in weed control, and minimize nutrient leaching (Samuelson et al., 2022; Vox et al., 2013). However, low-density polyethylene-based mulches (hereafter referred to as plastic mulch) are currently and predominantly used for agriculture mulching, particularly in horticulture (Akhir & Mustapha, 2022; Transparency Market Research, 2013).

About 1.9 million metric tons of plastic mulch is used in agriculture global within a cropping season (Wang et al., 2022). Over 2.6 million metric tons of plastic mulch were applied globally as of 2005 (Briassoulis & Dejean, 2010), while application in the U.S. was estimated to be used on 400,000 ha (Miles et al., 2007). Market research data in 2012 estimated a total of 254,013 metric tons of plastic mulch used annually in the U.S. resulting in 370,500 metric tons of accumulated plastic waste (Mancl, 2020). In recent estimations, the U.S. is projected to use 453,592 metric tons of plastic every year in the production of crops (Fessenden, 2019; Velandia et al., 2020). Only 9% of the resulting plastic mulch waste is recycled in U.S., while over 79% is accumulated in landfills or on farmlands, contributing to microplastic pollution (Sarpong et al.,

2024). While the usefulness of plastic mulch in agricultural production systems has been identified in literature, it takes decades to degrade and leads to accumulation of plastic wastes in soil and landfill sites (Immirzi et al., 2009; Vox et al., 2013) which is associated with ecologically and agronomically detrimental outcomes (Akhir & Mustapha, 2022; Madin et al., 2024).

For example, plastic residue in the soil in excess of 37.5 kg/ha significantly affect crop production due to reduction in tillers, reduce emergence of seedlings, and alteration of physically and chemical soil properties (Duis & Coors, 2016; Huerta Lwanga et al., 2016; Krehl et al., 2022; Zhang et al., 2020). Accumulation of plastic residue in soil in excess of 240 kg/ha results in significant crop yield decline (Gao et al., 2019). Farmers require an estimated 42 hours per hectare of labor and \$12 per 907.2kg to remove and dispose of plastic mulch scraps from the field after application (Madrid et al., 2022; Velandia, et al., 2019). Plastic mulch application also often results in simultaneous increase in soil temperature and soil moisture, which stimulates CO₂ emission from soil (Liu et al., 2016; Zhao et al., 2022). In addition, prior research has shown that microplastic pollution from farmlands can enter aquatic ecosystems and possibly contaminate the human food chain (Duis & Coors, 2016; Huerta Lwanga et al., 2016). In response to microplastic pollution, research efforts have increased toward developing and conducting field trials of more sustainable alternative mulching materials, such as biodegradable mulches (BDM).

BDM constitutes a family of environmentally sustainable polymer-based mulching materials intended to protect crops against climate variabilities and formulated to degrade through the action of living soil organisms (Bastioli, 1998). They are designed to retain their mechanical properties during deployment and biodegrade at the end of the growing season

(Schettini et al., 2004a; Vox et al., 2013). Their ability to naturally degrade and be tilled into the soil after use helps eliminate waste and disposal challenges associated with conventional plastic mulch. The use of BDM instead of plastic mulches has been shown to reduce soil carbon emissions by as much as 22.6% per hectare (Dong et al., 2022). Aside from protecting crops against climate variability and reducing microplastic pollution, BDM applications also help in weed control (Anzalone et al., 2010; El-Metwally & Shalaby, 2019), reduction in herbicide use (Khan et al., 2020), improve water quality, and could replace plastic mulching in agricultural regions (FAO, 2021). The emergence of invasive and herbicide resistant weed species in major crop production regions such as the Great Plains and Corn Belt in the U.S. presents serious ecological challenge requiring integrated sustainable innovations such as BDM application (DeDecker et al., 2014; Ervin & Jussaume, 2014). The use of BDM to control weeds could help reduce the cost of herbicides among farmers (El-Metwally & Shalaby, 2019; Hagner et al., 2020; Liebman et al., 2016). Relatedly, BDM application contributes to minimizing nitrate and toxic agrochemical pollution of waterbodies in the plains, Corn Belt, and Pacific regions (Ervin & Jussaume, 2014; Mathewson et al., 2020; Reilly et al., 2003). Given the general agronomic benefits of BDM, research into suitability of application in these regions will contribute to tackling the above issues and help boost farmers confidence in adoption.

While BDM presents a promising sustainable option, adoption and utilization among farmers are reported to be limited (Goldberger & Lyons, 2017; Thompson et al., 2019; Velandia et al., 2019). For example, Velandia et al. (2020) found that only 15% of sampled farmers in Tennessee used BDM compared to over 60% who reported using plastic mulch. Among the factors driving the limited adoption were predictability of degradation rate across local conditions (Goldberger et al., 2015; Samuelson et al., 2022), desired physical or mechanical

properties (Briassoulis, 2007; J. Goldberger & Lyons, 2017), as well as cost and availability (Goldberger & Lyons, 2017; Velandia, Galinato, et al., 2019). Moreover, recent evidence shows that site specific biophysical conditions influence BDM application suitability, which in turn influences farmers' adoption decision (Madin et al., 2024; Samuelson et al., 2022). In application of BDM, the suitability lies in the product's ability to provide agronomic benefits for crop production and degrade within desired or regulatory determined time limits (Hayes & Flury, 2018). Thus, whereas adoption decisions are multi-faceted and depend on many socio-economic, and biophysical factors, one key component of adoption decisions is determining if a practice is suitable for a specific biophysical context (Fleskens et al., 2014). Also, Moxey et al. (2010) noted that farmers make adoption decisions primarily based on technological constraints and profitability, of which biophysical suitability form a crucial part. As such, recent studies have focused on assessing the suitability of sites for adoption of innovations in agriculture (Deng et al., 2019; Etxano & Villalba-Eguiluz, 2021; Kutlu et al., 2021; Vincent et al., 2019).

However, existing studies maintain a primarily contemporary focus, and only rarely has research directly engaged in projecting or modeling the future scenarios of the biophysical suitability of sustainable innovations application in agriculture (Mao et al., 2021; Woods, 2012). Among the few studies, Deng et al. (2019) for example simulated the effects of BDM on crop yield and water use efficiency under various future climate scenarios, employing bare land cultivation as a control. Although biophysical environmental characteristics vary spatially, the study relied on validation at a single experimental site and did not provide a spatially explicit representation capable of depicting variations across different locations. Moreover, whereas a shift in the future scenarios of the biophysical conditions is likely to influence farmers' adoption decisions, there remain limited studies on how a shift in the future could shape agriculture

decisions. Research on future biophysical suitability can provide insight into how the interactions between climate, soil and agricultural land use might influence farmer decision-making in the future. Therefore, this study models future scenarios of spatial variation in biophysical suitability for BDM across the contiguous U.S. We conducted the analysis using a fuzzy Multi-Criteria Evaluation (MCE) model in GIS for three Shared Socioeconomic Pathways (SSPs). The analysis provides evidence on;

1. The BDM biophysical site suitability across the conterminous U.S. in recent past and under different future scenarios; and
2. The regional variability in BDM biophysical suitability under recent and future scenarios in U.S.

Focusing on BDM in this research offers unique research opportunities for several reasons. First, the substantial variation in degradation rates across farm locations, which is still largely unexplained and somewhat unpredictable, serve as a significant barrier to farmers adoption of BDM (Goldberger et al., 2015; Samuelson et al., 2022). As such, suitability analyses across locations will contribute greatly to adoption through identification of potential optimum degradation sites. This will increase farmers' confidence in the degradation capacity on their farm, which will be critical to improving on-farm adoption as a more sustainable alternative to plastic mulch. Finally, the likelihood of farmers adopting the mulch depends on local climate variability and soil characteristics (E. Liu et al., 2021), which remain largely unexplored.

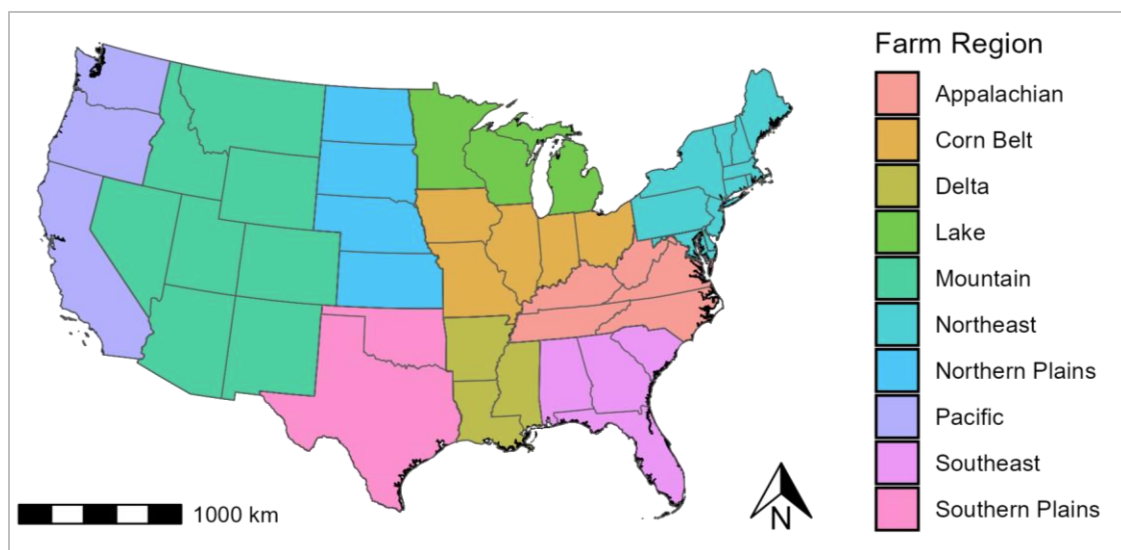
4.2 Material and methods

4.2.1 Study Area

The study area of this research covers all United States Department of Agriculture (USDA) farm production regions (USDA, 2023) in the conterminous U.S. (Fig. 1). The U.S. provides an ideal

context for assessment of BDM biophysical suitability because it is the second-largest consumer of plastic mulch after China (American Plastics Council, 2004; Sarpong et al., 2024), and plays a significant role in global agricultural production and food security (Boyer et al., 2013; FAO, 2021; Fischer et al., 2014). In recent estimations, the U.S. is projected to use 453,592 metric tons of plastic every year in the production of crops (Fessenden, 2019; Velandia et al., 2020). Besides, over 21.2% of global field trials of BDM are conducted within the U.S. (Madin et al., 2024), which provide sufficient data for the suitability model calibration.

Figure 4.1. Contextual map of farm production regions in the conterminous U.S



4.2.2 Modeling Approach

For the spatial modeling of biophysically suitable areas for BDM application using Geographic Information Science (GIS), we consider selection criteria related to two primary factors: 1) the likelihood of providing optimum agronomic benefits, and 2) the likelihood of degradation within the desired timeframe after deployment. To obtain the appropriate criteria variables for the suitability analysis (Carver, 2007; Yousefi et al., 2018), we conducted a systematic review on field trials of BDM for related important biophysical environmental factors (Madin et al., 2024). The selected biophysical environmental factors are discussed in the

following sections. Our modeling approach and evaluation process has two steps. In the first step, we defined the study objectives, obtained required variables, and used a reclassification tool and spatial data layers to process the variables into suitable input criteria. The second step involves the overlay of the input criteria to produce the final suitability maps. The defined objective is to assess the extent of BDM biophysical site suitability and the areas that are most likely to benefit under current and future climate scenarios. For the purposes of this study, we consider BDM to be mulch materials that have been synthesized or processed for agriculture applications. Thus, natural occurring biodegradable mulches such as straws, crop residues, animals' furs or feathers, and wooden chips are excluded.

In the final modeling step, we overlay the input criteria using fuzzy technique to produce the suitability maps. The fuzzy process is explained later in the subsequent sections. For the determination of suitable locations, restricted areas (e.g., waterbodies and developed areas) were excluded from BDM suitability assessment and the remaining areas are evaluated by fuzzy overlay to have a standardized evaluation of the entire region. Areas with smaller value are selected as biophysically suitable sites for BDM application.

4.2.3 Data and Criteria Selection

The data for the analysis comprise factors such as climate variables, soil attributes, and land use (Table 1) that previous studies have shown to influence the ability of BDM to provide optimum agronomic benefits and to degrade within a desired time frame after deployment (Li et al., 2014; Madin et al., 2024; Samuelson et al., 2022; Zhang et al., 2008). The method of GIS-based MCE traditionally utilizes discrete criteria that are usually defined by expert inputs or available literature evidence to assess suitability (Carver, 2007; Jankowski, 1995). Using appropriate literature evidence to select data variables ensures that the defined criteria are based

not only on economic, environmental, and technical principles but also on practical and regulatory requirements (Etxano & Villalba-Eguiluz, 2021; Yousefi et al., 2018).

Table 4.1. Input criteria data and definitions

Input Criteria	Definition	Temporal Range	Spatial Scale
Precipitation	Monthly total precipitation (mm). The monthly total precipitation values were summed up and averaged to the annual total.	2001-2020, 2021- 2040, 2041- 2060, 2061- 2080, 2081- 2100	1Km
Max. temperature	Monthly average maximum temperature (°C). The monthly average values were summed and averaged to the annual maximum temperature.	2001- 2020, 2021- 2040, 2041- 2060, 2061- 2080, 2081- 2100	1Km
Min. temperature	Monthly average minimum temperature (°C). The monthly average values were summed and averaged to the annual minimum temperature.	2001- 2020, 2021- 2040, 2041- 2060, 2061- 2080, 2081- 2100	1Km
Solar radiance	30-year normal monthly solar radiance (MJ m ⁻² day ⁻⁴)	1991-2020	1Km
Soil pH	The level of soil pH	-	30m
Soil Texture	Soil texture class measured as the percentage of silt and clay, respectively	-	30m
Available water storage (AWS) in the soil	Average available water storage capacity within 0-100cm depth as indicator of soil moisture content	-	30m
Soil cation exchange capacity (CEC)	The soil capacity to supply nutrient cations for plant uptake and maintain ideal pH level	-	30m
Land use/ cover	Contains attributes that help restrict non-agricultural areas that should not be assessed	2021	30m
Irrigated areas	Contains attributes that help discriminate irrigated fields from dry land farming areas	2007- 2017	250m

4.2.3.1 Climate Criteria

Climate variables such as precipitation, temperature, and solar radiance are reported as having significant influence on BDM agronomic effects and degradation rate in agricultural field trials. For instance, it is observed that studies conducted in global biomes with hot summer, arid, and or humid climate conditions were more likely to report positive effects of BDM application

irrespective of the agronomic factor being assessed (Madin et al., 2024; Tofanelli & Wortman, 2020). Field experimental evidence showed rapid loss of mulch functionality at high monthly precipitation of 127.5mm or 134.0mm (Zhang et al., 2008). Field trial results further observed higher degradation rates in warmer regions (Li et al., 2014; Samuelson et al., 2022). The selected climate criteria in this study therefore included monthly total precipitation (mm), monthly average maximum temperature (°C), monthly average minimum temperature (°C), and monthly solar irradiance (Table 1). The current (historical) climate variables with a range from 2001 to 2020 were obtained from [PRISM](#) climate data (Daly et al., 2008; Rupp et al., 2022) while the projected future scenarios data between 2021 to 2100 were obtained from the gridded [WorldClim](#) database (Fick & Hijmans, 2017).

The future scenarios comprised downscaled monthly future climate data using CMIP6 from two global climate models and three SSPs for the periods of 2021 to 2100. The scenarios have been used in previous studies and have been found to have ideal climate sensitivity in site suitability modeling (Benti et al., 2022; Sahoo et al., 2018). This study used a span of 80 years into the future, which is sub-divided into four 20-year periods (i.e., 2021-2040, 2041-2060, 2061-2080, and 2081-2100). These temporal periods have also been used in related earlier research for both regional and global studies (Feng et al., 2021; Jayasinghe & Kumar, 2019). The two global climate models used were GISS-E2-1-G and UKESM1-0-LL. These models were used to allow model averaging between a high climate sensitive model (UKESM1-0-LL) and low-medium climate sensitive GISS-E2-1-G. Refer to Nazarenko et al. (2022) for a detailed description of GISS-E2-1-G and Andrews et al. (2019) for the description of UKESM1-0-LL.

The three selected SSPs are SSP126, SSP370, and SSP585. The SSP126 represents the sustainability option where the world takes the Green Road with low challenges to mitigation

and adaptation efforts (Bond & Scott, 2022; Calvin et al., 2023). The SSP370 represents a world of regional rivalry characterized by concerns for regional food and energy security leading to high challenges to mitigation and adaptation (Bond & Scott, 2022). The SSP585 represents a scenario of fossil-fueled development and dependent resulting in high challenges to mitigation but low challenges to adaptation (Bond & Scott, 2022; Riahi et al., 2017). The SSPs originated from the sixth Report of the United Nations' Intergovernmental Panel on Climate Change (IPCC) and describe potential future environmental conditions under each scenario (Calvin et al., 2023). The monthly climate variables are averaged over 20-year periods at a spatial resolution of 30 seconds (~1km x 1km). The spatial resolution of the climate data from the PRISM website is 4km but to ensure consistent spatial resolution with the projected data from WorldClim, the PRISM data were downloaded and downscaled to 1km in Google Earth Engine.

4.2.3.2 Soil Criteria

Although the degradation and performance of BDM are influenced by multiple factors, mulch material properties (e.g., tensile strength and feedstocks), some place-specific factors such as climate conditions (e.g., rainfall, temperature), soil characteristics and soil microbial diversity and abundance are found to be crucial (Samuelson et al., 2022; Zhang et al., 2022). The soil attributes used in this study included soil pH, texture class, moisture content, and nutrients levels (Table 1). In terms of the soil characteristics of the studied sites, field trials showed that finer soil texture classes (silty and loamy soils) are most suitable for the BDM application (Samuelson, Reid, et al., 2022). Results further suggest that a soil pH between 6.2 and 7.5 provides optimal conditions for soil microbes involved in mulch biodegradation and for most crops growth (Islam et al., 1980; Nachtergaele et al., 2009; Suzuki et al., 2014). Soil moisture is found to be related to BDM agronomic effectiveness (Li et al., 2014; Samuelson et al., 2022). As such, available water

storage (AWS) was used as an indicator for soil moisture (Cisty et al., 2016). Finally, soil cation exchange capacity was used to represent nutrient levels required for agricultural productivity and buffer against soil acidity (Nachtergaele et al., 2009). The soil data were obtained from the United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), and Soil Survey Geographic (SSURGO) Database website (USDA, 2022) at a spatial resolution of 30m . The downloaded soil attributes were joined to the appropriate mapping unit keys and pre-processed into raster layers using R-Studio.

4.2.3.3 Constraint Criteria

Constraint criteria such as land use, protected areas, and floodplains are crucial variables to be considered in agricultural practice site selection (Kutlu et al., 2021; Mondo et al., 2024). Here, land use or cover and irrigated land data are used as constraint criteria (Table 1). The land use or cover data were obtained from the USDA Cropland Data Layer (USDA-NASS, 2022) while the irrigation data were sourced from Brown et al. (2019). The land use data layer was used to mask non-agricultural areas and wetlands that are not appropriate locations for BDM application. The use of irrigated land data as a constraint ensures that the model prioritizes areas suitable for innovative water conservation farm practices such as BDM use, aligning with both agronomic viability and resource sustainability.

4.2.4 Data Processing and Analysis

4.2.4.1 Classification of Input Data

The classification scheme (Table 2) was guided by relevant literature (Li et al., 2014; Madin et al., 2024; Nachtergaele et al., 2009; Samuelson et al., 2022) and machine learning (Decision Tree [DT]) regression was used to obtain the specific ranges of parameters of the criteria under each suitability class. The data used for the DT analysis were obtained from a

systematic review of 136 published experimental studies by Madin et al. (2024). The environmental (independent) variables used included monthly total precipitation, monthly average maximum temperature, monthly average minimum temperature, soil texture class, soil pH, and cation exchange capacity (CEC).

The dependent variables included reported BDM effects on studied agronomic factors and degradation rate after deployment on the field. The studied agronomic factors comprise crop yields, soil temperature moderation, soil moisture retention, and weed control compared to no-mulching or plastic mulch treatment. The reported BDM effects were categorized into negative effect, positive effect, neutral effect, or mixed effect. The category negative effect was applied if all trials with BDM were reported to have reduced or negative impacts relative to the comparison group or positive effect was applied if otherwise. The neutral category was applied if the study consistently reported no significant difference between impacts of BDM use and the comparison group while the mixed category was applied if the study reported positive impacts of BDM relative to the comparison group for some trials and negative impacts for other trials. DT regression using the ‘rpart’ package (Speybroeck, 2012) was used to classify the agronomic effects based on the abovementioned independent variables and the range of values at each node were taken as the benchmark suitability parameters (SI Table 1). Complete details of this analysis are described by Madin et al. (2025).

Table 4.2. Input variables classification scheme

Input Criteria	Suitable Values (Class = 1, 2, 3)	Unsuitable Values (Class = 4, 5)	Reference
Precipitation	$0 \leq x \leq 100\text{mm}$	$x > 100\text{mm}$	DT*, (Li et al., 2014; Y. Zhang et al., 2008)
Max. temperature	$5 \leq x \leq 34^{\circ}\text{C}$	$5 > x > 34^{\circ}\text{C}$	DT*, (Li et al., 2014; Samuelson et al., 2022)
Min. temperature	$-7 \leq x \leq 24^{\circ}\text{C}$	$-7 > x > 24^{\circ}\text{C}$	DT*, (Li et al., 2014; Samuelson et al., 2022)

Solar radiance	$x \leq 31 \text{MJm}^{-2}\text{day}^{-4}$	$x > 31 \text{MJm}^{-2}\text{day}^{-4}$	(de Oliveira et al., 2021; Marí et al., 2019)
Soil pH	$5.5 \leq x < 8.2$	$8.2 < x < 5.5$	DT*, (Islam et al., 1980; Nachtergaele et al., 2009; Suzuki et al., 2013)
Soil Texture	Loam, sand, silt	Clay	DT*, (Samuelson, Reid, et al., 2022)
Available water storage (AWS) capacity of soil	$x \leq 14.20$	$x > 14.20$	(Q. Liu et al., 2022; Sun et al., 2018)
Soil cation exchange capacity (CEC)	$10 \leq x < 45$	$0 \leq x < 10$	DT*, (X. Gao et al., 2021; M. Zhang et al., 2022)
Land use/ cover	Cropland, Grassland/Pasture	Wetlands, developed areas, waterbodies, forest, parks,	(Madin et al., 2024)
Irrigated areas	Drylands	-	(Brown et al., 2019; Wang et al., 2019)

*Determined by Decision Tree (DT) regression model, which formed part of the Madin et al.

(2025) published elsewhere.

The Reclassify tool in ArcPro was used to convert information in each input criterion raster into five (5) distinct suitability classes from 1 to 5 (highly suitable, suitable, moderately suitable, unsuitable, and highly unsuitable, respectively). Refer to SI Table 2 for the description of these classes. Areas with limitations for BDM application were restricted from the evaluation process based on land use data and irrigation data. In terms of selected criteria variables, the suitable sites were assigned value of 1 to 3 while unsuitable sites were assigned value of 4 and 5 (Gacu et al., 2023; Yousefi et al., 2018). For example, based on the decision tree analysis, sites with mean monthly precipitation between 0 -30mm were classified as highly suitable, 31 -63mm as suitable, 64-100mm as moderately suitable, 101 -200mm as unsuitable, and above 200mm amount is classified as highly unsuitable. Similarly, soil pH within the range of 6.2 -7.2 were classified as highly suitable, 7.3 -8.2 as suitable, 5.5 -6.1 as moderately suitable, above 8.2 as unsuitable, and below 5.5 amount is classified as highly unsuitable. Each resulting criteria layer provides five classes of sites within the defined suitability categories (SI Table 1). The reclassified input data were then transformed into a 0 to 1 probability membership scale by using

Fuzzy Small function. The Fuzzy Small transformation function is used when the lower input values indicate higher suitability (Zimmermann, 1998), which aligns with our reclassification scheme where smaller values represent optimal sites. This step was undertaken because Fuzzy Overlay, which is used in a following processing step, applies only to rasters with values that range between 0 and 1.

4.2.4.2 Generation of Fuzzy Maps and Analysis

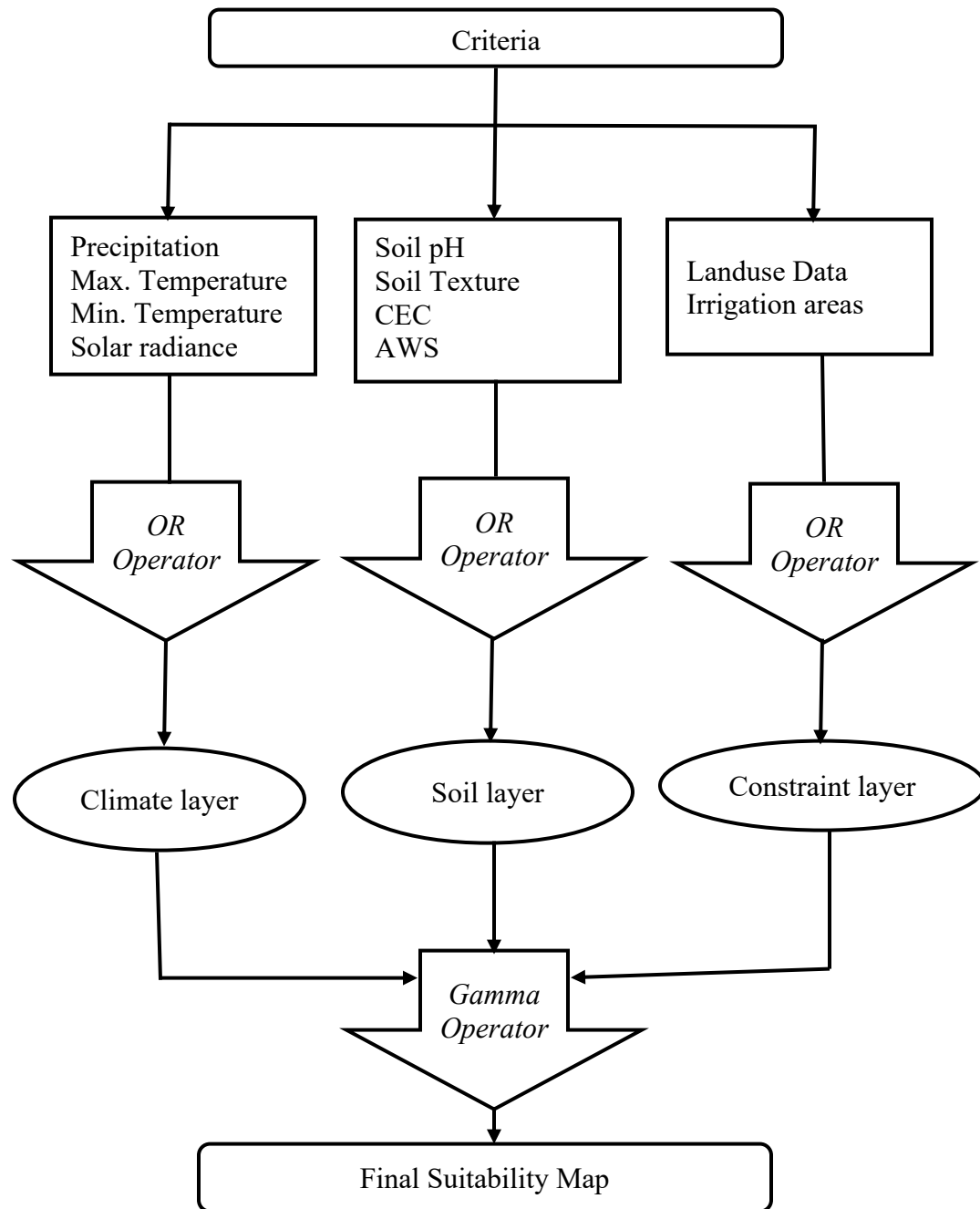
We adopted a GIS-based Multi Criteria Evaluation (MCE) decision analysis technique aided by Fuzzy Overlay model. MCE in GIS serves as a fundamental decision support operation used in the allocation of land to suit a specific objective or purpose based on their ability to meet predefined suitability criteria (Eastman, 1999). The MCE framework supports the integration of multiple spatial datasets— such as climate variables, soil attributes, and land use, which may include conflicting variables (Carver, 1991). The Fuzzy Overlay technique allows the evaluation of the possibility of a phenomenon belonging to multiple sets in a multicriteria overlay analysis (Vojteková & Vojtek, 2019). It assigns suitability class memberships to each pixel based on probabilistic (maximum likelihood) computations unlike other MCE methods such as weighted overlay that rely on subjective weights (Burrough et al., 1992).

Fuzzy overlay in GIS offers some advantages, including the ability to model nonlinear relationships and combinations, preserve the continuous nature of certain inputs, and provide flexible options for integrating variables (Bonham-Carter, 1994). Thus, unlike weighted methods that rely on subjective expert-defined weights, the fuzzy approach allowed us to model suitability probabilities in a more flexible and data-driven manner based on reclassified inputs guided by machine learning. The Fuzzy Overlay technique was particularly useful for handling inherent interactions and correlation in soil and climate data, as it assigns class membership likelihoods to

each location, reflecting the degree to which specific conditions align with suitability thresholds in Table 2. Fuzzy Overlay model has been widely studied, discussed, and applied by multiple suitability studies (Brimicombe, 2009; Vojteková & Vojtek, 2019; Zimmermann, 1998).

After generating reclassified criteria raster layers, they were combined with OR and Gamma operators using the Fuzzy Overlay MCE model. A fuzzy operator was selected to combine different layers based on the relationships and interactions between factors within each layer (Fig. 2). The reclassified criteria layers were combined in a hierarchical manner using OR fuzzy operator to combine sets of related criteria into a single climate factors layer, a single soil factors layer, and a single constraint layer (Fig. 2). The OR operator is most appropriate in situations where a condition can be satisfied by any one of several criteria, for instance temperature and precipitation are both climate factors and could be strongly correlated. The fuzzy OR operator returns the maximum value from the input criteria at each cell location. This means that if two inputs have high values, the final output is determined by the highest membership value, thereby minimizing correlations and interactions between inputs. The Gamma operator is useful for a flexible combination of dissimilar or conflicting criteria, which requires all conditions to be satisfied. As such, we used fuzzy Gamma operator to combine the three different layer maps (i.e., climate, soil, and constraint) into the final BDM suitability maps as illustrated in Fig.2.

Figure 4.2. The flow diagram of the GIS-MCE model estimating the site suitability of BDM



Gamma operator is defined based on fuzzy algebraic products and fuzzy algebraic sum as follows:

$$\text{Fuzzy Gamma} = (\prod_{i=1}^n \mu(x))^{\gamma} \times (1 - \prod_{i=1}^n (1 - \mu(x)))^{1-\gamma} \quad (1)$$

$$\text{Fuzzy OR} = \max (\mu_1, \mu_2, \mu_3, \dots, \mu_n) \quad (2)$$

Where γ is Lambda values 0 to 1, μ is the fuzzy membership values. Gamma operator with Lambda 0.9 was used to combine the sub layers into the final maps. Layers of constrained factors which are mainly related to land use data such as wetlands, waterbodies, forest areas, and irrigated areas were also combined using Gamma operator. For the projected future suitability for each scenario, the current climate criteria values were replaced with the climate values associated with each scenario and the model re-run to obtain the suitability map for that scenario (Fig. 3). This iterative modeling process was repeated until the suitability maps for all desired SSPs scenarios within 2021-2040, 2041-2060, 2061-2080, and 2081-2100 were generated. Analysis of aggregate suitability trends was conducted for the coterminous U.S. and by USDA farm production regions (USDA, 2023) illustrated in Fig. 1.

4.3. Results

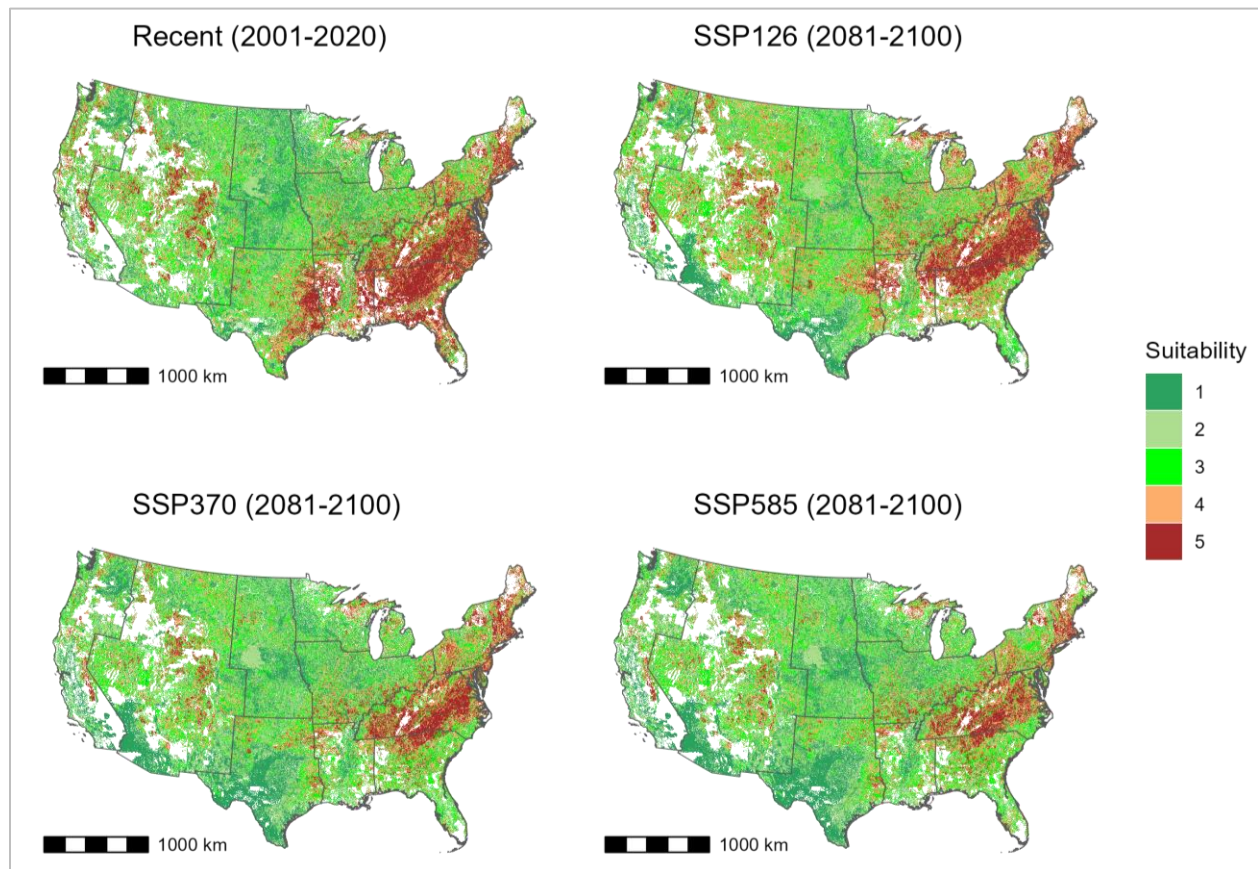
4.3.1 Maps of Biodegradable Mulch Biophysical Sites Suitability

The results of the heuristic model are illustrated as final suitability maps. A total of about 5,371,967 square kilometers area was evaluated for the biophysical suitability of BDM. The final maps are presented according to the temporal periods of recent past (2001-2020), projected 2021-2040, 2041-2060, 2061-2080 (see SI Fig 1-4), and up to the end of the century (2081-2100) in Fig. 4. The maps indicate optimal locations within the suitable areas of the study regions. The suitability maps are discussed in the subsequent sections. We also present summaries of suitable areas at national and farm production region levels.

4.3.1.1 Biodegradable mulch suitability to the end of the century

The map of the suitability model showed that under the recent past (2001-2020) conditions, existing croplands and potential farmlands in the conterminous U.S. are predominantly highly to moderately suitable for BDM application except in the Mountains and Eastern production regions (Fig. 3). The suitability areas are largely explained by the presence of drier and hotter climate conditions alongside the ideal soil characteristics of the regions. The Northern Plains have the largest suitable areas with 37.86% being highly suitable (1), 38.65% as suitable (2), and about 17.53% being moderately suitable (3) under the recent past conditions. The Northern Plains consist of parts of the Heartland, Northern Great Plains, and Prairie Gateway farm resource regions noted to produce corn, wheat, sorghum, cotton and rice, which span across states like Kansas, Nebraska, and the Dakotas (Fig. 1 and SI Fig. 1d). The second most suitable farm production region is the Lake region with 24.66%, 28.08%, and 24.58% of the total land being highly suitable, suitable, and moderately suitable, respectively (Table 3). The Lake region is noted for the production of general and cash grains (USDA, 2023). The Pacific production region follows closely with about 22.67% being highly suitable, 27.38% as suitable, and 21.34% being moderately suitable. The Pacific region encompasses fruitful rim resource region within Washington, Oregon, and California states (Fig.1). On the other hand, the Appalachian, Delta, Southeast, and Northeast farm production regions are the most unsuitable for BDM under recent past conditions. For instance, the Appalachian region has 27.30% unsuitable areas and 50.58% highly unsuitable areas, while the Southeast region has 25.32% of unsuitable areas and 62.32% of highly unsuitable areas. The most limiting factors accounting for the predominantly unsuitable characteristics are partly due to the higher precipitation, limiting soil characteristics, and more developed landuse.

Figure 4.3. Projected (2081-2100) biophysical suitability of BDM within the farm production regions in the conterminous U.S.

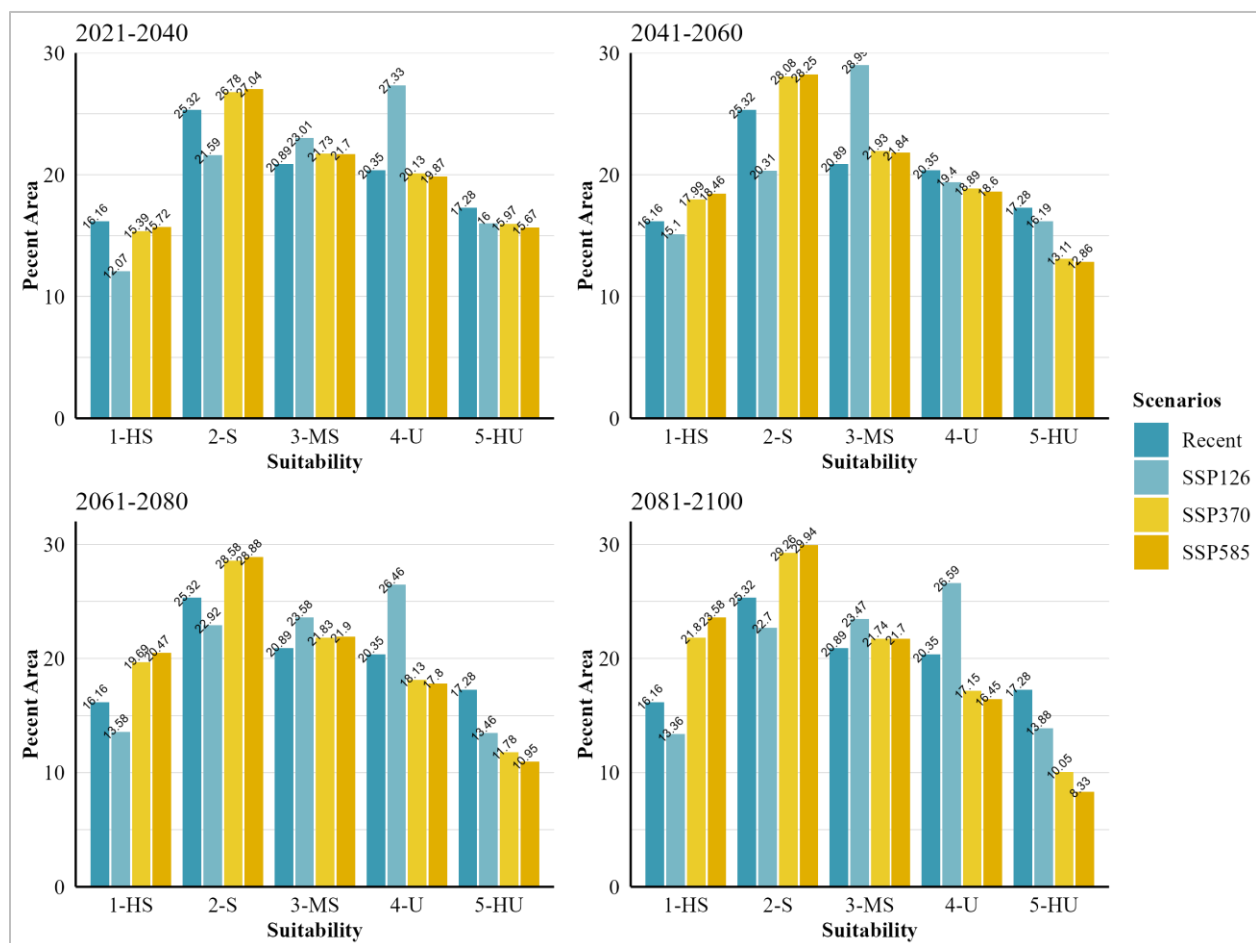


Note: 1= highly suitable, 2= suitable, 3= moderately suitable, 4= unsuitable, and 5= highly unsuitable.

For SSP126, which represents a more sustainable world, the area characterized as suitable for BDM application is reduced compared to recent past conditions (Fig. 3). Reduced suitability under SSP126 scenario reflects the relatively mild climate variability expected in this pathway as sustainability efforts will help stabilize environmental conditions (Calvin et al., 2023; Riahi et al., 2017). Within the near future (2021-2040), the percentage of highly suitable areas were 12.07% for SSP126 relative to 16.16% in the recent past (Fig. 4). Similarly, at the end of the century (2081-2100), the proportion of highly suitable areas reduced to 13.36% relative to 16.16% in the recent past (Fig. 4). The highly suitable area under SSP126 was also smaller compared to the other future scenarios that represent greater fossil fuel dependency, such as

SSP370 and SSP585. However, areas categorized as moderately suitable for BDM application were consistently higher under SSP126 compared to any other scenario across all the periods considered (Fig. 4). On a regional basis, the mountains, Lake, Appalachian, and upper parts of the Southern Great Plains remain generally unsuitable for BDM applications under SSP126 (Fig. 3 and SI Fig. 2-4). Contrary, the lower parts of the Pacific, Mountains, Southern Plains, Delta, and Southeast region appeared to be largely suitable under SSP126 at the end of the century compared to the recent period (Fig. 4).

Figure 4.4. Estimated BDM biophysical suitability areas in the conterminous U.S.



Note: Total area evaluated is 5,371,967 Km². 1-HS = highly suitable, 2-S= suitable, 3-MS= moderately suitable, 4-U= unsuitable, and 5-HU= highly unsuitable.

Most of the evaluated areas appeared to have increased BDM suitability under SSP370 relative to the levels of suitability in the recent past conditions (Fig.3). The SSP370 scenario will

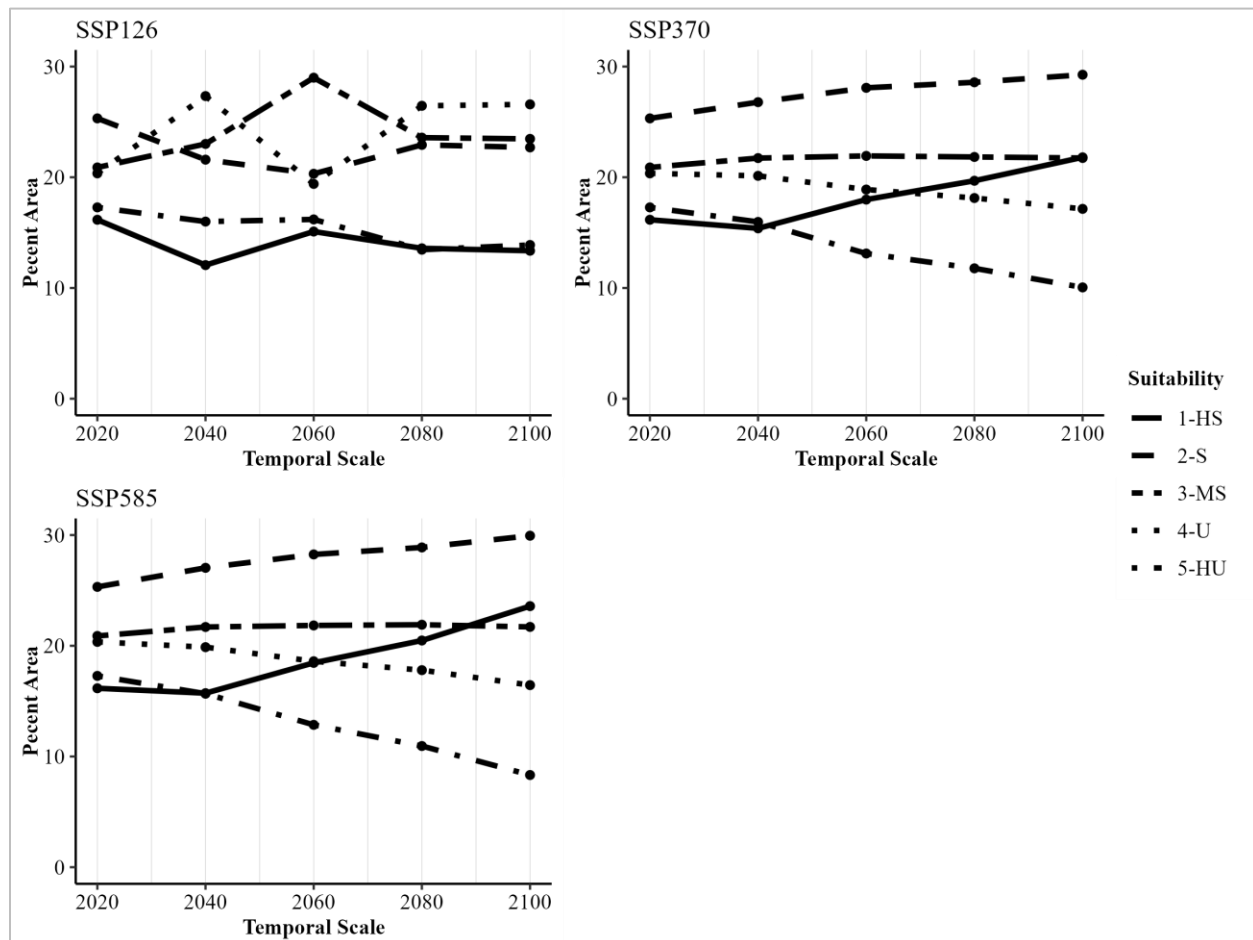
result in significant change in precipitation patterns, rising temperature, and weaker environmental policies due to regional rivalry for food and energy security that compromise sustainability efforts (Calvin et al., 2023). Thus, the overall areas categorized as highly suitable and suitable rose from 16.16% and 25.32% under recent past conditions to about 21.80% and 29.26%, respectively, under the SSP370 scenario by 2100 (Fig. 4). Compared to the SSP585 scenario, the SSP370 scenario had slightly less areas categorized as highly suitable, suitable, and moderately suitable for BDM application across the conterminous U.S.

The assessed areas generally increased in the proportion of sites categorized under the highly suitable to moderately suitable classes in the SSP585, especially at the end of the century compared with any other scenario. SSP585 represents the most severe climate change projections due to intensification of fossil-fueled development (Riahi et al., 2017), suggesting that moisture retention like BMD application will become critical under SSP585's arid conditions. The highest increase in suitable classes under the SSP585 is among the Corn Belt, Delta, Southeast, southern great plains, and Pacific regions (Fig. 3; SI Fig.2- 4). Within the Southeast farm production region for example, highly suitable areas increased from 0.83% under recent past conditions to over 4.32% under SSP585 by 2081-2100. Likewise, highly suitable areas within the Delta region increased from 5.48% in recent past to about 15.50% by 2100 under the SSP585 scenario. On the other hand, farm production regions such as the Appalachian, Northeast, and upper parts of the lake areas remained relatively unsuitable for BDM application even under SSP585 to the end of the century. The most limiting reason, accounting for the predominantly unsuitable nature is attributed to either higher precipitation or colder temperatures, and the nature of soil (SI Fig. 6).

4.3.2 Spatio-Temporal Trends of BDM Biophysical Sites Suitability

The temporal trends of BDM biophysical sites suitability across conterminous U.S. are illustrated in Fig. 5. In a more sustainable world scenario (SSP126 scenario), the pattern of the suitability classes proportions has no clear trend. The trend switches from predominantly suitable areas in the near future (2040) to moderately suitable in the medium-term future (2060), and then with unsuitable areas taking the largest proportion (26.59%) of the evaluated sites by 2100 under SSP126. The SSP370 and SSP585 present clearer temporal trends of the suitability of BDM application (Fig. 5). Under the SSP370 scenario, characterized by regional rivalry and high challenges to mitigate and adapt, there is an increasing trend in the proportion of suitable to highly suitable areas, with a corresponding decrease in the percentage of unsuitable and highly unsuitable sites by the end of the century. By 2100, areas predicted to be suitable for BDM application in crop production will have the largest share (29.26%), followed by highly suitable and moderately suitable areas in equal proportion (Fig. 5). Similarly, under SSP585, suitable areas will have the highest share (29.94%), with highly suitable areas surpassing moderately suitable areas.

Figure 4.5. Estimated BDM biophysical suitability areas under selected SSPs within the conterminous U.S.



Note: 1-HS = highly suitable, 2-S= suitable, 3-MS= moderately suitable, 4-U= unsuitable, and 5-HU= highly unsuitable.

The spatio-temporal shifts in the biophysical suitability of BDM across the farm production regions in the conterminous U.S. are presented in Table 3. The Delta, Southeast, and Southern Plains regions are the areas in the conterminous U.S. likely to experience an increase in the total area predicted to be suitable (i.e., moderately suitable to highly suitable) irrespective of the scenario considered. These regions also have the highest percentage differences between suitability under recent past conditions and projected scenarios by 2081-2100. For instance, suitable areas within the Delta region are projected to increase from recent past conditions by 16.39%, 38.44%, and 41.93% under SSP126, SSP370, and SSP585, respectively, by the end of

the century (Table 3). Likewise, the southern great plains area is expected to increase from recent past suitable areas in about 16.39%, 38.44%, and 41.93% under SSP126, SSP370, and SSP585, respectively, by 2100. While production regions such as the Pacific, Mountains, and Corn Belt are expected to experience reduced proportion of suitable areas under SSP126, they are projected to see significant increase in suitable areas under SSP 370 and SSP585 by 2100 compared to recent past conditions. These regions, for example, are projected to experience dwindled precipitation and or increased temperatures (SI Fig. 6), which increase the suitability of mulching under SSP 370 and SSP585.

Table 4.3. Spatial variability of estimated BDM biophysical suitability by 2081-2100

Farm production regions	Area evaluated (km ²)	Recent <i>SA</i> (%)	SSP126 <i>SA</i> (%)	SSP370 <i>SA</i> (%)	SSP585 <i>SA</i> (%)
Appalachian	474473	22.13	17.07	27.31	32.43
Corn Belt	385758	69.74	60.51	73.57	74.22
Delta	90650	29.46	45.85	67.90	71.39
Lake	243344	77.3	67.83	80.46	82.91
Mountain	1724074	73.54	61.82	76.81	79.44
Northeast	180324	34.49	21.45	34.09	42.47
Northern Plains	718725	94.04	84.01	92.64	92.95
Pacific	516584	71.19	73.94	84.08	85.65
Southeast	416438	12.36	39.52	58.6	59.38
Southern Plains	621597	62.68	74.79	87.40	89.45

Note: *SA* = Suitable Areas (*classes* = 1,2,3)

Although the Northern Plains have the highest proportion of suitable areas under all scenarios, the region is projected to experience a marginal reduction in suitable areas by the end of the century (Table 3). For example, the region has about 94.04% of the evaluated land to be suitable for BDM application, this is expected to reduce by 10.03%, 1.4%, and 1.09% under SSP126, SSP370, and SSP585, respectively, by 2100 (Table 3; Fig.3). The marginal decline in suitable areas is due to the projected decrease in temperatures in the upper most states (the Dakotas) within the Northern Plains (SI Fig. 6). The fall in temperatures makes the upper part of

the Northern Plains colder than required to obtain optimal agronomic benefits of BDM application.

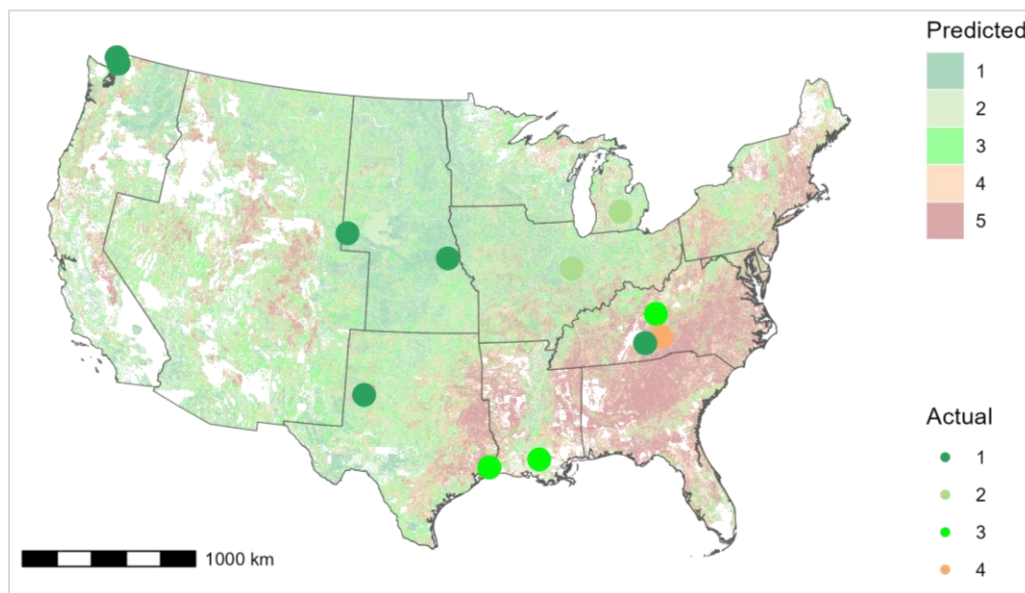
4.3.3 Sensitivity Analysis and Validation

Although the suitability of BDM application in agriculture is influenced by properties of the mulch materials (e.g., tensile strength, color, and feedstocks), environmental conditions, and the soil microbes, our modeling approach did not consider individual mulch properties. For instance, the climate, soil attributes, and microbes required for mulches with different thickness might differ. Taking this into account could have the potential to improve the model robustness and practicality. While we acknowledge this limitation, we do not think this significantly affects our results and findings we observed. Thus, given the generality of BDM reported in literature (Madin et al., 2024), we feel that the range of values used in our model to assess each suitability class is wide enough to capture variability among the diverse mulches. The use of a range of benchmark values (Table 2 and SI Table 1), instead of single point values, creates room for our modeling approach to capture possible differences in climate, soil nutrient, and microbe requirement among different BDM. In addition, the data used to construct our models is imperfect. The GGSURGO soil data lacks complete coverage across the entire U.S. and PRISM and WorldClim are known to have higher prediction error in remote areas, high-elevation areas, rain shadows, and dry areas (Jiang et al., 2018; Poggio et al., 2018; F. Zhang et al., 2023). For the case of PRISM and WorldClim the limitations identified are systematic and similarly affect both datasets, suggesting that comparative analyses (e.g., trends over time) remain robust.

To address data and model sufficiency we assessed our model prediction robustness with data from twenty published field experimental trials (SI Table 3) of BDM as compiled by Madin et al. (2024). The results indicate that our model performed well in predicting the biophysical

suitability sites for BDM application across conterminous U.S. (Fig. 6). Thus, from Fig. 6, it could be noted that highly suitable areas (indicated by deep green bubbles) based on the field data correlate well with sites predicted by our model to be highly suitable for BDM application. Specifically, results of experimental field trial at Lincoln, Nebraska indicating ideal degradation conditions for BDM application overlaps with areas predicted to be highly suitable by our model (Samuelson et al., 2022). Field trial of BDM at Urbana, Illinois reported effective agronomic benefits, which overlapped with our model predicted suitable location (Wortman et al., 2016). Also, a study conducted by Hayes et al. (2017) at Knoxville, Tennessee observed limited agronomic effects and rapid degradation of BDM because of excess rainfall, which overlapped with site predicted to be unsuitable by our model. Overall, the confusion matrix test (F1- score) indicated model suitability sites prediction accuracy of 76.9%. The individual class prediction accuracy was 70% for highly suitable class, 53.1% for suitable class, 71.9% for moderately suitable class, and 91.7% for unsuitable class.

Figure 4.6. Model prediction accuracy assessment under recent (2001- 2020) conditions



Lastly, we further assessed our model sensitivity to variations in the class cut-off values. We ran our model iteratively, first increasing each class cut-off values (width) by 5% and 10%, and then decreasing it by 5% and 10%. The assessment result showed that the predicted areas within each of the classes did not change significantly if the class widths were varied by plus 5% or minus 5% (SI Fig. 5a). However, the model showed sensitivity to larger variations in cut-off values when the class width of input criteria was changed by plus or minus 10%. Among all the input criteria, precipitation, maximum temperature, soil texture (silt percentage), and soil pH were the main input criteria that significantly changed the percentage of predicted suitability areas when input criteria class widths were varied by 10% (SI Fig. 5b). Therefore, careful attention is needed when setting class widths, as they may lead to significant variations in results.

4.4. Discussion and Conclusions

In response to increasing microplastic pollution from plastic mulch application and the need to mitigate and adapt to global environmental challenges, recent studies have made progress on developing more sustainable options like BDM (Madin et al., 2024). The potential for BDM to help farmers adapt to climate risks has received much attention but most of the research remains focused on present and past conditions with little consideration of future scenarios (Mao et al., 2021; Reilly et al., 2003; Woods, 2012). Adoption of sustainable agriculture practices such as BDM among farmers has the potential to directly contribute to the reduction and reversal of global environmental degradation (FAO, 1989), efficient resource use and natural resources conservation without sacrificing yield levels (Kassie et al., 2013a; Morris et al., 2007), and the realization of multiple SDGs (Piñeiro et al., 2020). While there are many factors that influence adoption decisions, biophysical suitability is a major constraint with strong implications for the utilization of BDM. As such, this study assessed the biophysical suitability of BDM under recent

and future scenarios through the products' ability to provide agronomic benefits for crop production and degrade within desired or regulatory determined time limits across conterminous U.S.

The results showed that roughly 16% (equivalence to 868,110 km²) of agricultural lands in the coterminous U.S. is highly suitable for BDM application nationwide under recent past conditions (Fig. 5). Locations categorized as highly suitable were characterized by the presence of drier and hotter climate conditions alongside optimal agricultural soil (SI Fig. 6). This result is consistent with several experimental field studies (Hayes et al., 2017; Madin et al., 2024; Samuelson et al., 2022; Tofanelli & Wortman, 2020). For example, Hayes et al. (2017) found greater positive agronomic benefits of BDM in experimental site at Mount Vernon, WA compared to that at Knoxville, TN because the field at Knoxville experienced much more abundant and frequent rainfall than that at Mount Vernon. This is also consistent with other findings showing that field trials conducted in global biomes associated with hot summer, arid, and or humid climate conditions were more likely to report positive effects of BDM (Madin et al., 2024). In addition, soil attributes such as the presence of silt and loamy soils and pH between 6.2 to 7.5 are found to be associated with reported optimum benefits of BDM application (Samuelson et al., 2022; Suzuki et al., 2013).

Our analyses indicate that under recent past conditions, the Northern Plains, Lake, Pacific, and Mountains farm production regions have the largest proportion of areas that are moderately to highly suitable for BDM applications (Table 3). The Northern Plains have the highest percentage, 90%, representing a total land area of 675,889 km² suitable for BDM followed by the Lake Region with 77%. These four regions contain the largest percent of farms (53%) and production value (59%) in the U.S. (USDA, 2023). General cash grain crops like

corn, wheat, and sorghum as well as high value fruits, vegetables, nursery, and specialty crops are predominantly grown within these regions (USDA, 2015, 2023). The general biophysical suitability of these crop production areas present a great opportunity for adoption and utilization of BDM among farmers (Goldberger et al., 2015; Velandia, Smith, et al., 2019). Aside from the agriculture nature of the regions, studies have also found these regions to be associated with climate variabilities [i.e., droughts, heat stress] (Boyer et al., 2013; Brown et al., 2008; Lu et al., 2020), which require adoption of innovative practices such as BDM to conserve soil moisture and moderate soil temperature.

However, we found that the Appalachian, Delta, Southeast, and Northeast farm production regions were largely unsuitable for BDM application in recent past conditions. The unsuitable nature of these regions is mainly due to non-agriculture landuse, lower temperatures, and higher precipitation experienced within the temperate and subtropical climate zones. For example, prior work has documented that farmers expressed concerns about unpredictable degradation across various sites, with those in Tennessee, located in the Appalachian region, being particularly worried about faster degradation (Goldberger et al., 2015). While these regions are largely unsuitable, for BDM some parts of the regions are sensitive to drought and present a challenge for adaptation under recent past conditions (Lu et al., 2020).

We observed an overall reduction in the total area projected to be moderately to highly suitable for BDM applications at the national scale under a more sustainable world scenario (SSP126) up to the end of the century. Thus, around 60% (i.e., 3,197,932 km²) of the total assessed area will be moderate to highly suitable under SSP126 by 2100 compared to about 62% in recent past conditions (Fig. 3-5). Predicted suitable area under SSP126 was also less than the suitable area predicted for the higher emission scenarios (SSP370 and SSP585). These results are

consistent with country-level projections suggesting possible improvement in conditions favorable for agriculture productivity requiring less adaptation efforts if the world take the path of the more sustainable scenario (Bond & Scott, 2022; Nazarenko et al., 2022). Projected suitability under SSP126 within most of the farm production regions is consistent with the national spatial pattern (Table 3). However, the southern parts of the Pacific, Mountains, Southern Plains, Delta, and Southeast region are estimated to experience increased suitability under SSP126 at the end of the century compared to the recent past period (Fig. 4). This finding is consistent with Hejazi et al. (2015)'s results, which suggest that potential reductions in water stress under a more sustainable scenario (SSP126) may not lead to improved conditions in certain parts of these regions.

The analysis indicates that the proportion of sites estimated to be moderately to highly suitable under SSP370 will increase relative to the recent past conditions and SSP126 up to the end of the century. However, compared to the SSP585 scenario, the SSP370 scenario will have slightly lower proportion of areas projected to be moderately to highly suitable for BDM application across the conterminous U.S. In general, the results suggest that if the world takes the path of SSP585 where there is fossil-fuel driven development resulting in large challenges to mitigation but increased need for adaptation, there would be more urgent need for BDM application in most areas to maintain or enhance crop production in the future. Thus, areas categorized as moderately to highly suitable will increase to about 75% (4,040,794 km²) under SSP585 by 2100 compared to 62% in the recent past conditions. Specifically, farm production regions including the Corn Belt, Delta, Southeast, Southern Plains, and Pacific regions are projected to experience the highest increase in areas that would benefit from BDM adoption under SSP585 by 2100. This is consistent with a study of the Southern Plains that predicted

increased future climate risks within the region, which will require adoption of more sustainable practices (Reilly et al., 2003). More recent studies in the plains and Pacific region projected severe climate risks (i.e., prolong droughts) that will likely affect surface waterbodies and soil moisture availability for effective crop production (Bond & Scott, 2022; Hejazi et al., 2015; Udall & Overpeck, 2017). The aquifer water that these regions rely on for irrigation to adapt to climate variability is also reported to be severely depleted (Boyer et al., 2013; Scanlon et al., 2012), making soil moisture conservation practices like BDM application imperative under SSP585.

The observed contrasting trends of BDM biophysical suitability under different climate scenarios underscore the possible effects of emissions mitigation and climate adaptation efforts on agricultural productivity. Specifically, the reduction in suitable areas under SSP126 demonstrates that lower emissions or mitigation efforts might reduce the need for innovations such as BDM in the future. This finding reaffirms existing knowledge in literature for more climate change mitigating farming (Lal et al., 2011; Niles et al., 2018; Smith & Olesen, 2010). It further raises research questions on the balance between mitigation efforts and agricultural adaptation strategies. The results also have significant implications on regional agriculture sustainability policies and future BDM development. For example, the increase in projected suitable areas within the Delta, Southeast, and Southern Plains irrespective of the scenario suggests that the use of BDM may help sustain agriculture in such regions. Policymakers would need to target these regions with specific interventions including farmer participatory trials to promote BDM use, assess its effectiveness, and develop improved BDM technologies. On the other hand, the observed limited suitable areas in regions such as the Appalachian and Northeast as well as reduced projected suitability in Northern Plains point to the need for regional-context

specific product development. The development of context specific products in Northern Plains and Appalachian regions is particularly important as these regions are found to be more sensitive to droughts (Lu et al., 2020) and water deficit (Gleick, 2010; Hejazi et al., 2015), and are vital producers of specialty crops noted for plastic mulch application (Velandia et al., 2020; Velandia, Galinato, et al., 2019). Whereas most of the BDM products currently perform better in hotter-drier climate conditions (Madin et al., 2024), the Appalachian regions has wetter condition while the upper part of the Northern Plains is projected to be colder and drier (SI Fig. 6).

Although evidence has shown that BDM rarely provides agronomic benefits over plastic mulches (Madin et al., 2024; Tofanelli & Wortman, 2020; Wang et al., 2019), information on potential degradation and assurance on more sustainable end-of-life management of BDM could greatly influence adoption among farmers (Dentzman & Goldberger, 2020; Ghimire et al., 2020; Warnick et al., 2006). Hence, the suitability analysis conducted in this study contributes to identification of optimum sites to enhance farmers confidence in the potentials of BDM performance and degradation on their farm, which is critical to improving on-farm adoption of BDM as a more sustainable alternative to plastic mulch. To build on our results and model, we recommend that future research explore modeling approaches that incorporate the interactive effects of mulch type and biophysical environmental factors.

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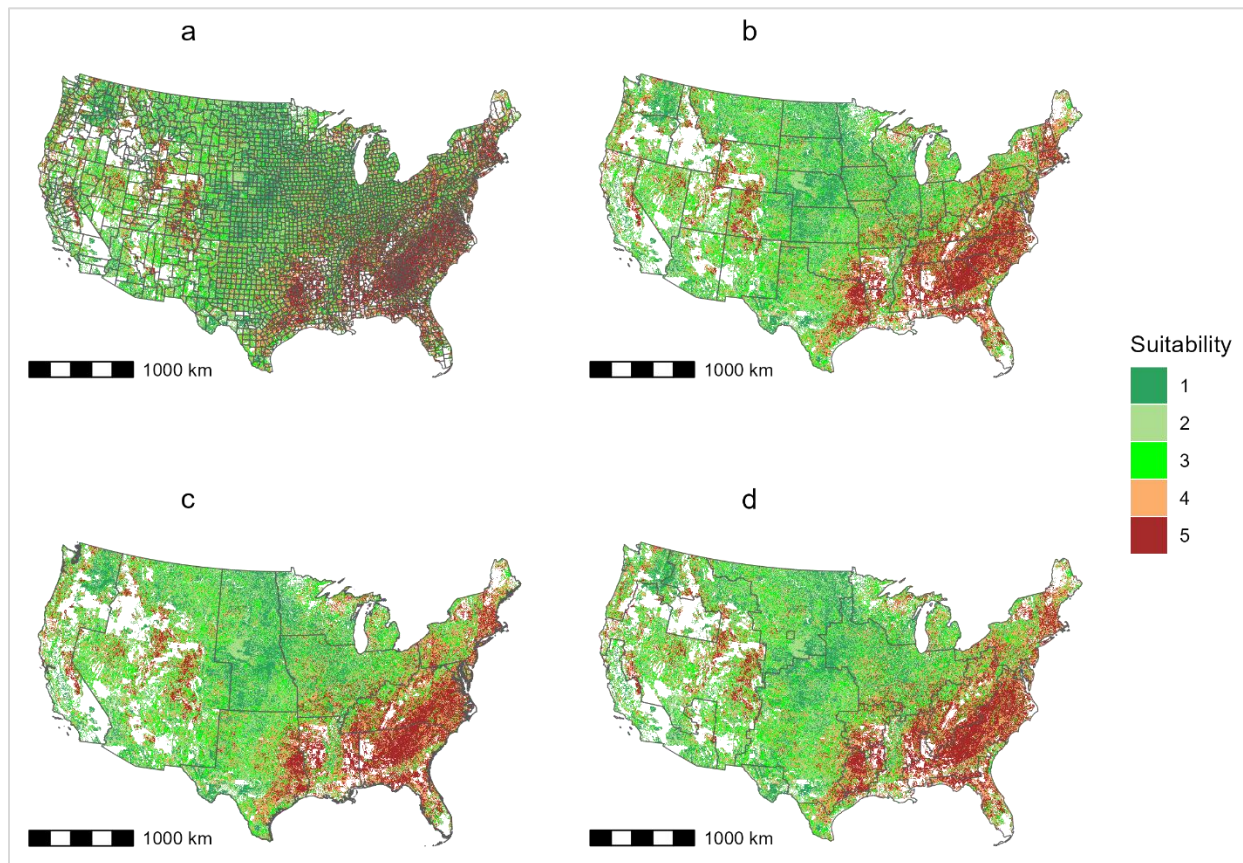
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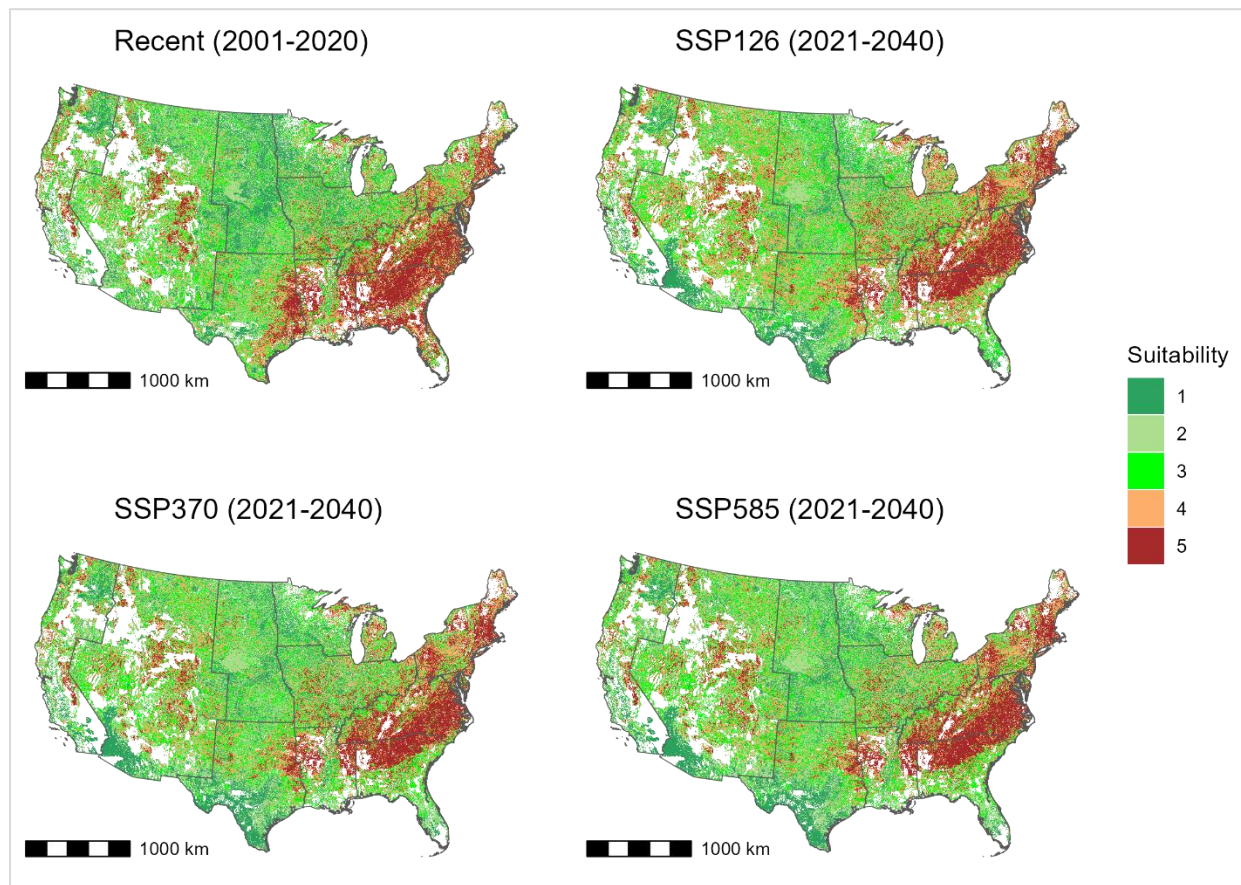
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Appendix C - Chapter 4 Supplementary Information

Appendix Figure 4.1. Recent past (2001-2020) biophysical suitability of BDM under each (a) Counties (b) States (c) Farm Production Regions, and (d) Farm Resource Regions in the conterminous U.S.

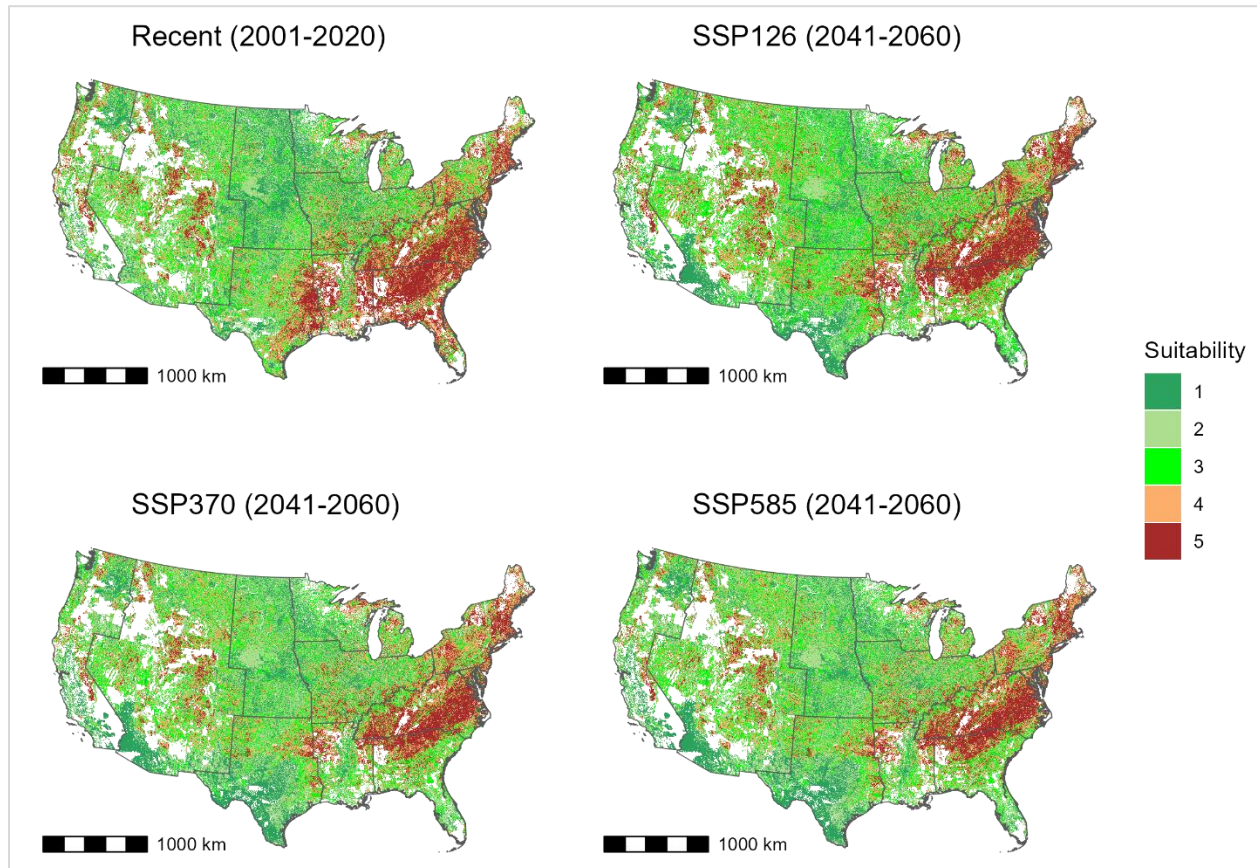


Appendix Figure 4.2. Projected (2021-2040) biophysical suitability of BDM under farm production regions in the conterminous U.S.

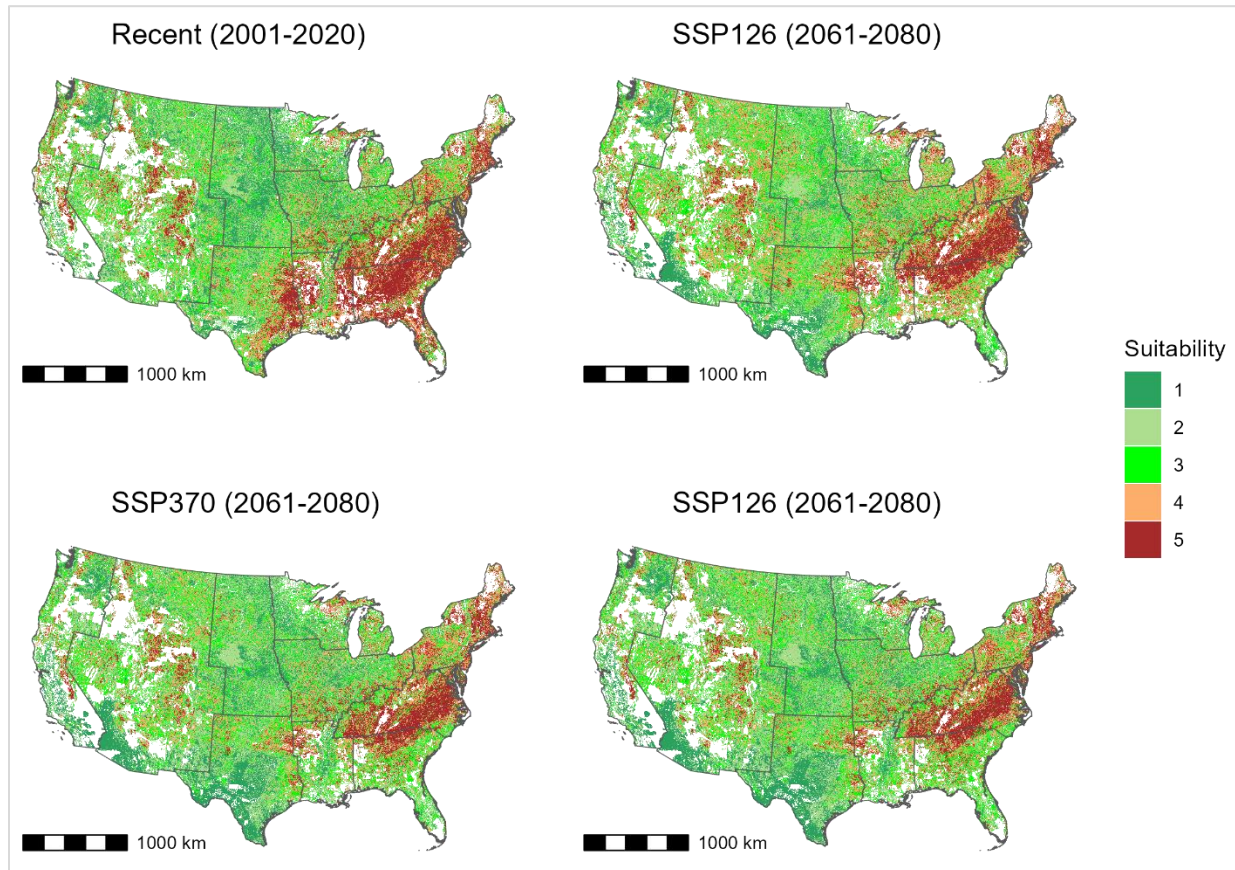


Note: 1= highly suitable, 2= suitable, 3= moderately suitable, 4= unsuitable, and 5= highly unsuitable.

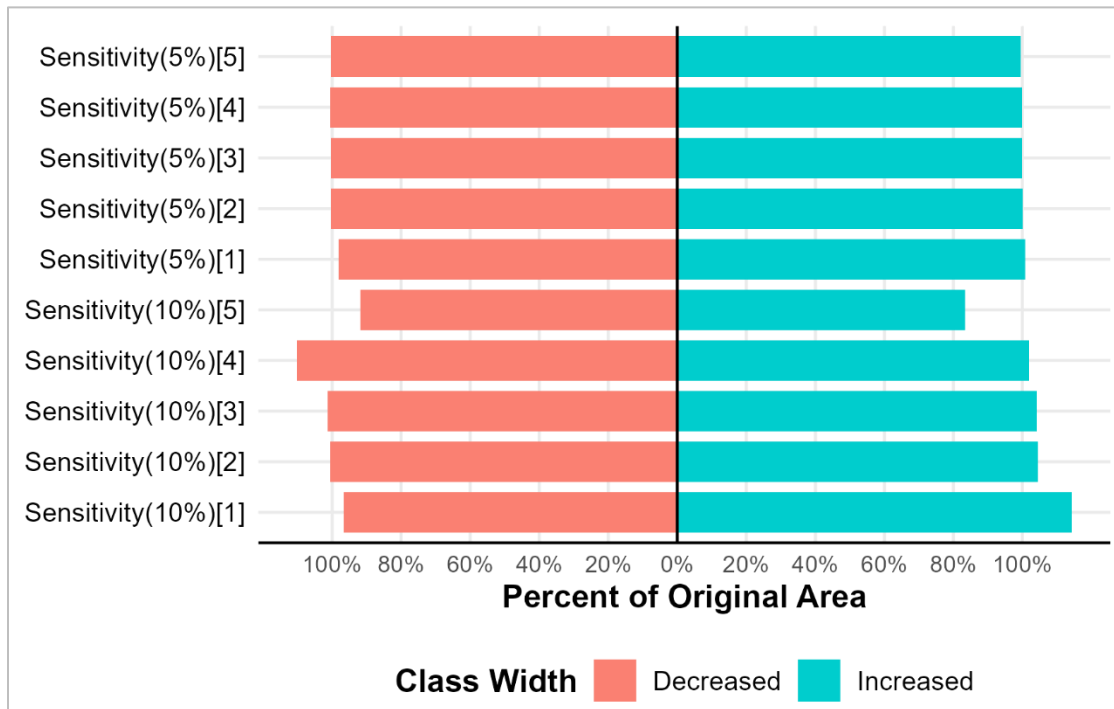
Appendix Figure 4.3. Projected (2041-2060) biophysical suitability of BDM under farm production regions in the conterminous U.S.



Appendix Figure 4.4. Projected (2061-2080) biophysical suitability of BDM under farm production regions in the conterminous U.S.

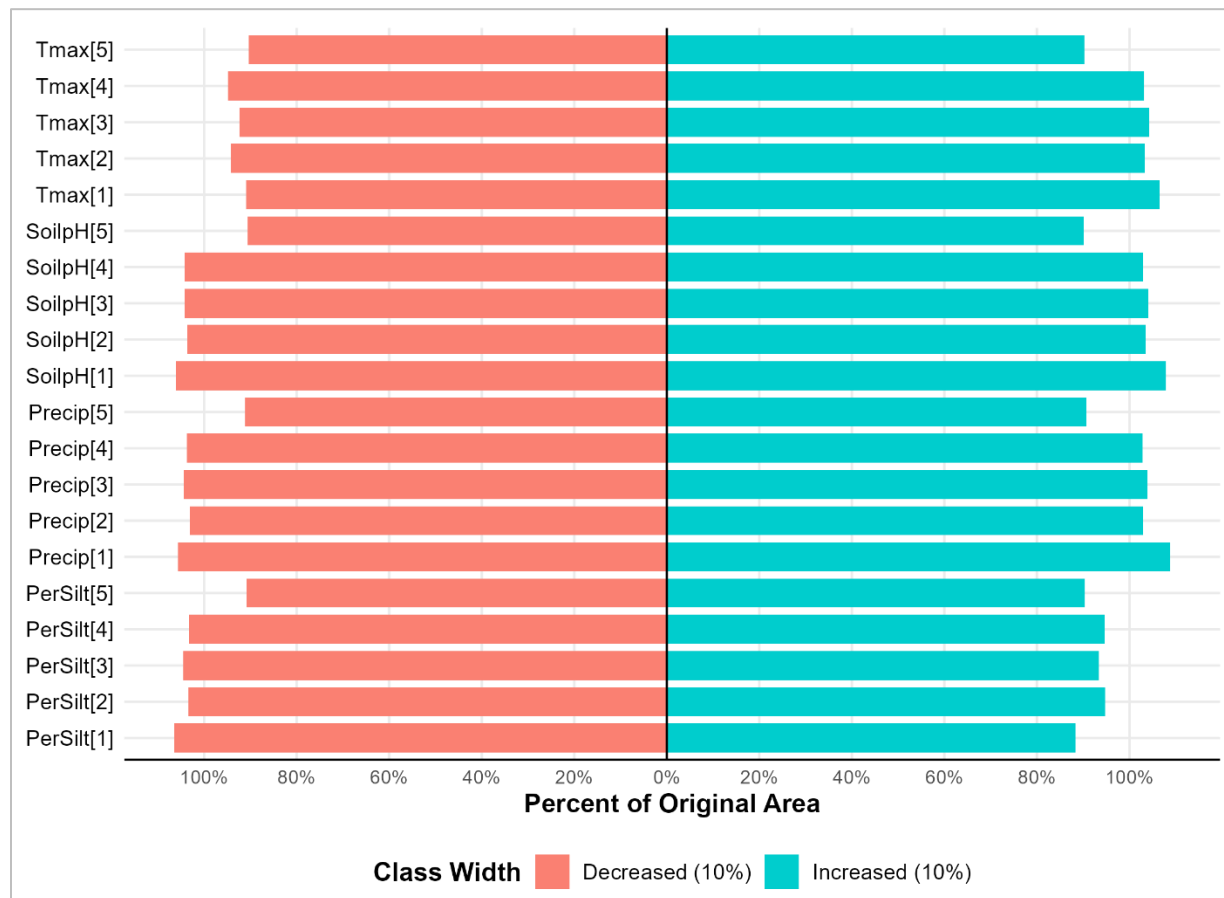


Appendix Figure 4.5. Model sensitivity to class width change and variability within suitability classes.



Note: The original percentage is 100%, a value more than 100% indicates an increase in the area under the given suitability class and vice versa. Sensitivity(5%)= class width increased by 5% or decreased by 5%. Sensitivity(10%)= class width increased by 10% or decreased by 10%. [1] = highly suitable, [2]= suitable, [3]= moderately suitable, [4]= unsuitable, and [5]= highly unsuitable.

Appendix Figure 4.6. Model sensitivity to class width changed by 10% and variability within suitability classes for most significant input criteria.

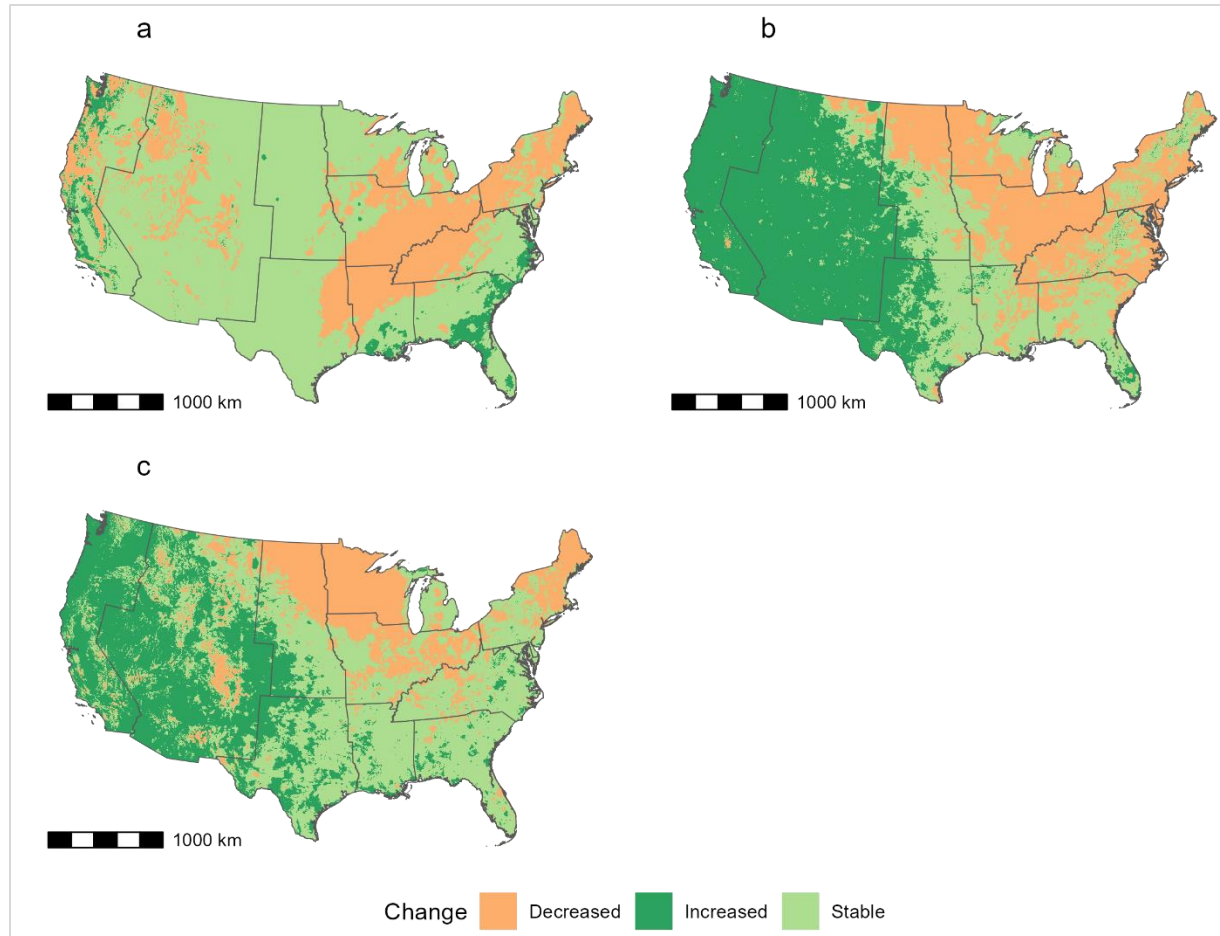


Note: The original percentage is 100%, a value more than 100% indicates an increase in the area under the given suitability class and vice versa. Tmax= Maximum temperature, SoilpH= Soil pH level, Precip= precipitation, PerSilt= Percent of silt. [1] = highly suitable, [2]= suitable, [3]= moderately suitable, [4]= unsuitable, and [5]= highly unsuitable.

Further explanation of Appendix Figure 4.5 & 4.6: The 5% and 10% thresholds were chosen because the ratio of the input criteria ranges to their standard deviation varied between 0.05 and 0.1. The variations in suitability areas were much smaller among the unsuitable classes compared to the suitable classes. For instance, the area of highly suitable class changed by 1.83% when the width of input criteria was decreased by 5% while highly unsuitable class only changed by about 0.34% when the class width of input criteria was changed by plus 10%, the area predicted as highly suitable increased by 14.26% while a changed by minus 10% decreased highly suitable class by 3.71% (SI Fig. 5a). Specifically, when only maximum temperature class widths were increased by 10%, it resulted in a significant increase in the percentage of areas under each suitability class except for the highly suitable and highly unsuitable (SI Fig. 5b). On the other hand, a 10% reduction in only silt percentage class widths led to a significant decrease in the percentage of areas under each class except for the highly unsuitable classes (SI Fig. 5b). These results imply that the model is robust and reliable when subjected to small variations in class

widths, but larger adjustments beyond 10% error margin could significantly affect the predicted areas, especially in the suitable classes.

Appendix Figure 4.7. Projected change in (a) precipitation (b) maximum temperature, (c) minimum temperature between the recent past conditions and projected climate conditions at the end of the century.



Appendix Table 4.1. Input variables classification scheme

Input Criteria	Classification scheme under the Suitability Classes				
	1	2	3	4	5
Precipitation	0-30	31- 63	64- 100	101- 200	>200
Max. temperature	16- 26	27- 34	5- 15	35- 43	<5
Min. temperature	3- 13	14- 24	-7 -2	26- 36	<-7
Solar radiance	10- 20	0- 9	21- 31	32- 40	>40
Available soil water supply (AWS)	0- 7.50	7.6- 11	11.10- 14.20	14.13- 20	>20
Soil Ph	6.2- 7.2	7.3- 8.2	5.5- 6.1	>8.2	<5.5
Soil Nutrients (CEC)	>40	20-40	10-20	4-10	<4
Soil Texture (%Clay)	10- 20	20- 30	30- 40	40- 70	70- 100
Soil Texture (%Silt)	70- 100	40- 70	30- 40	20- 30	0- 20
Irrigated land	Drylands	Drylands	Drylands	NA	NA
Land Use/cover	Cropland, fallow	Cropland, Grassland/ Pasture	Cropland, Grassland/ Pasture	NA	NA

Note: 1= highly suitable, 2= suitable, 3= moderately suitable, 4= unsuitable, and 5= highly unsuitable.

Appendix Table 4.2. Biophysical suitability classes

Category	Explanation
(1) Highly suitable [HS]	Biophysical attributes These are farmlands or potential agriculture areas where BDM is expected to degrade by at least 95% after 24 months of application, which is well within desired growing season and standard requirements (Briassoulis & Degli Innocenti, 2017; Kopitar et al., 2022). Agronomic conditions Agriculture farmlands where vegetables, fruits, and forbs crops are grown would be most ideal for BDM application. These areas are expected to generate the maximum desirable agronomic effects of BDM application.
(2) Suitable [S]	Biophysical attributes These are farmlands or potential agriculture areas where BDM is expected to degrade by at least 90% but less than 95% after 24 months of application, which is within desired growing season and standard requirements. Agronomic conditions Agriculture farmlands where graminoid crops are grown would be more suitable for BDM application. These areas are expected to produce more desirable agronomic effects of BDM application.
(3) Moderately suitable [MS]	Biophysical attributes These are farmlands or potential agriculture areas where BDM is expected to degrade by 60% in 4 months but rapid than 90% after 24 months of application due to limiting biophysical and soil characteristics. Agronomic conditions Agriculture land use or potential farmlands where crops other than above could be grown would be suitable for BDM application. These areas are expected to produce moderate agronomic effects of BDM application.
(4) Unsuitable [U]	Biophysical attributes These are farmlands where BDM will either rapidly degrade by the middle of the growing season or will not degrade by 90% after 24 months of application due to limiting biophysical and soil characteristics. Agronomic conditions

	Farmers in marginal farmlands where it would require extra cost to grow crops will unlikely use BDM (Fleskens et al., 2014; Si et al., 2021a). These is expected to produce minimal to no desirable agronomic effects of BDM application.
(5) Highly unsuitable [HU]	These are marginal areas unsuitable for agriculture or protected areas not intended for agricultural use.

Appendix Table 4.3. Published field experimental trials used for validation

Authors	Trial Year	Latitude	Longitude	Reference (DOI)
Anunciado et al.	2017	48°43'24"N	122°39'09" W	https://doi.org/10.21273/HORTTECH04922-21
Anunciado et al.	2018	48°43'24"N	122°39'09" W	https://doi.org/10.21273/HORTTECH04922-22
Anunciado et al.	2017	35°52'52"N	83°55'27" W	https://doi.org/10.21273/HORTTECH04922-23
Anunciado et al.	2018	35°52'52"N	83°55'27" W	https://doi.org/10.21273/HORTTECH04922-24
Shogren and Hochmuth	2000	37°17'50" N	82°59'07" W	https://doi.org/10.21273/HORTSCI.39.7.1588
Kijchavengkul et al.	2007	42°44'0" N	84°29'0" W	https://doi.org/10.1016/j.chemosphere.2007.10.074
Griffin-LaHue et al.	2020	48°26'22.66" N	122°23'09.71" W	https://doi.org/10.1016/j.scitotenv.2021.150238
Fontenot et al.	2020	30°5'9.78" N	94°6'6.66" W	https://doi.org/10.3390/horticulturae7090290
Fontenot et al.	2020	30°24'32.10" N	91°6'21.01" W	https://doi.org/10.3390/horticulturae7090291
Hayes et al.	2015	48°26'24" N	122°23'18" W	http://dx.doi.org/10.1016/j.polymertesting.2017.07.027
Hayes et al.	2015	36°06'18" N	82°50'43" W	http://dx.doi.org/10.1016/j.polymertesting.2017.07.028
Saglam et al.	2015	48°26'22.66" N	122°23'09.71" W	https://doi.org/10.1016/j.agwat.2017.08.011
Sintim et al.	2020	48°43'24"N	122°39'09" W	https://doi.org/10.1016/j.scitotenv.2020.138668
Sintim et al.	2020	35°52'52"N	83°55'27" W	https://doi.org/10.1016/j.scitotenv.2020.138669
Li et al.	2010	48°26'13.42" N	122°23'27.15" W	https://doi.org/10.1080/21683565.2014.884515
Li et al.	2010	35°52'52"N	83°55'27" W	https://doi.org/10.1080/21683565.2014.884516
Li et al.	2010	33°41'38"N	101°49'51" W	https://doi.org/10.1080/21683565.2014.884517
Samuelson et al.	2017	41°53'33.4" N	103°40'54.0" W	https://doi.org/10.1017/S1742170521000405
Samuelson et al.	2017	40°50'13.2" N	96°39'50.4" W	https://doi.org/10.1017/S1742170521000405
Wortman et al.	2013	40.08°N	88.22°W	https://doi.org/10.21273/HORTTECH.26.2.148

Chapter 5 - Synthesis and Conclusion

6.1 Introduction

This concluding chapter serves a three-fold purpose. First, through a synthesis of each manuscript findings, I put the results of the studies into direct conversation with one another, drawing connections and comparisons among cross-cutting issues. Secondly, I describe what the key findings might mean for scholars, policy makers, practitioners or producers, agricultural scientists, and concerned citizens seeking a better understanding of agriculture and sustainable food systems in U.S. and the world at large. I provide practical suggestions for addressing some of the major challenges identified in the manuscripts. Finally, I specify the contributions of the dissertation to research in human geography more broadly, and geographies of sustainable agriculture most specifically. To start the synthesis analysis, I begin by revisiting the interconnections among the integrated manuscripts that serve as the basis of this dissertation.

6.2 Synthesis, Contributions, and Future Research Directions

This dissertation comprehensively examines BDM from multiple perspectives including factors related to its effectiveness on agronomic factors, adoption, biophysical suitability, and resistance to change in suitable area under future climate. Although focused on the farm production regions within conterminous U.S., this research has theoretical and practical significance that are applicable in other global agricultural systems. First, Chapter 2 establishes the basis for analysis by reviewing global studies on BDM use, covering its agronomic benefits compared to conventional plastic or no-mulch and identified key contextual factors (i.e., climate and soil conditions) influencing its performance and degradation. This chapter provides an

overview of the current state of BDM studies in agricultural settings and sets the stage for later analysis by identifying key input variables required for GIS-based MCE analysis in Chapter 4.

Chapter 3 shifts focus into the broader context of adopting sustainable agriculture innovations by exploring key factors influencing farmers' decisions. This chapter of the dissertation identifies socio-economic and biophysical factors driving the adoption of sustainable innovations, emphasizing rural contexts where access to credit, education, and social networks are crucial. This chapter highlights how factors such as drought occurrence, education attainment, access to credit, and gender dynamics affect the uptake of sustainable innovations including BDM. The results provide a critical link between agronomic feasibility presented in Chapter 2 and real-world farmer decision-making, re-emphasizing the need to understand both biophysical and socioeconomic constraints to adoption.

In Chapter 4, the research methodology shifts from a literature-based review to a spatial modeling approach and assessed BDM's biophysical suitability across the U.S. under recent and future climate scenarios. The findings reveal distinct spatial patterns with regions such as the Northern Plains and Pacific emerging as highly suitable areas while others like the Appalachian and Northeast regions were predominantly unsuitable due to soil and climate constraints. Thus, BDM suitability across U.S. production regions suggests that hotter, arid zones (e.g., the Plains and Pacific) are ideal sites while colder and wetter regions (e.g., Appalachia) are unfavorable. These results reaffirm how BDM effectiveness is shaped by contextual and climate conditions dependencies identified in Chapter 2.

This dissertation makes significant contributions to understanding BDM suitability and adoption within the broader framework of sustainable agriculture. For example, Chapter 2 makes

empirical contributions to literature by identifying specific biophysical factors influencing BDM suitability. Unique biophysical factors influencing site suitability of specific sustainable innovations such as BDM are currently limited in existing reviews and meta-analysis as most of the reviews focus primarily on farmers' socio-economic characteristics (e.g., Begho et al., 2022; Piñeiro et al., 2020; Ruzzante et al., 2021). The identification of the specific biophysical conditions related to BDM agronomic effectiveness and degradation helped to establish benchmark values for key variables, which were previously unknown (Madin et al., 2025).

Chapter 3 synthesizes the factors influencing innovations adoption decision including providing information on direction and context-specific details. Although there are studies that have reviewed empirical research on factors influencing farmers' adoption decisions (e.g., Foguesatto et al., 2020; Ruzzante et al., 2021), the results are often too general, dispersed, and disconnected. For example, it is evidence from prior reviews that stronger social networks, higher educational levels, and income are enabling factors in adopting innovations among farmers, while land tenure arrangement, floods, and limited access to credit are barriers (Begho et al., 2022; Prokopy et al., 2019). But these are normally reported without specificity to a given practice (i.e., BDM or organic fertilizer) or across the urban-rural divide. Thus, it is unknown if the enabling and barrier factors would remain same among all practices and across space. Consequently, the results of this chapter contribute substantially to filling this scholarly gap. For instance, the synthesized results on rural areas across the globe suggest that the effects of gender, education, and adequate access to credit on farmers' adoption are stronger in more rural or less developed regions. The uptake of farm management-based sustainable practices was found to be more positively correlated with education whereas capital embodied practices were not. Also, most adoption studies rely on binary models that classify farmers simply as adopters or non-

adopters, overlooking the continuous and multivariate nature of adoption decision-making (Rogers, 2003). Hence, such models often miss important contextual factors, including why farmers may discontinue or readopt practices, indicative of the need for alternative approaches like continuous path-dependent analyses.

Chapter 4 presents an assessment of current and future biophysical sites suitability of BDM in a spatially explicit extent across the contiguous U.S. The development and adoption of sustainable innovations have received considerable amounts of research, but future scenarios of suitability remain limited (Mao et al., 2021; Woods, 2012) and assessment are often conducted at field scale (Deng et al., 2019; Ennaji et al., 2018; Kutlu et al., 2021). Therefore, by building upon the existing studies (Deng et al., 2019; Ennaji et al., 2018; Kutlu et al., 2021), alongside Talukder et al. (2018) and Zabihi et al. (2015), this chapter provides human geographers with a valuable new perspective of thinking about transition to sustainable food systems. Moreover, the GIS-based suitability modeling introduces a crucial methodological contribution that allows for scenario-driven predictions of BDM applicability in agriculture. This approach has the potential to strengthen long-term agricultural planning and informed adaptive policy measures.

The findings from this dissertation offer several possibilities for future work. For example, although my systematic review of BDM effectiveness compared to plastic mulch provided useful qualitative information, meta-analysis on evidence of the exact magnitude of these differences and the extent of variability across trials would be highly relevant to agricultural scientists and policymakers. Besides, while dichotomous analysis of factors influencing innovation adoption is valuable, its predominance in literature comes with limitations of binary models as indicated in Chapter 3. As such, future research should explore adoption as a continuous multistage process using path-dependent analysis to help us understand how farmers

transition from non-adopters to adopters and whether they discontinue or re-adopt if they discontinue.

Given that GIS-based Fuzzy model utilized in Chapter 4 does not explicitly consider interaction terms of the input variables, I recommend that future research explore other modeling approaches that incorporate the interactive effects of crop type, mulch type, and biophysical environmental factors. Future work should also investigate how different soil types and climates influence microbial-driven degradation rates, particularly, in wetter and colder regions where BDM appears to be predominantly unsuitable. While Chapter 4 focused solely on the biophysical suitability for adoption, further research is needed to assess the scenarios of spatial adoption likelihood by incorporating the socio-economic factors identified in Chapter 3, which are also critical in shaping farmers' decision-making. Incorporating socioeconomic factors into spatial adoption models will require future research to project key socioeconomic variables (consistent with SSPs) that influence farmers' adoption decisions.

In the context of the geographies of sustainable agriculture studies, innovations adoption research could further be significantly enriched through a broader understanding of the following. Since this dissertation results suggest that BDM suitability varies across different climate pathways, there is the need to explore the trade-offs between mitigation strategies (reducing emissions) and adaptation strategies (i.e., adopting sustainable innovations). This would help examine whether BDM should be positioned as a long-term solution or a transitional adaptation tool in specific regions. Moreover, Chapter 2 revealed economic and social barriers to adoption, however, further research testing the influence of specific interventions such as farmer field schools and participatory trials on BDM uptake will offer added insights. Conducting similar assessments presented in Chapter 4 within other agricultural regions, particularly in

developing countries where plastic mulch application is growing (Kiran & Kunal, 2024; Shah & Wu, 2020), would open scope for additional contributions.

6.3 Conclusion

This dissertation makes a significant contribution to understanding BDM application within the broader framework of sustainable agriculture. The results present significant implications for the geographies of sustainable agriculture through providing a spatially explicit understanding of how environmental factors contribute to shaping effectiveness or suitability of BDM as a sustainable innovation and defies predominantly aspatial approaches. Thus, the results of Chapter 4 clearly showed that BDM uptake is not only based on socio-economic context but also mediated by place-based biophysical conditions. The findings reiterate that sustainable agricultural innovations are not universally applicable but are highly dependent on regional biophysical conditions and underline the importance of place-based agricultural strategies that consider local environmental conditions when promoting sustainable practices (Allison & Hobbs, 2004; Pawera et al., 2024; Tittonell et al., 2016). These present direct policy implications for sustainable agricultural planning at local, regional, and national scales.

The research offers crucial perspectives to human-environment interaction and sustainable food systems transition. The spatial analysis of biophysical factors aligns with the core concerns of the subfield of human-environment interactions, which emphasize understanding the dynamic relationship between human and environmental systems (Dearing et al., 2006; Stern, 1993). The approach presented here challenges segregated analysis and argues for the need for multifaceted and interdisciplinary research in sustainability to connect the perspectives of the social and physical sciences. For example, Chapter 3 identifies gendered adoption patterns (e.g., male-headed households in rural areas showing higher uptake), reflecting

cultural geographies of agricultural decision-making. While Chapter 4 illustrates that under high-emission scenarios (SSP585) suitability for BDMs will expand to about 75% by 2100 driven by hotter and drier conditions, highlighting climate change as a reconfiguring force that could increase the urgency for BDM adoption. Therefore, if we fail to capture region-specific strategies that account for both biophysical feasibility and socioeconomic context, we will risk obscuring and replicating the very mechanisms through which the current rate of sustainable innovation adoption continues to remain limited.

Relatedly, this study contributes to discussions on agriculture productivity amidst climate variability by illustrating how future climate scenarios will influence the spatial dynamics of suitability and uptake of BDM as adaptation strategy. Thus, under high-emission scenarios (SSP370 and SSP585) suitable area for BDM application will increase which suggests that as climate conditions intensify, BDM could become an increasingly relevant adaptation option.

The dissertation further contributes to broader discussions on sustainable food systems transition by illustrating how innovations like BDM, which serve as alternative to plastic mulch, could eliminate microplastics pollution and support long-term agricultural sustainability. However, the GIS-based model outputs provided empirical evidence of disparities in regional suitability of BDM, suggesting uneven spatial distribution of sustainable farming opportunities. This points out possible regional disparities in transitioning away from plastic mulch. The finding raises important questions about environmental issues and equitable access to viable innovations central to the sustainability of agriculture.

This study contributes to the application of geospatial techniques in agricultural sustainability research through the use of GIS-based model for spatially explicit assessment of the suitability and adoption likelihood of BDM. The contribution is important because prior

geospatial application in sustainable agriculture suitability often focus primarily on present biophysical conditions with limited consideration of future scenarios. Thus, the use of GIS-based model alongside climate scenario projections in this study presents a unique framework for holistic agricultural sustainability assessments. Second, the application of Fuzzy Overlay analysis within GIS-based MCE allows for a probabilistic assessment of land suitability rather than relying on subjective weight-based binary classifications. This approach is particularly relevant in sustainable agriculture context where suitability is often multiclass rather than subjective binary. However, future studies could include uncertainty quantification techniques such as Monte Carlo simulations to further refine geospatial assessments. Third, the use of SSPs illustrates how geospatial applications can project future changes in agricultural land suitability under different climate scenarios to give planners, policymakers, and producers the leverage to anticipate regional shifts in innovation suitability.

Lastly, this dissertation research indicates the growing importance of high-resolution spatial datasets and remote sensing techniques for assessing agricultural sustainability at various scales. The use of high-resolution spatial datasets alongside SSPs climate projections challenge traditional land suitability models that often provide a snapshot in time. Innovation suitability is a dynamic process influenced by changing climate conditions, land management practices, and policy shifts and requires dynamic modeling approach such as the one presented in this study. But future geospatial research in agricultural sustainability should explore spatiotemporal analysis techniques such as agent-based modeling to predict real-time adoption patterns and long-term land-use changes to help track real-time changes in innovation suitability.

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