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REVIEW

Determinants, outcomes, and feedbacks associated with microeconomic adaptation to climate change

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Abstract
Actors across all economic sectors of society will need to adapt to cope with the accelerating impacts of climate change. However, little information is currently available about how microeconomic actors are adapting to climate change and how best to support these adaptations. We reviewed the empirical literature to provide an overview of (1) the climate change adaptations that have been undertaken in practice by microeconomic actors (i.e. households and firms) and their determinants; and (2) the outcomes of these adaptations and the manner in which public policies have supported them. About a quarter of actors across the studies included in our review took no adaptation measures to climate change. Of those that did, the most commonly identified determinant of adaptation was assets, which were predominantly discussed as facilitating diversification within livelihoods. Few (14 out of 80) of the studies we reviewed which described empirical climate change adaptations evaluated the outcomes of these adaptations. Of those that did, evidence suggests that conflicts exist between the microeconomic outcomes of adaptations, social and environmental externalities, and long-term resilience. Different public policy interventions intended to support adaptation were discussed (57 in total); the provision of informational support was the most prevalent (33%). Our analysis suggests that microeconomic adaptation occurs as a cycle in which social and ecological feedbacks positively or negatively influence the adaptation process. Thus, efforts to facilitate adaptation are more likely to be effective if they recognize the role of feedbacks and the potential diversity of outcomes triggered by public policy incentives.

Keywords Climate change adaptation · Adaptive capacity · Social-ecological systems · Microeconomics · Agriculture

Introduction

The world is expected to experience temperatures 2–3 °C above pre-industrial levels in the second half of this century (Randers et al. 2016; DNV 2021). As a result, the impacts of climate change on both human and natural systems are expected to increase in magnitude (IPCC 2022). Global warming will affect ecosystems and the services and benefits that they provide to people in a wide variety of ways, with profound direct and indirect effects on human society. In this context of rapid and escalating change, the ability of human communities to cope with and adapt to climatic change is critical (Eisenack et al. 2014; Freeman et al. 2015; IPCC 2022). Adaptation can be viewed as a process that encompasses vulnerability and risk assessments, identification of strategies and options, planning, implementation, monitoring, evaluation, and review (Moloney and McClaren 2018). Adaptation takes place across different scales (Adger et al. 2005), e.g. at the governmental, community, or individual-actor level. Microeconomic adaptation to climate change specifically deals with the individual-actor level, e.g. households and/or firms, responding to climate signals by changing their behaviour (Fankhauser 2017).

We have limited empirical knowledge about whether, how, and for what reasons microeconomic actors are adapting to climatic change, and what barriers might impede their ability to adapt (Linnenluecke et al. 2013; Nordhaus 2013; Mortreux and Barnett 2017; IPCC 2022). The adaptation literature has focused on identifying potential adaptation

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options and assessment alternatives (Ford et al. 2011), with adaptive capacity often assessed as a proxy for potential adaptation (Mortreux and Barnett 2017; Siders 2019). Recent work has also studied people's motivations, intentions, and preparedness to adapt to climate change (van Valkengoed and Steg 2019). Yet little is known about how preparedness, intentions, and specific adaptive capacity characteristics translate to actual (implemented) adaptations to experienced effects of climate change. The relationship between adaptive capacity and implemented adaptations in this context has been argued to be far from direct, and better theories are needed to understand underlying mechanisms (Mortreux and Barnett 2017; Barnes et al. 2020; Green et al. 2021).

We also have very limited knowledge about the success of implemented adaptations to climate change. Not all implemented microeconomic adaptations should automatically be considered appropriate in terms of their outcomes (Maddison 2007). From a traditional microeconomic point of view, the outcomes of adaptation measures tend to be measured using Net Present Value; in other words, adaptation measures are considered efficient if they lead to the highest net benefit to a firm or household's income over a defined period in the future (Fisher 1930). However, a broader definition of adaptation outcomes is provided by Doria et al. (2009, p. 815), who classify a successful adaptation as "any adjustment that reduces the risks associated with climate change, or vulnerability to climate change impacts, to a predetermined level, without compromising economic, social, and environmental sustainability". Social and environmental factors are strongly related to the economic notion of market externalities (Pigou 1920). The factors explaining risk and vulnerability are linked to the concept of resilience in social-ecological systems (Engle 2011), and are not usually part of a microeconomic approach.

Government policies or support from non-government organizations (NGOs) may help microeconomic actors to successfully adapt to climate change. However, it is unclear what kind of interventions and policies are most effective. Intervening successfully in "dynamic webs of barriers" (Eisenack et al. 2014, p. 870) requires understanding of the complexities within the adaptation process. Governments aim to provide legal, regulatory, and socio-economic incentives to facilitate autonomous adaptation to climate change by microeconomic actors (Fankhauser et al. 1999; Repetto 2008; Urwin and Jordan 2008; Levin et al. 2013; Fankhauser 2017). However, well-intended government interventions aimed at promoting adaptation can lead to negative rather than positive welfare effects (Mendelsohn 2000; Repetto 2008; Levin et al. 2013; Bennett et al. 2016). For example, public crop insurance programs have in some cases reduced the incentive for farmers to adapt to climate change (Mendelsohn 2006; Repetto 2008). Public policies can also be more influenced by power dynamics than by market failures, favouring the protection of the status quo and special interest groups rather than creating a level playing field for cost-efficient adaptation (Cinner and Barnes 2019).

Governments are often heavily focused on macroeconomic outcomes, and the adaptations made by microeconomic actors are among the determinants of these outcomes. However, the design and implementation of effective incentives and policies to facilitate microeconomic adaptation to climate change remain an understudied topic (Fankhauser 2017). In order to know how best to support microeconomic adaptation, we need to know what adaptive actions are being taken in response to actual impacts from climate change, and what the broader outcomes of these actions are.

Here, we reviewed empirical research over a 25-year period (from 1995 to 2020) to provide an overview of what is known about the actual adaptations made by microeconomic actors and their relationship to the private and public sectors, respectively. Specifically, we assessed (1) the kinds of climate adaptations that have been applied in practice by microeconomic actors (i.e. people and businesses) affected by climate change and the determinants of those adaptations, and (2) the outcomes of these implemented adaptations and the public policies that have supported them. Consideration of gaps and uncertainties in this literature suggests a need for a broader, more dynamic framework that connects adaptations, adaptive capacity, and adaptation outcomes. In the final sections, we provide the beginnings of such a framework.

Methods

Recent reviews have focused on how individuals and households respond to climate change risks, and most notably on identifying the psychological drivers of pre-emptive action to the expected effects of climate change (Koerth et al. 2017; Bamberg et al. 2017; Hamilton et al. 2018; van Valkengoed and Steg 2019). Changes made in response to climate change impacts (whether experienced or predicted) can be considered an adaptive behaviour. We focused our review on the latter, i.e. the adaptive behaviour of microeconomic actors to experienced impacts of climate change.

Berrang-Ford et al. (2011, 2021; Ford et al. 2011, 2015) provided prior comprehensive reviews of adaptive behaviour to the experienced effects of climate change. They systematically reviewed peer-reviewed literature published in the period 2006–2009 dealing with adaptation efforts at a global scale (Berrang-Ford et al. 2011), in developed nations (Ford et al. 2011), and in Africa and Asia (Ford et al. 2015). A recent systematic review provided a global stocktake of human adaptation to the experienced effects of climate change focused on implemented adaptations by both private (i.e. microeconomic) and public actors that were discussed

in the peer-reviewed literature between 2013 and 2019 (Berrang-Ford et al. 2021). Here, we build on this important foundation by reviewing the literature specifically focused on implemented adaptations to the experienced impacts of climate change by microeconomic actors.

We aimed to review the academic and grey literature on microeconomic adaptation to climate change over a longer period of time than has previously been studied, enabling us to provide a snapshot of key studies and concepts within the field. The time frame we chose for our sample was 1995 to 2020. We began in the year 1995 because the following year saw one of the first key empirical studies published on microeconomic adaptation to climatic change (Smit et al. 1996). We scoped different review approaches to address our research aims. Due to our chosen time period, it was not feasible to do a systematic review using general search terms, which are typically focused on shorter periods of time (Berrang-Ford et al. 2011, 2021) or specific locations (Robinson 2020). For example, a search process in Web of Science using the search terms "climat* chang*" AND "adapt*" (Berrang-Ford et al. 2011) for the time period 1995–2020 identified some 52,000 papers. Instead, our research aim was more suited towards a systematic search and review, which combines the strength of a comprehensive search process with those of a critical review to address broad questions in order to produce the best evidence synthesis (Grant and Booth 2009). We chose to use Google Scholar (GS) because of its greater breadth of grey and interdisciplinary literature than other alternatives. This process helped us to identify a World Bank paper (Maddison 2007) that was a key initiator of many subsequent academic studies on climate change adaptation. GS was also found to be a more comprehensive database for social science papers as compared to Web of Science (Kousha and Thelwall 2007).

Table 1 gives an overview of the inclusion and exclusion criteria that were used for our systematic search and review. GS was last consulted on April 20, 2020. Our review process was performed through the different stages outlined in Table 2 and was as exhaustive as possible. For each search term, we reviewed the first 100 results because the GS retrieval algorithm ranks the papers according to the importance of their citations. Though citations are not a perfect measure of importance, the beginning of GS search results is argued to largely pick up the most relevant studies for a critical review (Chen et al. 2007). Overall, we reviewed some 3000 papers. Most of the papers returned through this search

Table 1 Inclusion and exclusion criteria for our critical review process

Inclusion	Exclusion
Phase 1: Keyword search	
English	Non-English
Time period: 1995–2020	Pre-1995 or post-2020
Retrievable through Google Scholar database	Non-retrievable through Google Scholar database
Phase 2: Abstract and methodology review	
Human system adaptation	Natural system adaptation
Empirical evidence of actual implemented adaptations to the experienced effects of climate change	Papers focused on attitudes and intentions towards adaptation, and/or the discussion of potential adaptation options
Adaptation by microeconomic actors (i.e. households and firms)	Adaptation by public actors (i.e. governments)

Table 2 Overview of literature review process. "Results" indicate the number of papers reviewed following the inclusion and exclusion criteria described in Table 1

	Method	Results
Step 1	Search GS database using "climate change" in conjunction with the additional terms: "actual adaptation" (1050 results), "implemented adaptation" (832 results), "adaptive response" (17,600 results), "adaptive behaviour" (3550 results), "adaptive action" (2710 results), and "adaptation outcome" (1350 results) for the time period 1995–2020	54 papers
Step 2	Search GS database using a more general search with the terms "adaptation" AND "climate change", which came up with over 2 million hits. We filtered these results by year to identify relevant papers that had not yet been picked up in Step 1	13 papers
Step 3	Search within identified papers through Steps 1 and 2 for relevant cited papers that had not yet been picked up in our review (i.e. cross-referencing)	10 papers
Step 4	Search in the databases of recent reviews on adaptation to climate change (van Valkengoed and Steg 2019), flooding (Bamberg et al. 2017), wildfires (Hamilton et al. 2018), and sea level rise (Koerth et al. 2017) to identify relevant papers that had not yet been picked up in our review based on our inclusion criteria	3 papers

process focused on attitudes and intentions towards adaptation, and/or the discussion of potential adaptation options, but did not contain empirical evidence of actual, observed, or stated adaptations. We did not include these papers as we were looking only for empirical evidence of actual implemented adaptations by microeconomic actors. The 80 papers that were identified were widely dispersed among different journal outlets. Specifically, we identified publications in more than 50 different scientific journals, reducing the probability of bias due to publication outlet in the results.

The selected papers were critically evaluated based on theoretical gaps that have been identified with regard to microeconomic adaptation to climate change, as referred to in the introduction. These theoretical gaps include:

1) A lack of knowledge on adaptation to experienced effects of climate change rather than potential or preventive adaptations (Berrang-Ford et al. 2011; Barnes et al. 2020).
2) Adaptive capacity as proxy for adaptation is poorly understood (Mortreux and Barnett 2017; Mortreux et al. 2020; Barnes et al. 2020; Green et al. 2021), in particular the multidimensional character of adaptive capacity (Mortreux and Barnett 2017; Cinner and Barnes 2019).
3) Discussion of the broader outcomes of adaptation should be considered in evaluating the success of adaptation, rather than taking a binary approach (Adger et al. 2005; Doria et al. 2009; Berrang-Ford et al. 2021).
4) Government policies to facilitate adaptation by microeconomic actors are understudied (Fankhauser 2017)

We first recorded the type of climatic impacts to which the microeconomic actors adapted. We did not find an applicable microeconomic adaptation categorization framework in the literature, and we thus developed our own categorization of adaptive behaviour based on the empirical evidence found in this review. To understand the determinants of adaptation, we classified factors that were identified as facilitating adaptation using the different domains of adaptive capacity described by Cinner and Barnes (2019). Cinner et al. 2018; Cinner and Barnes, 2019) developed their adaptive capacity framework based on a review of empirical and theoretical work on (social) adaptation in social-ecological systems. Their framework acknowledges the multidimensional nature of adaptive capacity (Smit and Wandel 2006; Adger et al. 2009; Engle 2011), and approaches adaptive capacity holistically through the assessment of six interdependent domains. The domains that are argued to represent adaptive capacity are *assets* (e.g. access to financial resources), *flexibility* (e.g. to switch between adaptation strategies), *learning* (e.g. capacity to generate, absorb, and process information about climate change), *(social) organization* (e.g. social networks, social capital), *agency* (e.g. the power and freedom to change), and *socio-cognitive constructs*. The domain of socio-cognitive constructs reflects so-called second-generation theories on adaptive capacity, which have focused on the psycho-social factors that enable the mobilization of assets and other determinants (such as flexibility) to successfully adapt to climate change (Grothmann and Patt 2005; Mortreux and Barnett 2017; van Valkengoed and Steg 2019; Wilson et al. 2020; Cologna and Siegrist 2020; Bechtoldt et al. 2021).

We evaluated whether the reviewed papers discussed any outcomes of the adaptations by microeconomic actors and classified them according to Doria et al.'s (2009) definition in terms of economic outcomes, externalities, and resilience. For economic outcomes, we looked for any evidence of the impact of adaptive behaviour on indicators like productivity, income, and yields. For externalities, we looked for social and environmental consequences as a result of the implemented adaptations. This could, for example, include impacts on natural capital or public health. For resilience, we looked for evidence of the adaptations on the actors' exposure and vulnerability to future climate change.

Finally, we identified whether the reviewed papers included the effects of government policies to facilitate microeconomic adaptation and whether these policies had a positive or negative effect on adaptation. We classified adaptation policies in a number of broader policy categories. We did not find an applicable microeconomic adaptation policy categorization framework in the literature, and we thus developed our own categorization of policies based on the empirical evidence found in this review.

Results

Microeconomic adaptations to climate change

A majority of the papers identified in our review were written post-2007, following the release of a large-scale study by Maddison (2007) on adaptation to climate change in Africa. This report remains one of the most cited publications about empirical adaptation to climate change, and many of its methods and recommendations have been used in later studies. Almost half of all studies included in our review took place on the African continent. Twenty-nine percent were in Asia, 12% in South America, 7% in Europe, 6% in North America, and 1% in Australasia. Case studies were most frequently from Bangladesh (12), South Africa (8), and Ethiopia (7). The majority (72 out of 80) of the empirical studies we identified were focused on farmers. We found that 88% (63 out of 72) of the studies on farming dealt with farmers at the smallholder level, primarily focused on household level analyses. The remaining (9 out of 72) studies on farming dealt with larger-scale farms. Other microeconomic actors featured in this body of literature included fishers, tourist operators, urban dwellers, hunters, and pastoralists. Gradual changes in precipitation and temperature

were the most frequently experienced climate impacts by the microeconomic actors in the papers we reviewed (Fig. 1).

Empirical evidence for microeconomic adaptations, determinants, and outcomes

About two-thirds (50 out of 80) of the papers in our dataset explicitly assessed the ability of microeconomic actors to perceive historical climate change that affected them, although different time horizons are used in the studies. In those 50 papers, the majority of respondents perceived climate trends that corresponded with climatic data records. In all papers in our review, we have attempted to explicitly identify adaptive behaviours linked to the impacts of climate change, although it must be acknowledged that microeconomic decisions are made on the basis of a myriad of interwoven pressures (e.g. including changes in markets and demographics). For the microeconomic actors identified to have been affected by climate change, diversification (within livelihoods) was the most common measure of adaptation, followed by changes in the mode of operating and the management of natural resources (Table 3). Measures to protect livelihoods were the least common, and this category included both ecological measures (e.g. planting trees) and financial measures (e.g. taking up insurance).

About a third (26 out of 80) of the papers in our dataset provided a quantitative estimate of the percentage of microeconomic actors that did not implement *any* kind of adaptation. The average non-adaptation rate was 26% ($\sigma = 22\%$). Based on the 11 papers that provided a quantitative estimate for both the percentage of actors that do not perceive climate change and the non-adaptation rate, it appears that most actors that do perceive climate change are implementing at least some kind of adaptation. In these papers, the average percentage of actors that did not perceive climate change was 20% ($\sigma = 10\%$), and the average percentage of actors

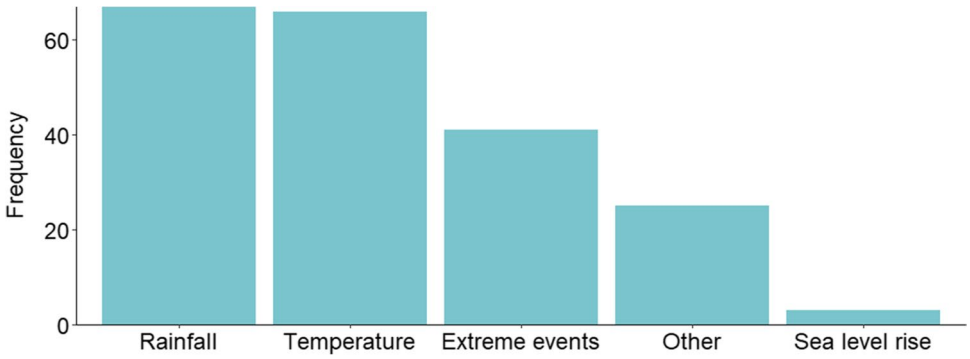

Fig. 1 Categorization of climatic impacts to which microeconomic actors adapted, based on a total of 202 climate impacts featured in the 80 reviewed papers. Extreme events include droughts (14), floods (13), (undefined) extreme weather (6), storms (3), coral bleaching (1), and cold spells (1). Other includes wind, radiation, soil salinity, biomass productivity, access to coastal resources, weed/insect pressure, disease from water shortage, crop disease, heat stress, loss of nutrients in waterways, sickness of fish, water temperatures, glacial shrinkage, rock fall, and delayed monsoon onset. Rainfall and temperature include gradual trends in land-based climate. Sea level rise includes coastal erosion

Table 3 Categorization of microeconomic adaptation measures. Based on a total of 370 adaptation measures featured in the 80 reviewed papers. Div. BL includes off-farm activities, migration, and switching to wage labouring. Div. WL includes changing crop types and varieties, livestock (and feed) types, and firm location. MO includes changing harvesting dates and seasonality, land use (e.g. switching to dual land use, mixed cropping), crop rotations, changing crop inputs, and other farm and crop management. NRM includes water conservation, soil conservation, irrigation, fertilizer use, reforestation, and land improvements. Protection includes planting trees for shading and sheltering, building sea walls, land elevation, using pesticides, artificial drains, ventilation against heat, and the use of risk management (e.g. risk sharing, crop insurance). Relief includes selling livestock, seeking social and financial support, relying on savings, reducing consumption, crop storage, prayer, changing diet, and intercommunity trade

Adaptation category	Definition	Frequency	Example
Div. WL	Diversification within livelihoods	96	Crop type
MO	Changes in mode of operating	83	Harvesting dates
NRM	Natural resource management	80	Water conservation
Div. BL	Diversification between livelihoods	40	Off-farm activities
Relief	Reduction of immediate impact	37	Selling livestock
Protection	Protection of livelihoods	34	Planting trees

that did not undertake any adaptation was 22% ($\sigma = 15\%$). In the following section, we will focus on the determinants of adaptations, under the assumption that most actors that *do* perceive climate change (and thus are likely to be affected by it) will at least implement some kind of adaptation.

The determinants of the different adaptation categories, as identified and discussed by the authors of the papers included in our review, were clustered within the adaptive capacity domains proposed by Cinner and Barnes (2019). Here we have included those factors that were identified and/or discussed as having a statistically significant effect on the implementation (e.g. positive) or non-implementation (e.g. negative) of specific adaptation measures (Fig. 2).

Assets and learning were the most common determinants of adaptation measures identified in our review, followed by flexibility. Assets and learning were both identified as being strongly, positively related to the implementation of adaptations to diversify within livelihoods as well as adaptations related to natural resource management. Flexibility appeared to be the most frequently identified determinant of adaptation to diversify between livelihoods. Having assets was described as decreasing the likelihood of making livelihood changes. Overall, the domains of agency, (social) organization, and socio-cognitive constructs were less commonly identified as determinants of adaptation measures in the studies we reviewed. This may partly be explained by there being fewer papers that considered factors that fit within these domains.

Few of the reviewed papers (14 out of 80) evaluated the outcomes of implemented adaptations as a measure of the success of the adaptation process. Only three studies (Abid et al. 2016; Khanal et al. 2018; Gorst et al. 2018) were explicit and quantitative about adaptation outcomes on a

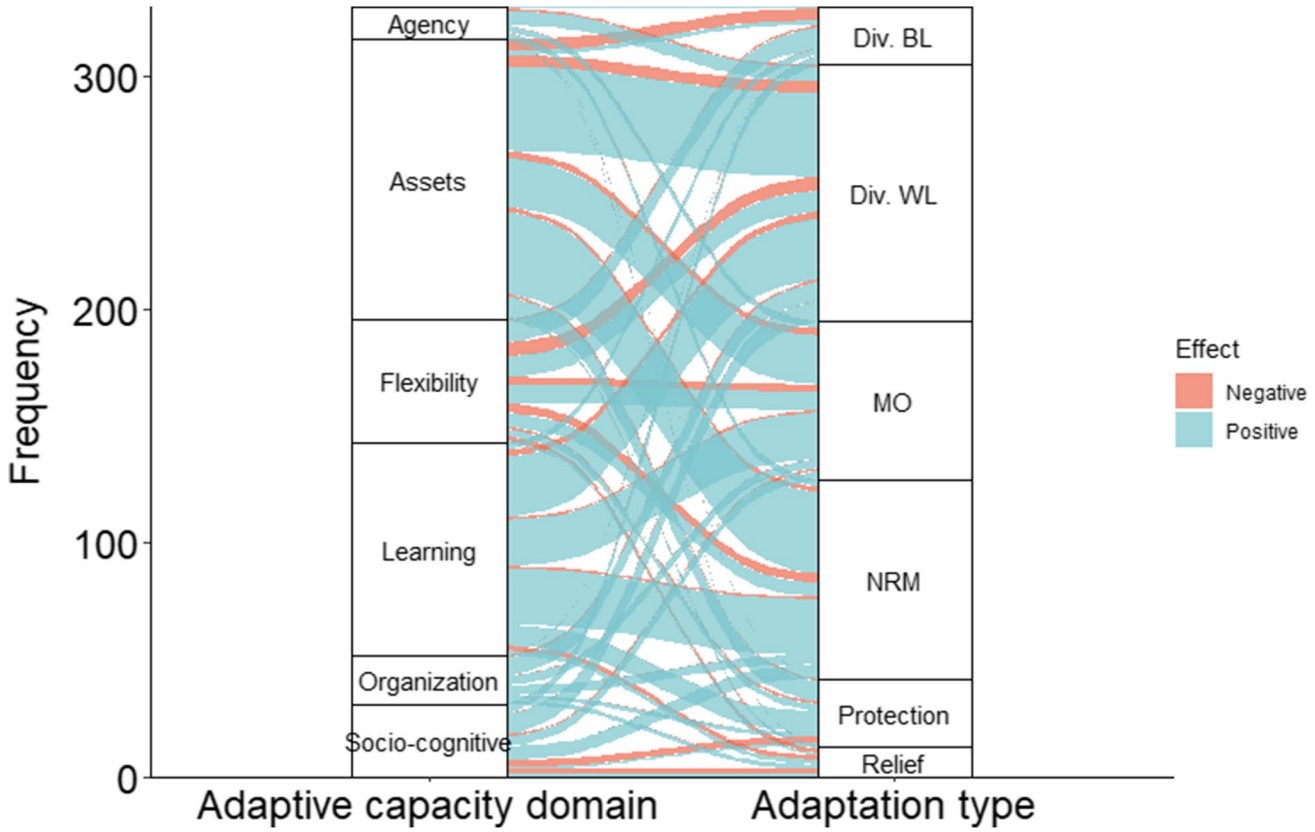

Fig. 2 Categorization of determinants for individual microeconomic adaptation categories, based on a total of 330 determinants featured in the 80 reviewed papers. This figure shows which indicators within one of the adaptive capacity domains have been found to have a significant effect on the likelihood of implementing a particular kind of adaptation measure. It includes evidence only from studies that have analyzed the relationship between adaptive capacity and individual adaptation measures. In this case, agency includes land ownership and joint decision-making power. Assets include land availability (e.g. farm size), labour availability (e.g. household size), income, savings, access to credit, and water availability. Flexibility includes access to markets, soil fertility, alternative livelihood options (e.g. low dependency on particular livelihood), younger age, diversity of skills, elasticity of market demand, and access to electricity and digital technologies. Learning includes education, access to extension services, local knowledge (e.g. farming experience), access to weather/climate information, and knowledge about advanced adaptation measures. (Social) organization includes social networks, association membership, and government support. Socio-cognitive constructs include prior experience with climate change, (high) attitude to risk, (low) place attachment, (high) trust in government/NGOs/traders, attitude towards innovation, perceived easiness of adaptation, and perception of future climate change

Table 4 Multidimensional outcomes of microeconomic adaptations. Based on a total of 25 outcomes featured in the 80 reviewed papers. Papers that mentioned outcomes of particular adaptation measures in terms of physical or financial outputs are classified under microeconomic. Non-economic outcomes that might extend beyond the microeconomic actor are classified under externalities. Outcomes in terms of exposure or vulnerability to future climate change (CC) are classified under resilience

Category	Adaptation	Microeconomic	Externalities	Resilience	Source
Div. WL	Crop type	Higher returns per unit area of land		Susceptible to future CC	Kabir et al. (2017); Manandhar et al. (2011)
	Crop variety		Conserves water resources	Increases resilience	Antwi-Agyei et al. (2018); Biggs et al. (2013)
Div. BL	Migration	Decreases farm productivity		Reduces vulnerability	Antwi-Agyei et al. (2018); Biggs et al. (2013)
	Off-farm employment	Decreases farm productivity; lower gross income per workday			Gorst et al. (2018); Kabir et al. (2017)
MO	Integrated farming			More resilient to severe CC	Seo (2010)
NRM	Irrigation	Increases farm productivity	Resource depletion (water)		Gorst et al., (2018); Antwi-Agyei et al. (2018); Laube et al. (2012); Udmale et al. (2014)
	Organic farming	Lower crop production	Soil conservation; deforestation		Antwi-Agyei et al. (2018)
	Mulching	Higher crop yields		Increases resilience	Antwi-Agyei et al. (2018)
Protection	Pesticides		Pest resistance		Manandhar et al. (2011)
Relief	Reducing consumption/ utilizing savings			Increases vulnerability	Hisali et al. (2011)
	Selling livestock	Increases short-term income		Increases vulnerability	Antwi-Agyei et al. (2018)
	Reducing food consumption	Increases income from selling food	Health consequences	Increases vulnerability	Antwi-Agyei et al. (2018)

micro level. They found a positive impact from adaptation on crop yields. However, taking a wider definition of outcomes, based on Doria et al.'s (2009) definition of successful adaptation, we found some evidence for potential negative adaptation externalities on social and environmental sustainability and resilience (Table 4). For example, there was evidence that adaptions involving the use of irrigation and organic farming lead to groundwater depletion and deforestation, respectively. Adaptations such as crop switching and selling livestock were also linked to potential increases in vulnerability to future climate change impacts. On the other hand, switching to stress-resilient crop varieties, mulching, and integrated farming was found to increase a microeconomic actor's resilience.

Private and public responsibilities

Empirical evidence for public interventions and their impact on adaptation

About 40% of the reviewed papers (29 out of 80) discussed how interventions and policies by government and/or NGOs have influenced the adaptation process. Support in the form of information was the most frequently discussed intervention, followed by financial support and social protection (Fig. 3). Importantly, a majority of reviewed papers looked at whether the policies had a positive effect on the likelihood of implementing any adaptation. Therefore, there was often no discussion on the qualitative nature of the adaptations, e.g. whether government intervention led to adaptations which could be deemed more successful in achieving specific outcomes.

Among the studies included in this review that did evaluate the outcomes of adaptation, providing information and technical advice had the most positive effect on the likelihood that the actors would implement any kind of adaptation. This seems intuitive as many such interventions directly recommend particular adaptation measures. Policies aimed at general economic development and market liberalization also had a positive effect in the majority of cases where these strategies were implemented. Our review suggests that general economic development may come with a trade-off, as it was found to give farmers more flexibility and choice on how to adapt given local circumstances (Mertz et al. 2009), but might not be sufficient in regions where the affected

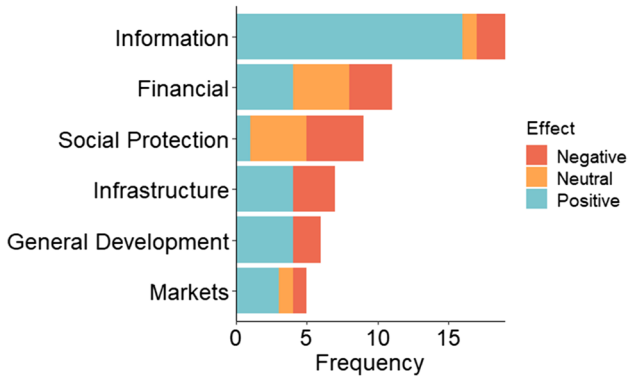

Fig. 3 Most frequently mentioned public interventions affecting microeconomic adaptation to climate change, based on a total of 57 interventions featured in the 80 reviewed papers. Financial includes farm support, (micro) credit, and subsidies (water, fuel, and fertilizer). General development includes general economic development, job programs, land-use policies, and access to electricity. Information includes extension advice, technology-linked support, agro-forestry, seasonal forecasts, and communication networks. Infrastructure includes infrastructure support, for example drainage systems. Markets includes market access and deregulation. Social protection includes social protection schemes, crop insurance, and food aid

industries, such as farming, are already considered weak and might require more direct support (Deressa et al. 2011).

We found conflicting evidence for the efficacy of a number of other government interventions. Infrastructure support had a positive effect in half of the cases we reviewed that examined adaptation outcomes. Negative effects of infrastructure support related to inequity (e.g. the infrastructure did not benefit all actors equally) (Barbier et al. 2009; Udmale et al. 2014), unreliability (Udmale et al. 2014), and increased vulnerability as compared to informal infrastructure (Laube et al. 2012). Financial support in the form of access to credit and direct financial support had a mostly positive effect on adaptation. Subsidies had a mostly neutral or negative effect, because of unreliability (Gandure et al. 2013) and overdependence on the support (Fosu-Mensah et al. 2012). However, fuel subsidies had a favourable impact on the use of irrigation pumps in one case (Sarker et al. 2013).

For social protection measures, when implemented, there was little evidence of a positive effect on adaptation. In the case of food aid, there were, as with other interventions, concerns about inequity (Barbier et al. 2009) and overdependence (Belay et al. 2017). Crop insurance was deemed to subsidize inaction on the part of the microeconomic actor (Mase et al. 2017).

Discussion

Based on our review of key empirical studies on microeconomic adaptation to the experienced effects of climate change from 1995 to 2020, we found some important gaps as compared to theoretical discussions on adaptation. First, we found that most adaptation studies remain focused on potential adaptation to future climate change rather than actual adaptations to the experience impacts of climate change. We did not review related research on "preparedness" for climate change, "intentions to adapt", and "stated adaptive choices" when faced with climate scenarios. As a recent review on preparedness for climate change (van Valkengoed and Steg 2019) showed, most studies focusing on responses to forecasted "climate risks" take place in OECD countries. Our contrasting results which show that the majority of studies on actual adaptive behaviour by microeconomic actors focus on actors in Africa and Asia could mean that while OECD countries are largely in the preparing phase for climate change, microeconomic actors in non-OECD countries are already affected by actual climate change effects and thus have already begun to adapt (in contrast to "intending"). Non-OECD countries also generally have a higher share of households working in primary industries, such as farming, that may be more directly impacted by climate change (Nordhaus 2013). This may help to explain why most (72 out of 80) of the empirical studies we identified that focused on microeconomic adaptation to the experienced effects of climate change were focused on farmers. Additionally, our sample of studies consisted mainly of small-scale microeconomic actors such as farming households. These households might be most vulnerable to climate change impacts. Our results thereby complement other recent studies focused on adaptation by small-scale microeconomic actors (Shaffril et al. 2018; Karki et al. 2020; Green et al. 2021).

A recent review on responses to forecasted climate risks by the general (urban) public found that adaptive action consisted mainly of protective measures, such as taking up insurance and relocation/evacuation (van Valkengoed and Steg 2019). While urban households may be mostly affected by the impacts of extreme climate events, rural households are affected by a wider range of climate impacts (see Fig. 1), as their livelihoods tend to be directly dependent on natural resources (and the effects of climate on the output of these resources). Therefore, given that the vast majority of published papers discussing implemented microeconomic adaptations focus on African and Asian farmers to changes in temperature and precipitation, we find a wider range of adaptive behaviours to climate change impacts as compared to studies focused on urban households. We thus classified adaptations with a slightly different scheme, using six categories that reflect the actual implemented adaptations made by microeconomic actors at both short- and long-term scales (Table 3). Most of the studies identified through our review dealt with adaptation to gradual changes in temperature and precipitation, while extreme events was also frequently

studied. Although the importance of health impacts related to climate change has been identified as an important issue (Patz and Olson 2006; Huntingford et al. 2007), this topic was only scarcely covered in our sample of empirical studies. Future review studies aimed at clustering evidence of adaptations to actual health impacts from climate change may help to shed light on this important topic.

Innovation can play a key role in adaptation (Westley et al. 2011), and we find it dispersed over different adaptation categories. For example, it occurred in natural resource management (irrigation, mulching, agrochemical use), diversification within livelihoods (climate-resistant crop varieties), mode of operating (mixed cropping, mechanization), and protection (pesticides, artificial drains, sea walls). Migration was part of our diversification between livelihoods adaptation category, which was the fourth most frequent in our review. It is interesting to note that within this category, migration related to one or multiple people within the households migrating to diversify income streams. Notably, given that we study adaptation to the experienced effects of climate change (rather than potential or planned adaptation), if a full household had decided to migrate, the empirical papers would likely not have been able to capture this as an adaptation as the household would not be a part of the sample population anymore. Thus, this adaptation category might be underestimated.

Our findings shed some further insights into the complex relationship between adaptive capacity and adaptation (Mortreux and Barnett 2017; Barnes et al. 2020; Green et al. 2021). Most notably we found that factors related to the adaptive capacity domains of "assets" and "learning" were significant predictors of adaptations to diversify within livelihoods and natural resource management. However, the limited number of studies that included factors related to the (social) organization and socio-cognitive domains is a limitation of the current empirical evidence. A recent study found that social organization was an important determinant of transformative adaptation for coastal households (Barnes et al. 2020).

Most of the empirical papers identified in our review did not include an evaluation of the adaptation outcomes. In the papers that did assess outcomes, we found some evidence for trade-offs between different outcome categories (e.g. economic vs. environmental), which point towards an avenue for further study. A discussion of the broader outcomes of adaptation should be considered in evaluating the success of adaptation, rather than taking a binary approach (Adger et al. 2005; Doria et al. 2009).

Finally, our results provide some initial evidence on the effectiveness of different government policies to facilitate adaptation by microeconomic actors (Fankhauser 2017). Currently, providing information and technical advice is the most common intervention discussed in existing empirical studies (Fig. 3). While most papers conclude that this policy has a positive effect on adaptation, we identified three reasons why it may not. First, it will be necessary to understand the outcomes of the kinds of adaptations that are advised by external actors, and whether they incorporate enough knowledge about local environmental conditions. Second, the effect of extension activities on microeconomic actors' adaptive capacity should be evaluated to see whether interventions help to build the capacity to respond to future impacts, rather than creating dependence on external advice. Third, decades of psychological research have shown that information provision is not sufficient to promote behavioural change (Sims and Baumann 1983; Arnott et al. 2014; Varotto and Spagnolli 2017). Although informational strategies might not be effective to overcome socio-cognitive barriers to adaptation, they might be effective in terms of educational barriers. We therefore require further knowledge about the effect of specific government policies on the different domains of adaptive capacity, rather than assessing only the binary effect on adaptation (i.e. adaptation or not). Other common policies are focused on increasing assets, for example through farm support, (micro) credit, and subsidies. Although access to assets was identified as the most common determinant of different adaptation measures, there is little evidence for a positive impact from asset-focused policies on adaptation. Conflicting evidence was found for other interventions such as infrastructure, and some (e.g. crop insurance) were found to promote adaptations that might reduce microeconomic actors' resilience in the long term.

Limitations

Here we provided a snapshot of key empirical studies, published between 1995 and 2020, on microeconomic adaptation to the experienced effects of climate change. Given the sheer volume of potential studies over this period (i.e. 52,000 papers), we focused our search strategy on picking up the most relevant studies for a critical review. For feasibility reasons, we therefore chose to conduct a systematic search and review of key empirical papers on microeconomic adaptation to climate change, rather than a systematic review of all 52,000 papers. This strategy is not without its limitations. While this methodological decision would have inevitably resulted in potentially relevant papers being missed, our search process within the constraints we operated within was comprehensive (Tables 1 and 2), and we minimized any potential bias towards older publications (which would likely be more highly cited) by doing a separate search for each of the years in our sample period. We also checked for any additional relevant papers that had been missed using cross-referencing (Table 2, Step 3), and reviewed every paper referenced in all recent reviews on adaptation to climate change and were sure to include them (Table 2, Step

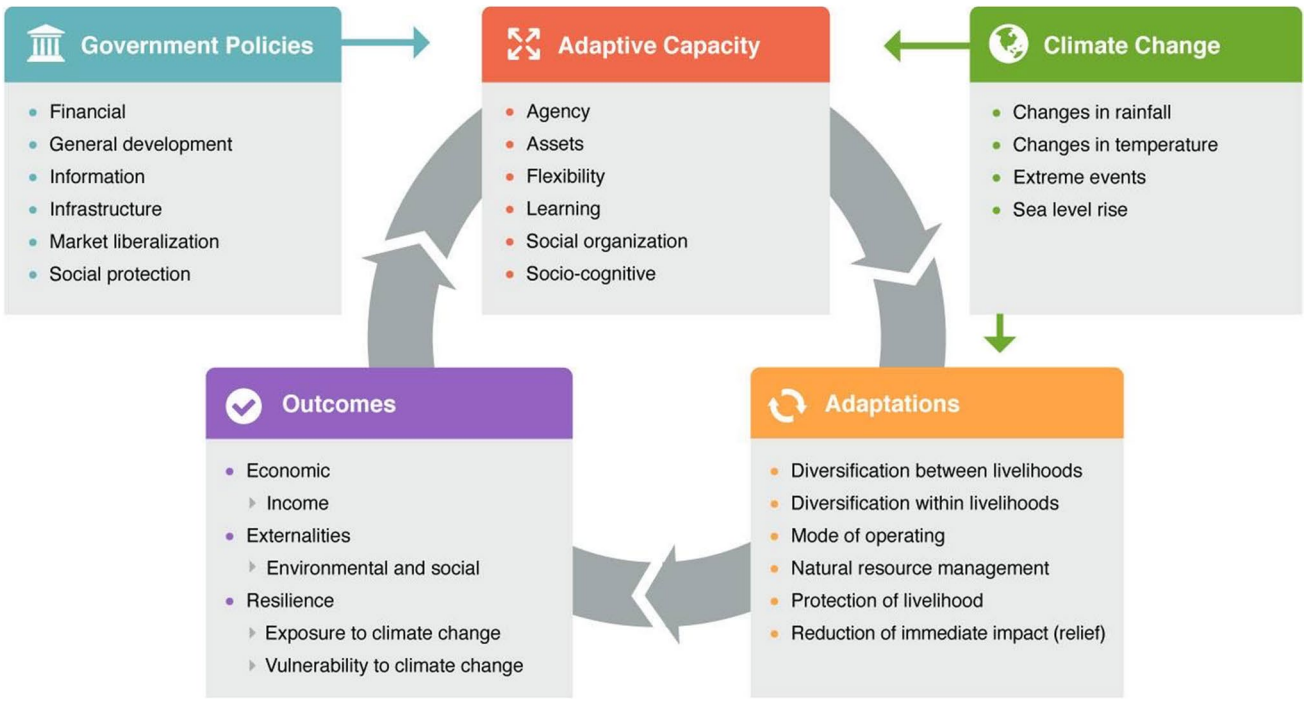

Fig. 4 Conceptual framework: microeconomic adaptation to climate change. This figure describes the interdependent relationships and consequential linkages between adaptive capacity, adaptations, outcomes, and government policies. Government policies here are only those that facilitate microeconomic adaptations. Policies that are directly implemented by governments are not a part of the microeconomic adaptation process. The type of climate change and its severity are seen here as a mediating factor on the kind of adaptations that are implemented. Adaptive capacity domains from Cinner and Barnes (2019); outcome indicators from author's own synthesis of prior findings by Doria et al. (2009); adaptation categories from synthesis of empirical literature

4). Though these steps surely helped to ensure we covered as much ground as was feasible, it is still possible that we missed key information regarding novel adaptation strategies discussed in less well known (and less cited) papers. Our findings should thus not be considered exhaustive.

Synthesis: Towards a framework for microeconomic adaptation to climate change

The outcomes of adaptation become visible over time; thus, analysis of the microeconomic adaptation process demands a dynamic perspective (Nelson et al. 2007; Vincent 2007; Engle 2011; Eisenack et al. 2014; Schill et al. 2019). As we identify in this review, there are sequential linkages between adaptive capacity, implemented adaptations, and adaptation outcomes. Over time, adaptation outcomes are expected to have an effect on a microeconomic actor's adaptive capacity. Our analysis of the theoretical and empirical underpinnings of microeconomic adaptation thus suggests a complementary and dynamic framework for climate change adaptation that is particularly focused on microeconomic actors. Our findings that studies of implemented adaptations often related to natural resource management (NRM), and that some common adaptations resulted in negative environmental outcomes, strengthen the argument for integrating an SES perspective into the microeconomic approach (Gallopín 2006). Thus, we propose that microeconomic adaptation is best understood as a process involving several key social and ecological feedbacks that might positively or negative influence the adaptation process (Fig. 4). Our approach complements other studies that have emphasized the importance of adaptation feedbacks (Onyango et al. 2016; Simpson et al. 2021) by explicitly focusing on the feedbacks related to the adaptive capacity of microeconomic actors.

We found evidence for some adaptation feedbacks in the papers considered in this review. For example, in one paper, migration of labour (adaptation) was found to cause a reduction in social cohesion (outcome), which in turn reduced the strength of social networks (adaptive capacity) which are beneficial for sharing best practices and organizing collective action (Berman et al. 2015). Another study found that an ineffective response to climate change led to high damage costs (outcomes) which reduced financial assets (adaptive capacity), thereby leaving microeconomic actors less able to invest in adaptation to future impacts (Brouwer et al. 2007).

Feedbacks might also be helpful in explaining differences between adaptation to experienced climate change, the focus of this review, and adaptation to expected

climate change (e.g. climate risks) (Bamberg et al. 2017; Hamilton et al. 2018; van Valkengoed and Steg 2019). Cognitive factors, such as trust in governments, beliefs and attitudes towards climate change, and adaptation confidence, might be a significant barrier for preparatory responses. It is possible however that cognitive factors may be less prone to impede adaptation by people that are already experiencing climate change impacts (Barnes et al. 2020). Actors that do not take preventive action might be more heavily impacted by actual climate change (i.e. high damage cost), which reduces their financial assets, as discussed earlier. The impacts from climate change as experienced by microeconomic actors are also likely to have an impact on their socio-cognitive constructs, at least in terms of the perceptions about the reality and severity of climate change (Truelove et al. 2015). On the other hand, investing in preventive action comes at a cost and impacts microeconomic outcomes now, while also creating sunk costs and potential lock-ins, which might give the actors less flexibility to respond in the future.

Environmental feedbacks can also affect the adaptation cycle. For example, farmers might respond to reduced rainfall by increased use of irrigation, which could improve overall farm productivity (Gorst et al. 2018). However, in this example, a negative externality occurred in terms of depletion of water resources (Gorst et al. 2018), which can decrease the available water (assets) for future use and adaptation to further reductions in rainfall (Laube et al. 2012; Udmale et al. 2014; Antwi-Agyei et al. 2018). Adaptations to switch to drought-resistant crop varieties, on the other hand, can reduce water use, thereby having the opposite effect (Antwi-Agyei et al. 2018). This raises the question as to what extent positive environmental externalities linked to some adaptation measures can compensate for potential lower benefits in microeconomic terms.

We previously discussed how flexibility on a micro response level provides microeconomic actors with options to adapt to climate change in ways that can improve their resilience, e.g. through switching between livelihood options. On a larger scale, such as the industry or community level, diversity in responses of individual actors has been argued to increase resilience (Carpenter et al. 2012; De Vos and Cumming 2019; Grêt-Regamey et al. 2019; Ember et al. 2020). This macro response diversity could be measured by looking at the diversity in adaptations that are implemented. A counter argument could be made that some of the best adaptation measures might require cooperation between microeconomic actors, and thus a lower response diversity. Examples would include the building of protective infrastructures, reforestation, and/or land elevation. Such adaptation would be strongly linked to the adaptive capacity domain of social organization. Social organization can enable the collective (lobbying for) funding required for high-cost adaptation solutions (Nunn and Kumar 2019). For such collective adaptations, it might become more efficient to switch from private to public responsibility.

A better understanding of the dynamic complexities and feedbacks within the adaptation process will provide key insights for policy making (Eisenack et al. 2014). Interventions to foster successful adaptation to climate change should take account of adaptation cycle dynamics and conflicting interests between microeconomic outcomes, social and environmental externalities, and resilience. Microeconomic outcomes, through their effect on savings, have proven to be a key enabler of adaptation. They are likely the first concern for microeconomic actors. However, the market might not automatically promote adaptations that have positive outcomes for social and environmental externalities and resilience. Economic incentives could promote adaptations with negative environmental outcomes, particularly in the case of common-pool resources and ecosystems. Government intervention might be required to give sufficient value to vital ecosystem services. To foster resilience, government-provided crop insurance or other social protection measures might reduce the incentive for microeconomic actors to take actions to protect against extreme climate events. Overall, we thus identify a strong need to recognize the temporal and spatial complexities involved within the microeconomic adaptation process, and the potential problems of interventions for which the effects on adaptation feedbacks are poorly understood.

Implications for practice

Our analysis of key empirical papers on microeconomic adaptation to climate change provides some important implications for practice. First, based on our clustering of the initial evidence of relationships between adaptive capacity and adaptation (Fig. 2), we identified a bias in empirical literature towards the adaptive capacity domains of "assets" and "learning". Recent evidence has found that "(social) organization" and "socio-cognitive" constructs might be critically important domains of adaptive capacity (Mortreux and Barnett 2017; Barnes et al. 2020). Most adaptation support programs are focused on increasing assets and flexibility (Lemos 2007; Cinner et al. 2018), and without considering the other domains integrally, this might limit their effectiveness. Second, our findings reveal, in line with other studies (Berrang-Ford et al. 2021), the need to better track the outcomes of adaptations. Most empirical studies on adaptations currently evaluate adaptation in a binary way (i.e. adaptation or not), rather than evaluating the diversity of adaptive responses and what outcomes are produced by particular adaptation strategies. Similar to adaptive capacity, adaptation outcomes should be evaluated in a multidimensional way. Third, most empirical papers evaluate policies

to facilitate microeconomic adaptation in a binary way, whether they increase the likelihood of adaptation. However, for policy makers, it will be necessary to understand whether their policies lastingly increase the adaptive capacity of their communities and economies to respond to future changes in climate (and other impacts). More studies are required to evaluate the impact of government policy on adaptive capacity and whether it influences these domains of adaptive capacity that are most likely to lead to successful adaptation strategies by microeconomic actors. Finally, through the framework (Fig. 4) we have provided in this study, we emphasize that studies that take into account the feedbacks between adaptive capacity, adaptation, outcomes, and policies could help untangle some of the complex interdependencies involved in the (microeconomic) adaptation process.

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