Operationalizing cultural adaptation to climate change: contemporary examples from United States agriculture

Waring, Timothy; University of Maine, Mitchell Center for Sustainability Solutions, https://orcid.org/0000-0001-7364-1130, correspondence: timothy.waring@maine.edu
Niles, Meredith; University of Vermont, Nutrition and Food Sciences
Kling, Matthew; University of Vermont, Biology
Miller, Stephanie; University of Maine, Mitchell Center for Sustainability Solutions
Hébert-Dufresne, Laurent; University of Vermont
Sabzian Papi, Hossein; University of Maine, Mitchell Center for Sustainability Solutions
Gotelli, Nicholas; University of Vermont, Biology
McGill, Brian J.; University of Maine, School of Biology and Ecology

Abstract
It has been proposed that climate adaptation research can benefit from an evolutionary approach. But related empirical research is lacking. We advance the evolutionary study of climate adaptation with two case studies from contemporary United States agriculture. First, we define 'cultural adaptation to climate change' as a mechanistic process of population-level cultural change. We argue this definition enables rigorous comparisons, yields testable hypotheses from mathematical theory, and distinguishes adaptive change, non-adaptive change, and desirable policy outcomes. Next, we develop an operational approach to identify 'cultural adaptation to climate change' based on established empirical criteria. We apply this approach to USDA data on crop choices and the use of cover crops between 2008 and 2021. We find evidence that crop choices are adapting to local trends in two separate climate variables in some regions of the US. But evidence suggests that cover cropping may be adapting more to economic incentives than climatic conditions. Further research is needed to characterize the process of cultural adaptation, particularly the routes and mechanisms of cultural transmission. Furthermore, climate adaptation policy could benefit from research on factors that differentiate regions exhibiting adaptive trends in crop choice from those that do not.

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1. Introduction

The impacts of climate change are already intense, globally distributed and projected to worsen (IPCC 2022). They pose a potentially existential threat to human societies (Kemp et al. 2022). The applied research and policy framework of 'climate adaptation' seeks to identify and accelerate the solutions to better endure a changing climate (IPCC 2022). It is presumed that numerous changes to human cultural systems will be required across the domains of technology, laws, institutions, and behaviour (McNeeley and Lazarus 2014). However, efforts to change aspects of culture and society are contentious and political. Therefore, the politics of climate change require that people understand misinformation, public opinion, and social influence in mechanistic and practical terms. For this reason, the scientific study of cultural evolution has clear value for designing effective climate adaptation policy. It has been proposed that climate adaptation research can benefit from an evolutionary approach (Brewer & Riede, 2018). And, climate adaptation research has lacked a mechanistic framework for studying adaptive change in human culture, for which the evolutionary research provides useful tools (Pisor et al. 2020, Jones et al. 2020).

The integration of the evolutionary science of culture within climate adaptation is straightforward because the two research communities view the role of human culture in adaptation to a new climate in very similar ways. Both fields see 'culture' as composed of ideas, norms and behaviours that influence human and ecological outcomes, and are iteratively spread and refined within a population. In climate adaptation research, culture is defined as all the "*learned ideas and behavior patterns that are acquired, shared, and modified by people as members of a society*" (McNeeley and Lazrus 2014). While in research on human cultural evolution, culture is defined as: "*information capable of affecting individuals' behavior that they acquire from other members of their species through teaching, imitation and other forms of social transmission*" (Richerson and Boyd 2005).

Both communities also view 'adaptation' as a process which improves the fit between human groups and their environment. In the evolutionary science of culture, 'cultural adaptation' to the environment occurs when cultural traits that benefit human survival and reproduction spread among individuals or groups (Boyd & Richerson, 1985, Henrich 2015). Similarly, 'climate adaptation' is the "*process of adjustment [by human systems] to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities*" (IPCC 2022 Report, pp. 43). Thus, the process of cultural adaptation responds to rapid or gradual changes in the environment.

Climate adaptation research sees culture as both driving and constraining adaptation to climate change in addition to factors such as individual innovation. Cultural differences in worldviews, perceptions, social relatedness between communities or stakeholder groups can hamper the success of collective adaptation outcomes (McNeeley and Lazrus 2014). The cultural history of a group can determine how its members perceive environmental change and how the group responds (Crate 2011). Consequently, society's ability to respond effectively to climate change may be limited by cultural factors and states (Adger et al. 2009). On the other hand, successful adaptations are partly determined by local culture, traditions and institutions and will often be locally specific (Crate 2009) and fit within the internal norms of the group (Few et al. 2021). Thus, efforts to accelerate adaptation to climate change must be made with an explicit understanding of their cultural context (Marks et al. 2022).

In this paper, we advance this integration and develop an operational research agenda on 'cultural adaptation to climate change'. First, we enumerate the benefits of adopting an evolutionary theory of culture in climate adaptation efforts. Next, we develop a simple conceptual framework to study cultural adaptation to climate change in humans. We then apply this framework to two case studies from contemporary agriculture in the USA.

2. The science of cultural evolution can benefit climate adaptation research

Over generations, human societies have evolved countless skills, traditions, habits, technology and sophisticated place-based knowledge that enhances our ability to thrive in diverse environments (Henrich et al., 2016). Advantageous elements of culture, such as fire use, bow hunting, animal husbandry and agriculture have helped our species spread around the world (Henrich 2015). Such *adaptive cultural traits* are the product of *cultural adaptation,* the population-level evolutionary process by which culture becomes beneficially-tailored to the local environment. Cultural adaptation is an important topic in cultural evolution research.

The science of cultural evolution is the study of cultural change in human populations (see Henrich 2015, Mesoudi 2011). Culture, as socially transmitted information, can be thought of being composed of different pieces, or cultural traits. Defining a cultural trait is a matter of practical convenience. For example, an *individual-level cultural trait* might be a unit of language (e.g., words, phonemes, phrases, stories) or aspects of behaviour (e.g., teaching practices, design patterns, musical motifs, cooperation), components of belief (e.g., narratives, values, norms), or even the adoption of technology (e.g. bicycle, handaxe, sewing machine). Human groups may likewise hold *group-level cultural traits* such as institutions (e.g. rules, positions, laws), or infrastructure (e.g. irrigation networks, water mills, nuclear power plants) (Voorhees 2022). As it is both mechanistic and population-level, the theory of cultural evolution provides a set of advantages in studying cultural adaptation for both science and application. These include (a) empirical criteria for the identification of cultural adaptation as compared to maladaptation or non-adaptive processes cultural change, (b) testable hypotheses on cultural adaptation derived from mathematical models, and (c) the conceptual and practical separation of adaptation from policy goals or beneficial outcomes for society.

First, cultural evolution provides empirical criteria for identifying cultural adaptation. Cultural change in human populations includes the same core factors of variation, selection and transmission necessary to produce adaptative evolution in genetic systems. Thus, cultural adaptation can be defined in parallel to genetic adaptation, as a population-level process which increases the functional fit of individuals to their environment. *Cultural adaptation* (as a process) occurs when individuals or groups adopt cultural traits that enable them to better survive and reproduce in their environment. To identify cultural adaptation one must establish (i) a cultural trait that (ii) benefits the individual (or group), and which is (iii) transmitted among individuals (or groups), typically because of the benefits (Mesoudi & Thornton 2018). An *adaptive cultural trait* (a product of cultural adaptation) is a trait which benefits those individuals or groups that adopt it.

In an evolutionary framework, there is no assumption of optimal or beneficial change. Moreover, in cultural evolution theory predicts that *cultural maladaptation* may often result from the same social learning mechanisms that also create adaptive outcomes (Henrich and McElreath, 2003). For example, attention-grabbing traits, such as inflammatory misinformation, often spread more rapidly and more broadly than factual information (Vosoughi et al., 2018), precisely because human social learning mechanisms favour them. Such traits are undesirable for society and could be harmful for those who adopt them. However, the dimensions of *adaptive* and *likely to evolve* are distinct. By distinguishing the adaptive value of a trait from its transmissibility, we can refine our expectation of the likelihood of and the societal benefit of cultural adaptation.

In addition, cultural adaptation needs to be distinguished from other, non-adaptive processes of cultural change, such as cultural drift, the change in frequency of a cultural trait due to random chance (Hahn and Bentley, 2003) and cultural hitchhiking, in which non-adaptive traits spread due to their association with other adaptive cultural traits (Yeh et al., 2019). In any real-world population, a mix of both adaptive and non-adaptive processes may be occurring simultaneously for individuals and groups, with important implications for both science and policy. In scientific endeavours, having consistent empirical criteria for identifying cultural adaptation can enable more rigorous cross-case comparisons. And, distinguishing adaptive processes that spread traits that help individuals in their environment from non-adaptive processes that merely spread cultural traits can be a key in good policy design.

Second, mathematical theory has provided testable hypotheses for cultural adaptation. For example, Henrich's (2004) model suggests that population size might constrain the ability of a group to achieve ongoing cultural adaptation. Models by Rogers (1988) and Enquist et al. (2007) suggest that without environmental information on adaptive value of traits, a population of social learners can rapidly spread maladaptive behaviour. And Fogarty and Kandler's (2020) model of *cultural evolutionary rescue* specifies the conditions when cultural adaptation can help an endangered human group survive a potentially deadly environmental change (Fogarty and Kandler, 2020). These models provide specific and testable hypotheses for the study of human adaptation to climate change.

Third, cultural adaptation is not always the appropriate policy goal. In fact, sometimes cultural adaptation is the problem. Cultural evolutionary science differentiates the process of adaptation (or adaptive traits) from desirable policy outcomes. For example, drilling a deeper water well can be an individually adaptive response to declining groundwater levels, but doing so will increase groundwater depletion and is not generally beneficial for society. Some farmers indicate they would pump more groundwater in drought-like conditions as a climate adaptation strategy (Haden et al. 2012). Thus, cultural adaptation in one population may sometimes be detrimental for society. For example, the uses of pesticides and fertilizers are clearly cultural adaptations for human farmers, but can cause environmental and health damage. Or, adaptation in one population may be detrimental for another population. For example, fossil fuel companies might adapt to a growing unease with their business model by influencing regulatory processes to retard or halt climate action. Therefore, the process of cultural adaptation may itself be problematic. Thus, cultural evolution highlights the importance of both using empirical criteria to identify cultural adaptation to separate the process of adaptation from the relevant societal goals and policy objectives.

Finally, there is also a growing body of empirical evolutionary research on cultural adaptation. A quantitative ethnographic study of cultural adaptation in food customs in Fiji found that food taboos often helped pregnant women avoid poisonous seafood, and that these taboos spread culturally between women (Henrich and Henrich, 2010). A historical study of lobster fishing found that territorial behaviour and conservation practices were both beneficial and spread culturally among the lobster fishing population in multiple waves (Waring and Acheson, 2018). Cultural adaptation can also spread beneficial institutions among groups. For example, a historical analysis shows that a set of organisational principles which emerged in England, helped co-operative businesses survive, and spread between co-operatives worldwide (Waring and Lange, 2019). Cultural adaptation is also important in domains such as language (Tamariz and Kirby, 2016), technology (Ziman, 2003), institutional change (Ocasio and Joseph, 2005), health interventions (Barrera Jr. et al., 2013), and archaeology (Dugmore et al., 2012; Brown et al., 2022), and genetics (Beja-Pereira et al., 2003). We contribute to this evolutionary research on cultural adaptation by first setting out an empirical framework to identify cultural adaptation to climate change. We then argue that cultural adaptation is already strongly evidenced in agricultural systems everywhere. Finally, we use the empirical framework to explore the evidence for cultural adaptation to climate change among US farmers in two case studies: crop choices and cover crop planting.

3. Operationalizing the study of cultural adaptation to climate change

The process of adaptation improves the fit between individuals and their environment. The process of cultural adaptation can be identified with a set of empirical criteria, themselves a subset of the criteria for cumulative cultural evolution (Mesoudi and Thornton, 2018). Simply put, cultural adaptation occurs when a cultural trait spreads in a population due to the concrete benefits it provides in a specific environment (see Figure 1). Note that it is necessary to distinguish an adaptive trait *as a product* of adaptation with added survival value from *the process* of adaptation itself, which generates and spreads such traits. Three criteria are necessary to identify a process of cultural adaptation:

I. *A cultural trait*. Cultural traits are not biological traits (e.g., eye colour), biological states (e.g., infected) or economic states (e.g., wealthy), but must be potentially transmissible and learnable by others. Traits may be defined to suit the target of study, for example 'planting Bt corn' might be a trait in one study, while 'farming' may be a useful trait in another. Trait identification is often equivalent in climate adaptation research, in which an 'adaptation behaviour' could be a trait in an evolutionary analysis.

II. *Context-specific performance improvement*. The trait must enhance the evolutionary performance (i.e., fitness, survival, and reproduction) of the individuals or groups who adopt it within the relevant environment (say, increased temperatures). Defining reproduction and fitness in cultural terms is not simple. See Ramsey and DeBlock (2017) for discussion. In practice, evolutionary researchers typically use proxies of fitness: measurable trait-derived benefits. For our purposes, these benefits may be biological (health, food, shelter, reproduction), economic (savings, income, efficiency), or social (status, influence, power), but must always be evaluated in the relevant environmental context. Benefits of an 'adaptation behaviour' are commonly addressed in climate adaptation research, but not always in environmental context.

III. *Increase in relative frequency*. So, the relative frequency of the trait must increase over time. It must be transmitted through the population to a greater degree than alternative traits. Cultural transmission may occur through numerous pathways including social learning or imitation, teaching, or transfer of information or materials (such as technology, books). Transmission can also occur in more opaque fashion such as via population migration or intra-organizational learning (Kline et al., 2018). Field studies have identified the cultural transmission of subsistence knowledge (Henrich and Broesch, 2011), trust (Karaja and Rubin, 2022), urban legends (Eriksson and Coultas, 2014), environmental values (Litina et al., 2016), and literacy (Barza and von Suchodoletz, 2016) and other traits. Current climate adaptation research rarely measures the transmission of 'adaptation behaviours' through a population.

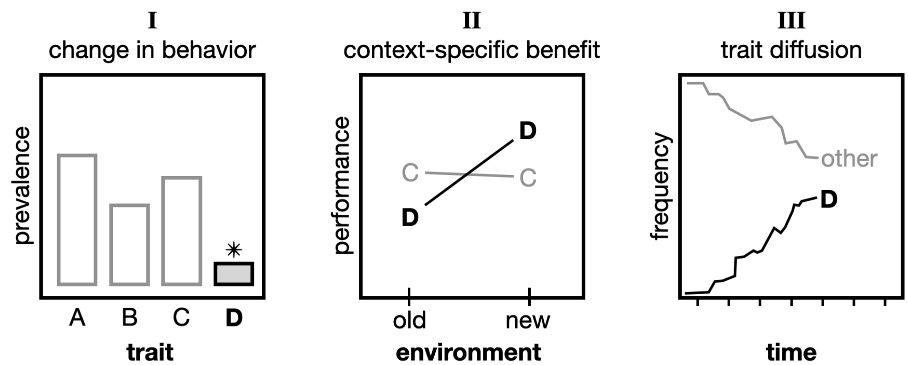

Figure 1. An empirical heuristic for cultural adaptation. Evidence of cultural adaptation in the cultural evolution of alternative trait D can be documented with three patterns: (I) trait D can be learned socially, (II) those exhibiting trait D experience improved performance in the relevant environment, and (III) trait D increases in relative frequency over time. Additional empirical patterns provide further corroboration.

There are more types of 'selection' in cultural evolution than in genetic systems. In evolutionary biology, natural selection drives adaptive evolution. Consequently, the ultimate evidence of adaptive evolution is evidence that the increase in relative frequency of the trait is due to the fitness benefits (increase in individual reproductive performance) it provides. Therefore, the simplest approach to measuring natural selection is to compare different types in their success at survival and reproduction (Linnen and Hoekstra, 2009). Selective processes are also necessary for adaptation in culture, so similar evidence would be useful. But because there are multiple strong selective forces in culture (Boyd et al., 2011), only some of which favour the spread of adaptive traits, it is not coherent to use the spread of a cultural 'type' as evidence for adaptive evolution.

Like in genetic systems, natural selection on culture favours adaptive cultural traits. So, for example the bankruptcy of companies that invest heavily in environmental efforts causes fewer of such companies to exist over time. However, in addition to natural selection on culture, humans also engage in selective social learning which may or may favour maladaptive cultural traits. So, success-biased social learning can accelerate the spread of adaptive behaviours. For example, if farmers adopt a harvesting tools based on observable impacts in harvest efficiency, the result will be improved harvest performance: a cultural adaptation in harvest tool use. But conformist social learning, in which individuals preferentially adopt traits by their popularity, can favour the spread of cultural traits with no adaptive value or even net costs to adopters. For example, corporate environmental policies may spread widely among businesses (perhaps because of their popularity) but fail to increase businesses success or profit. This underscores the point that common outcomes are less likely to be adaptive in cultural evolution. This fact has been vexing for philosophers and scientists as it makes the question of whether cultural evolution produces adaptive cultural structures difficult to evaluate, and makes cultural fitness challenging to define. For a thorough discussion see Ramsey & DeBlock (2017). For these reasons, we suggest that applied work should use the actor-centered approach of Mesoudi and Thornton (2018) for identifying cultural adaptation, which is composed of three empirical criteria: (I) a learnable trait, which causes (II) an improvement in performance for the actor, and which undergoes (III) an increase in relative frequency.

Although conceptually simple, Mesoudi and Thornton (2018)'s empirical criteria can be difficult to satisfy. For example, cultural transmission can be extremely rapid and leave almost no trace, making cultural transmission nearly impossible to identify outside of laboratory settings (e.g., Tan and Fay, 2011; McElreath et al., 2005; Mesoudi and Whiten, 2008). Additional empirical indicators can help resolve the likelihood of cultural adaptation. In a given environment, ongoing cultural adaptation can produce refined and complex cultural systems that provide concrete benefits. Mesoudi and Thornton provide extended criteria for identifying such systems, including (a) multiple functionally dependent cultural traits, (b) diversification into multiple lineages, (c) recombination across lineages, (d) cultural exaptation, and (e) cultural niche construction (Mesoudi and Thornton, 2018). Kline and co-authors (2018) provide additional indicators of *group-level* cultural adaptation, which are characteristics of cultural traits that are unlikely to emerge via individual-level selection such as costly cooperation, institutions or infrastructure that reinforces cooperation (Kline et al 2018). For a more detailed treatment of how cultural evolution at multiple levels interacts in determining sustainability outcomes see Waring et al. (2015). In climate adaptation, relevant group-level traits might include regional irrigation infrastructure. The most well-studied examples of these are Ostrom's (1990) institutional design principles, which provide a general blueprint for policy changes that may facilitate climate adaptation by aligning individual and group needs.

On measuring cultural transmission

Quantifying the transmission of culture can be difficult. For example, the increasing frequency of a trait only means that a behaviour is growing in popularity, it does not establish a mechanism. So, distinguishing between various routes of cultural transmission or social learning biases can be impossible with population-level trends alone (Barrett 2019, Kandler et al. 2017). For example, the spread of a climate-relevant behaviour (e.g. electric bike use) could look the same in the aggregate if it were caused by social learning between peers or by instruction from centralized media outfit. Spatial data may help resolve a pattern of spread if, for example, new expressions of the trait are correlated in both time and space. In epidemiology, spatial correlations between disease cases can be a signal of potential transmission, after controlling for covariates (e.g., Case et al. 2022). Even then, a growing spatial cluster does not imply causation and must be interpreted carefully (Ryan 2009). Therefore, a few empirical considerations and some lessons from epidemiology are worth noting in studying cultural transmission.

(i) <u>Cultural transmission is the default</u>. Culture, and cultural transmission are universal human characteristics (Antweiler 2016, Brown 2004). Consequently, the best prior for empirical study of humans in any society is that cultural transmission occurs in abundance. The goal of studying cultural transmission is not to demonstrate its existence, but to characterise its nature and measure its strength.

(ii) <u>Study the process of cultural transmission</u>. The most revealing evidence of transmission comes from individual-level data on how people share and adopt traits, such as behavioural, observational, or ethnographic data, surveys (e.g., Cavalli-Sforza et al. 1982), or records of contact. Combining incidence time series with related behavioural data (e.g., Althouse et al. 2015) is a promising approach.

(iii) <u>Cultural transmission may matter even if we can't observe it</u>. Epidemiological models can forecast the spread of an epidemic and test hypotheses about specific interventions even when the specific modes of transmissions are unknown (e.g., Christley et al. 2013). For example, numerous models forecasted the COVID-19 trend before the World Health Organization recognized that COVID transmission was airborne (Lewis 2022), and many remained valid despite using a mechanism-agnostic definition of transmission. A similar mechanism-agnostic epidemiological approach can be used to study the spread of cultural traits (see e.g. Hébert-Dufresne et al., 2022).

4. Cultural adaptation in agriculture

Human agriculture is one of the preeminent examples of human cultural adaptation. Agriculture is a domain rich with innovation and selection of alternative subsistence strategies which have been transmitted, accumulated, and refined over generations. Altmann and Mesoudi (2019) explain how agriculture is the product of multiple adaptive processes in cultural evolution, including *cumulative cultural evolution*, as seen in the refinement of crop varieties, irrigation, mechanisation, fertiliser, and biotechnology, *cultural niche construction* in which agricultural practices modify the environment in which humans live, and consequently *gene-culture coevolution* such as the coevolution between dairying practices and human genes for lactose digestion (Beja-Pierera et al. 2013). Thus, not only has adaptive cultural evolution produced modern agricultural technology and practices but cultural adaptation in agriculture is ongoing.

Research on agricultural practice adoption is easily compatible with cultural evolution. Rogers' (1962) diffusion of innovations framework is commonly used to study agricultural practice adoption. It focuses on the social process by which innovations such as improved crop varieties spread through a population, a core requirement of cultural adaptation. Rogers' framework was always implicitly evolutionary as it is primarily concerned with a process of behavioural and cultural inheritance. Moreover, Rogers linked his framework with complex adaptive systems models (Rogers et al., 2005), it provided a key example for early models of cultural evolution (e.g., Boyd and Richerson 1985), and it is increasingly incorporated in applied cultural evolutionary research (Clark et al., 2022). Recently, the diffusion of innovations theory has been rebuilt with cultural evolutionary mechanics to better test the assumptions about the efficacy of classical intervention approaches (Tverskoi et al., 2022). Lybbert and Bell (2010a, 2010b) applied cultural evolutionary principles to the applied question of how well drought tolerant (DT) crops might spread. They created a model that combined economic choices, and cultural transmission via payoff-biased social learning among neighbours to compare the time needed for DT crops to saturate a population in comparison to Bt. Lybbert and Bell also evaluate diffusion under climate change. Although the authors do not use the term 'adaptation', the model provides a ready roadmap for applied work on agricultural adaptation.

The vast literature on agricultural practice adoption highlights the central role of social learning in agricultural change. Three main findings are worth noting.

(i) *Farmers learn agricultural practices from professional advisors*. In the United States university agricultural advisors called 'cooperative extension' agents have traditionally worked to spread best-practices among farmers (e.g., Arbuckle et al. 2014). Related research focuses on determining the learning methods that farmers prefer (e.g., Chavas and Nauges 2020).

(ii) *Farmers learn agricultural practices from their peers*. Farmers may trust information they seek from peers more than information offered through training from advising organisations (Kilpatrick and Rosenblatt, 1998), making farmer-to-farmer learning an important driver of behaviour (Lubell et al. 2014). However, in adopting novel crop varieties, farmers are selective in the peers from which they choose to learn (Maertens, 2017).

(iii) *Social networks constrain practice learning*. Social learning among farmers is constrained by social networks, and the difficulty of inference in the complex environment of social learning in agriculture (Conley and Udry, 2001). This makes social networks important in creating agricultural change (e.g., Wood et al. 2014, Lin et al. 2021).

Despite these complementarities, cultural evolutionary research on modern agriculture has only just begun (see Hillis et al. 2018, Hanes and Waring 2018). Here, we apply the empirical rubric developed above to study cultural adaptation to climate change in two cases from contemporary US agriculture using a literature review and a data science approach.

5. Cultural adaptation to climate change in US cover cropping practices

I. Cultural trait

Cover cropping is the practice of growing crops "for the purpose of protecting and improving soil between periods of regular crop production" (Schnepf and Cox 2006). This practice has multiple dimensions of variability. Different species or species mixes can be used, fertiliser can be applied, the cover crops can be terminated with tilling, herbicide, or grazing, and the timing of planting and termination can vary. Cover cropping has various agro-ecological effects: it can improve soil health, enhance weed suppression, reduce nitrate runoff, increase soil organic carbon, and reduce soil erosion (Kaspar and Singer 2011; Jian et al., 2020; Osipitan et al., 2019).

There is no question that cover cropping can be learned. The learning and adoption of agricultural practices are complex processes with many dimensions (Han and Niles, 2023). For example, US farmers typically trial cover crops on small plots of land before a wider adoption (Pannell et al., 2006). Moreover, the decision to trial cover cropping may differ from a decision to increase its extent (Thompson et al. 2021), with initial adoption being sometimes motivated by environmental stewardship goals (Prokopy et al., 2019), and the decision to increase extent being more dependent on meeting economic necessities (Pannell et al., 2006).

Cultural traits do not evolve in isolation, but within a complex system of interacting traits (Buskell et al., 2019). This appears to be the case with cover cropping. Cover cropping complements no-till practices and crop diversification in multiple studies. Farmers who adopted cover cropping are likely to have adopted no-till practices (Lira and Tyner 2018; Lee and McCann 2019). And cover cropping is positively correlated with crop diversification in multiple studies (Lee and McCann 2019; Arbuckle and Roesch-McNally, 2015). Cover cropping has also been adopted more by those with irrigated fields (Bergtold et al. 2012) and greater precipitation (Lee and McCann 2019). Farmers who consider themselves "systems thinkers" are more likely to adopt cover crops (Church et al. 2020), and farmers who worked to integrate the practice with multiple aspects of their operation including equipment modifications and nutrient applications were more likely to adopt the practice (Roesch McNally et al., 2018). Here, we consider the presence or absence of cover cropping as a simple binary trait for simplicity.

II. Context-specific benefits

The benefits of cover cropping depend on environmental and economic context. Cover cropping carries short-term costs including the costs of seed, planting, fertiliser, application, and termination (Bergtold et al., 2017). So, economic benefits can take time to accrue (DeVincentis et al. 2020), cover cropping can save on fertiliser costs, and can increase grain crop yields in the longer term (Bergtold et al., 2019). In

Iowa, cover crops were economically beneficial for farmers grazing livestock or growing forage, while the practice had net costs for other farmers (Plastina et al., 2018). Abdalla et al. (2019) found that the practice could increase or decrease grain yields depending on cover crops used. Some cover crops can remove soil nitrogen and reduce cash crop yield and profitability (Deines et al. 2023) and Lira et al. (2018) found no impact on crop yield after five years.

We do not have direct evidence of the benefits of cover cropping under a changed climate. In Indiana, cover crop use was higher on steeper fields due to its ability to lessen erosion (Lira et al. 2018). And a cover crop of hairy vetch may be a net economic benefit in irrigated but not dryland corn fields (Bergtold et al., 2017). Thus, cover cropping might provide benefits under climate change in places where precipitation and erosion increase or where irrigation becomes more important under climate change. This is supported by a recent review which concludes that the practice can help farmers better retain soil nitrogen and handle novel weather events by reducing vulnerability to erosion, droughts, and extreme rainfall (Kaye and Quemada 2017). Evidence suggests that cover cropping can provide benefits under climate change if climate change exacerbates erosion.

The relevant context also includes social and economic factors. For example, Zhou et al. (2022) show that the recent surge in cover cropping may be dependent on federal and state incentives programs designed to support the practice. Nonetheless, cover cropping did somehow spread among farmers, and perhaps via payoff-biased social learning.

III. Increase in relative frequency

Cover cropping has increased in relative frequency in the Midwest in recent years by multiple measures. Remote sensing data shows that since 2005 cover crops have increased (from 2.3% to 3.8%) while winter commodity crops have declined (from 11.3% to 8.2%) as a fraction of row crop acres in midwestern states (CTIC, 2022; Gustafson et al., 2019). And the USDA Agricultural Census shows the practiced nationally although it remains rare in US agriculture overall (Figure 2).

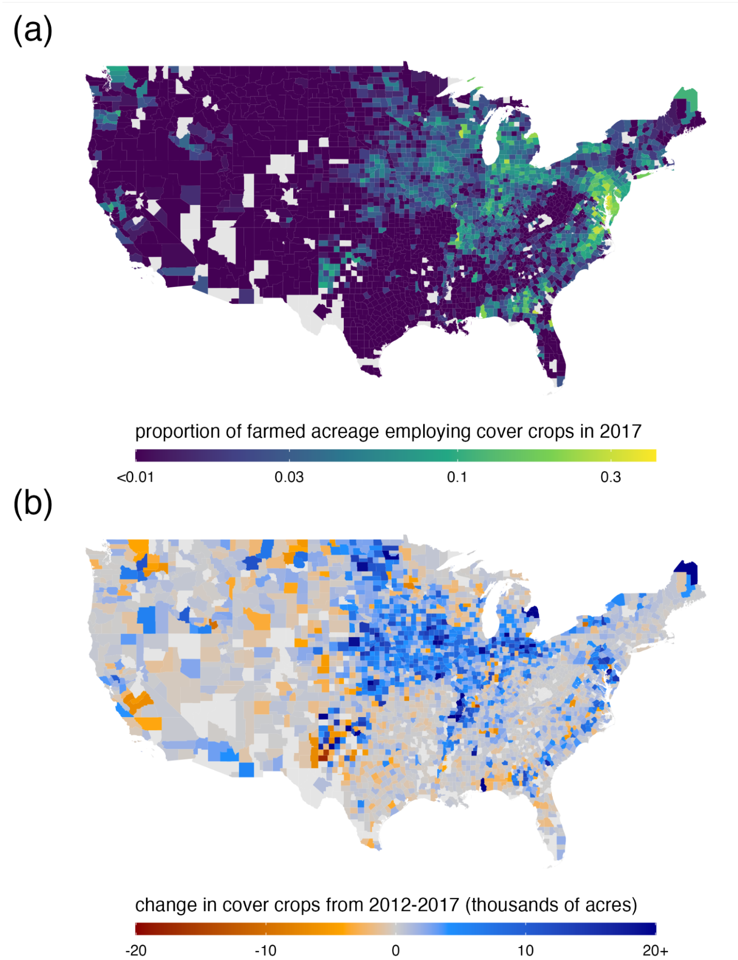

Figure 2. Cover cropping is rare but growing in the US. (a) Spatial distribution of cover crop prevalence as a fraction of total county farmland in 2017. (b) Temporal trends in cover crop acreage, calculated as acreage differences between 2012 and 2017. All data are from the USDA Agricultural Census, and are available in the archive at Kling (2023). Nationwide, total cover crop acreage increased from 10.2 million acres in 2012 to 15.3 million acres in 2017, a ~50% increase that was concentrated in the Midwest and northern Great Plains.

There is significant evidence that cover cropping is culturally transmitted. For example, in Iowa, contact from public sector programs increased the adoption of cover crops but contact from agribusinesses had a negative effect (Lee et al. 2018). Focus groups in three midwestern states revealed that social factors likely drive the adoption of cover crops (Popovici et al., 2020). Popovici et al. (2020) found that the differences in cover crop adoption between otherwise similar counties could be explained by social factors including the existence of social networks of farmers who use cover crops, collaboration between advisor organizations, and extra efforts to promote cover crops by advisors. Applied efforts to encourage also cover cropping provide useful detail on how it is spread through social learning. One such program is the "Cover Crop Champions" program of the National Wildlife Federation. The program increased the likelihood of the transmission of cover cropping between farmers by supporting two aspects of social learning growing farmer-to-farmer networks and enhancing between-farmer by training farmers to describe tangible benefits, use simple language, normalise the practice, tell personal stories, and use hands-on experience (Bressler et al. 2021).The current evidence suggests that cover cropping is transmitted between farmers via social learning, and by contact with public advisors.

Evaluation

In summary, evidence shows: (I) that cover cropping is a learnable practice, which is culturally transmitted via social learning and facilitated by direct experience and individual testing, (II) that cover cropping provides agroecological benefits by reducing erosion and maintaining soil quality in places where steep slopes, irrigation and rainfall are important, and (III) that cover cropping has increased in relative frequency in the Midwest since 2011. However, evidence also suggests that the recent spread of the practice has resulted from changes in the economic environment (Zhou et al., 2017), rather than from a changed climate. Therefore, the case for cultural adaptation to climate change in cover cropping is presently incomplete.

6. Cultural adaptation to climate change in crop choice among US farmers

As a contrast, our second case study asked whether remote sensing data on crop choices among US farmers exhibit signs of cultural adaptation to recent climate change.

I. Cultural trait

Crops are cultural traits. Farmers choose which crops to plant and learn about the characteristics of various crop varieties from others. The cultural transmission of crop varieties is well established. Research in India demonstrates that social information they receive from peers influences the choice to plant high yield varieties (Foster and Rosenzweig, 1995; Munshi, 2004), hybrid crops (Matuschke and Qaim, 2009), and transgenic Bt crops (Maertens, 2017). The same is true in the US where farmers use social learning in choosing to adopt genetically modified corn (Yoo and Chavas, 2023). Farmers also adopt crops through social learning from professional advisors (e.g., Marsh et al., 2000). More detail is needed on the nature of social learning of crop adoption.

Crop switching is not a trait, but the change between two traits. On a given field, a new planting choice can take the form of crop switching (introducing a new crop), alteration of crop rotations (adjusting an existing crop rotation), fallowing cropland (deciding not to plant at least temporarily), and cropland conversion (deciding to begin or discontinue cultivation entirely). Collectively, these behaviours cause changes in land area planted in different crop types, which can be detected using remote sensing.

II. Context-specific benefits

Some crops are better suited to a given environment. Although farmers often switch crops to become more profitable, we cannot assume that any given switch is beneficial. Recent research estimates that optimal crop choices could reduce economic losses under climate change (Rising and Devineni, 2020). We are interested to know if switching crops provides a benefit under a changing climate now.

We measured the agronomic benefit of switching crops under a changed climate by analysing whether farmers switch to crops with growing requirements that better match new climate conditions. We analysed historical relationships between changing climate and changing crop types across US counties between 2008 and 2021. Data on crop type comes from the USDA's Cropland Data Layer (Boryan et al. 2011) representing a high-resolution map of crop types for each year in the time series, which we summarised to county-level acreages for each crop and year. We then combined these with data on each county's climate (Karger et al. 2017), using two ecological climate variables that integrate temperature and precipitation information: climatic water deficit (a measure of aridity) and actual evapotranspiration (a measure of the combined water and energy available for plants).

For each climate variable we calculated an index of the climatic affinity of each crop type, estimating the nationwide average conditions under which farmers chose to plant a given crop across all 14 years. Then, for each county for each year, we calculated a "farm climate index" for each climate variable as the area-weighted average of these crop index values across the crops grown in the county. For example, a high farm climate index value for climatic water deficit indicates that the crops planted in a county in a given year are likely to be well adapted to arid conditions. Finally, for each county, we calculated the rate of change in these mean crop climate indices over time and compared these to the rates of observed climate change in the climate variables themselves. The results are displayed in Figure 3.

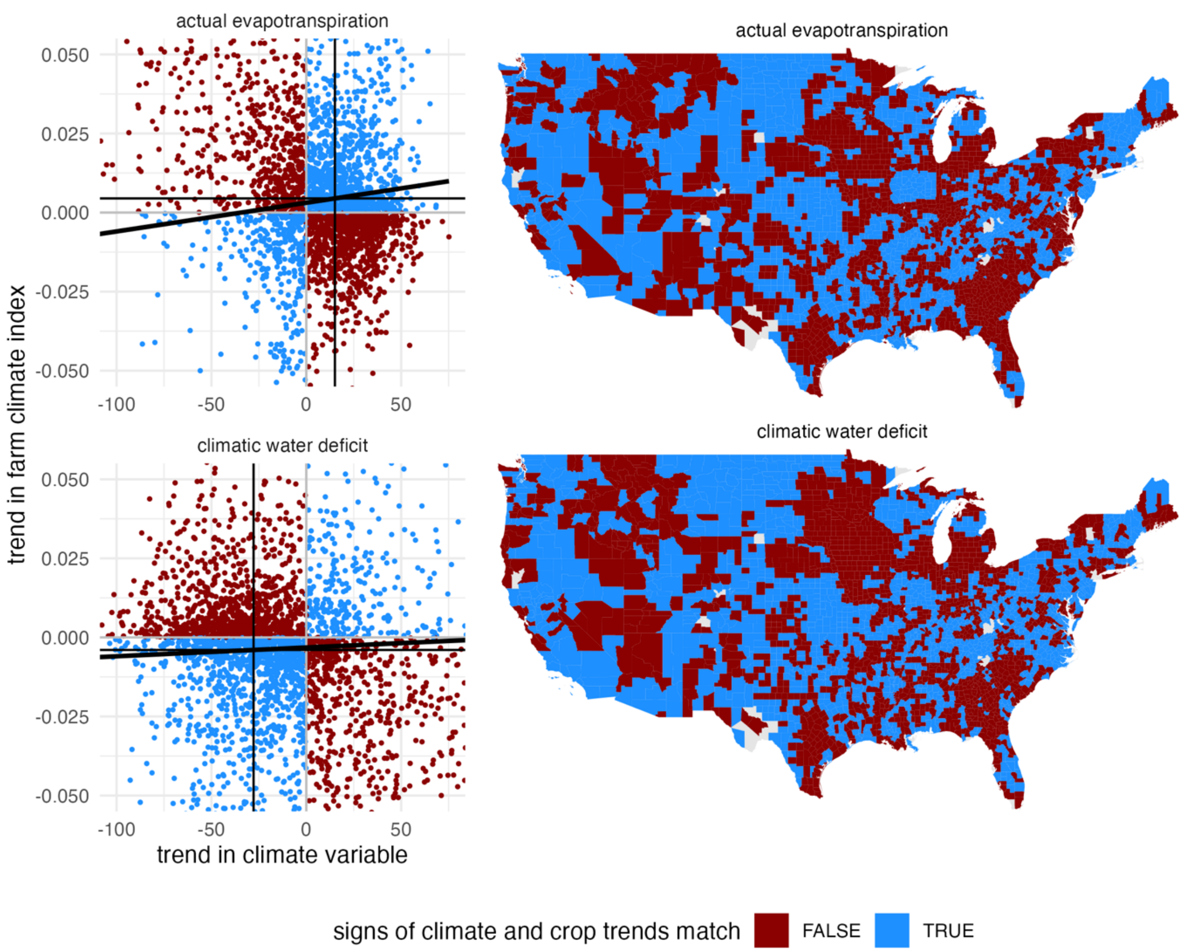

Figure 3: **Spatial and temporal trends in farmer's crop choices are consistent with cultural adaptation to climate change**. Scatterplots show recent trends in farm climate index versus trends in observed climate change for each of the two climate variables, actual evapotranspiration and climatic

water deficit; black crosshairs indicate overall means (which we expect to fall in the blue quadrants under climate change adaptation), thick black trend lines indicate linear regression fits (which we expect to be positive under adaptation), and colour indicates whether the two variables changed in the same direction. Maps show the spatial distribution of counties where crop choices moved in the same direction as observed climate change.

If farmers adapted to climate change by changing to crops that are better suited to the new local climate, then for a given climate variable, we would expect farm climate index and observed climate change to move in the same direction on average across the study area, and we would expect variations around this average to be positively correlated as farmers in different locations adapted to different rates of climate change. And indeed, both of these predictions are seen in the empirical data for both of the climate variables (Figure 3). On average nationwide, actual evapotranspiration increased and climatic water deficit decreased over the study period, and there were matching directional changes in the mean farm climate index for each variable; there was also weak but detectable positive covariance in individual counties' deviations from the mean for both variables.

As a preliminary test, we fit linear regressions for each climate variable, predicting trends in farm climate index as a function of trends in climate. Predictors were centred to have means of zero before regression, making the intercept coefficient a test of the region-wide average hypothesis and the slope coefficient a test of the county-level variation hypothesis. In a standard regression model, both results were significant at $p < 0.01$ in the hypothesized direction for both climate variables, while in a more conservative spatial autoregressive error model accounting for spatial autocorrelation, all four effect directions remained consistent with adaptive change but only the intercept term for actual evapotranspiration and the slope term for climatic water deficit were significant. The dataset and reproducible analysis code are available in the archive at Kling (2023).

III. Increase in relative frequency

Our analysis demonstrates an increase in the relative frequency of a set of cultural traits (crops that more closely match recent local climate change), relative to crops that do not match recent climate change. Further analysis is required to detect how specific crops have changed in relative frequency in accordance with changing climatic variables.

Evaluation

In summary, evidence shows: (I) that crops are a cultural trait that is readily learned between farmers and advisors, (II) that between 2008 and 2021 US farmers planted crops that more closely match recent national and local changes in two climate variables, and (III) that the more climate-matched crops are increasing in frequency relative to less matched crops in multiple regions of the United States. Our analysis of crop switching demonstrates the basic requirements for cultural adaptation to climate change.

7. Conclusion

The evidence for cultural adaptation in agriculture is abundant. Research strongly suggests that adaptive cultural evolution in agriculture is ancient, influential, and ongoing. But there has been very little evolutionary research on agricultural practices in modern contexts. We present preliminary evidence that cultural adaptation in US agriculture is responding to contemporary climate change.

Climate change is not the only driver of agricultural adaptation. Other economic, technological, or social factors are often more influential, as we can see in the recent response of cover cropping practice to financial incentives. Future work should explore the relative contribution of climate change within the soup of factors that contribute to cultural evolution. We encourage applied researchers to study the routes and mechanisms of cultural transmission which underlie adaptive and maladaptive change.

Climate adaptation research and policy efforts can make theoretical and empirical strides with the explicit study of cultural adaptation to climate change. Climate change presents a new environment in which agricultural practices will adapt through processes of cultural evolution. The ability of human agricultural systems to adapt as the climate continues to change will almost certainly be enhanced by a better understanding of the process of cultural adaptation itself.

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