PERSPECTIVE
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Governance of social dilemmas in climate change adaptation

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In the field of adaptation governance research, current discussion on the barriers to adaptation shows that theoretical explanations for why institutions emerge and how they enable or constrain adaptation are underdeveloped. In this Perspective, we show that there is a significant opportunity to advance the understanding of adaptation governance by integrating insights that have been developed in the extensive commons literature on the institutions that work to overcome social conflicts or dilemmas. 'Realist-materialist' approaches to understanding such collective action are particularly valuable to adaptation governance research because they emphasize how biophysical conditions give rise to certain types of social dilemma. Climate change affects these biophysical conditions, and thus may alter dilemmas or create new ones. Based on realist-materialist reasoning, this Perspective describes six types of dilemma, illustrates each with a case from the adaptation literature and draws on insights from the commons literature regarding relevant contextual conditions and effective policy instruments for overcoming social dilemmas. The dilemma types provide entry points for rigorous comparative adaptation research to deepen understanding of how context influences adaptation governance processes.

Adaptation governance is an emerging research field that strives to understand the role of institutional arrangements in adapting to climate change. This Perspective aims to show that there is a significant opportunity for advancing the understanding of adaptation governance through the integration of complementary research that focuses on institutions that work to overcome social conflicts or dilemmas — in particular, realist-materialist approaches to understanding such collective action. Social dilemmas are situations in which "individual rationality leads to an outcome that is not rational from the perspective of the group"[1]. Classical examples are common pool resources (CPRs), in which it may be rational for an individual to over-harvest, and the collective provisioning of public goods, in which it may be rational for an individual to 'free-ride'.

The importance of formal and informal institutions in overcoming conflicts has long been recognized to be central in the field of adaptation[2–4]. Meta-analyses of case studies in this field point towards collective adaptation challenges being an important problem[5]. The recent Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) emphasizes in its Summary for Policymakers[6] that "governance structures, and institutions to resolve conflicts" are needed to advance adaptation. More specifically, recent work on adaptation governance has highlighted the importance of institutions for the private provisioning of collective adaptation goods[7,8]. Finally, the now substantial literature on barriers to adaptation[9] identifies institutional barriers that arise from legislative and regulatory frameworks[10] or conflicting values[11–13].

Despite this recognition, the hard-won insights from a large body of commons literature, offering a wealth of theories and approaches for understanding and overcoming social dilemmas[14–16], have so far barely been applied to the problems of climate change adaptation. For example, a recent special feature publication on adaptation governance[17], although covering a wide range of approaches (including comanagement[18], participatory approaches[19] and policy analysis[20,21]), did not touch on the vast commons literature. Moreover, the above-mentioned research on institutional barriers has put little emphasis on explaining why barriers arise and how they hinder adaptation[22,23]. This gap presents an opportunity for adaptation governance scholarship to increase understanding on how institutions hinder or contribute to adaptation, and how to improve them by making use of theory that has been developed through several decades of comparative empirical[24,25], theoretical[1] and experimental[26] research on CPRs and public goods.

This Perspective argues that the realist-materialist branch of this commons scholarship is particularly valuable to adaptation governance research. Generally, realist-materialist approaches aim at understanding governance mainly through assuming that actors follow some sort of calculative rationality, and analysing the material incentives that actors face, which are incentives related to obtaining resources or avoiding harm to material things[27,28]. In the commons literature, these approaches focus on explaining how biophysical conditions of the environment give rise to material incentives and associated social dilemmas[29,30]. Through changing biophysical conditions, climate change affects these material incentives and thus may alter dilemmas or create new ones. For example, climate change may introduce water scarcity in a shared aquifer, leading to conflicts over water use[31]. The realist-materialist branch of the commons literature is most prominently embodied in Ostrom's Institutional Analysis and Development (IAD) framework[32] and the transaction cost economics approach applied to nature-related sectors[33,34].

Realist-materialist approaches may be contrasted to 'ideational-constructionist' approaches, which aim at understanding governance through ideational aspects such as mental models, discourse, social norms, legitimacy, power and cultural values[28]. By focusing here on realist-materialist approaches, we do not intend to imply that ideational-constructionist approaches are less important. Our aim is to instead show how realist-materialist categories complement those of other branches of governance research, and that this is specifically valuable for adaptation governance research because climate change impacts on material conditions. It is also important to note that although realist-materialist approaches emphasize material conditions, they often also include ideational aspects in their explanation of governance[28].

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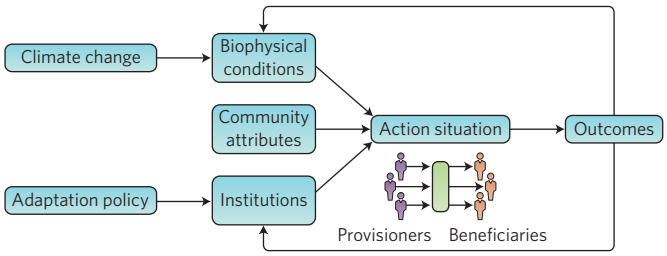

Figure 1 | The Institutional Analysis and Development (IAD) framework adjusted for adaptation governance analysis. The action situation includes providers and beneficiaries of a collective adaptation good, whose interdependence is characterized by three sets of variables (biophysical conditions, community attributes and institutions). Climate change affects the situation through its impact on biophysical conditions and adaptation policy through its effects on institutions.

The research strategy of realist-materialist approaches starts with analysing the precise structure of material incentives arising through specific biophysical conditions in a social dilemma. Social dilemmas ('action situations' in Ostrom's terminology) are thereby conceptualized as specific forms of interdependencies between actors[32]. Interdependence exists when the actions of one actor lead to consequences for another actor. An example would be one actor appropriating resources and reducing their availability for others. These consequences are also referred to as externalities[30]. Such interdependence reasoning has been applied intensively to analyse local CPR problems in pastures, communal forests, fisheries and irrigation systems[24], but has also been extended to other CPRs and public goods such as electricity grids[35] or communication infrastructure[36].

Realist-materialist research proceeds with understanding institutional arrangements that regulate such interdependencies. Institutions, understood as the "formal and informal prescriptions humans use to organize all structured and repetitive interactions,"[32] thereby take shape through a mix of three kinds of processes (see Fig. 1). Internal processes, involving the actors physically interacting with the resource, may generate institutions either deliberately through resource users establishing rules (for example, co-operatives) to manage their collective resources (called self-organization by Ostrom[32]), or spontaneously through the emergence of social norms. External processes generate institutions such as policy instruments through bureaucratic or legislative policy processes (here, adaptation policy).

A major achievement of Ostrom's work has been to show that all three kinds of processes — that is, self-organization, the emergence of social norms and external policy processes — are important and interact in overcoming social dilemmas. For example, the self-organization of actors is more likely to be successful if higher levels of government formally recognize the rights of a community to design and enforce their own rules[37]. The way those three processes interact is further mediated through a range of contextual factors that include community attributes such as heterogeneity of endowments and group size. Ostrom's work thus highlights that the external effort of designing policy instruments should consider the internal institutional context (for example, local rules and norms), as the effectiveness of policy instruments is influenced by their interaction with internal processes.

Drawing on the commons literature, we illustrate the application of the realist-materialist approach for explaining social dilemmas arising in adaptation and how external policy instruments may help to overcome these.

Three dimensions of interdependence in adaptation

Adaptation is defined by the IPCC for human systems as the process of adjustment that seeks to moderate or avoid harm, or exploit beneficial opportunities from the actual or expected effects of climate[6]. Here, we are interested in discussing collective adaptation in human systems. Generally, collective adaptation can be thought of as one group of actors (providers) providing a collective adaptation good to either themselves or another group of actors (beneficiaries)[5]. We define collective goods as non-excludable goods, that is, goods for which it is difficult or costly to exclude third parties from benefiting. This includes 'pure' public goods — goods that are both non-excludable and non-rivalrous[38] — and CPRs, which are non-excludable but 'rival'. The term rival means that the use of a good by one actor reduces the ability of another actor to use the good. Here, we treat both types of goods together because the dilemmas arising in the supply of these two are similar and it is sometimes difficult to establish a clear cut between the two[39]. So-called impure or congestible public goods such as roads or parks may become rival at high levels of consumption.

We proceed by distinguishing between three dimensions of interdependence. The first dimension refers to interdependence between providers and beneficiaries of the collective adaptation good. We distinguish between the following two configurations:

1. One-way interdependence. Providers and beneficiaries are different groups of actors. This is the opposite of a pollution problem, whereby an upstream group can provide benefits to a downstream group but not vice versa. Typical examples involve river basin water quality maintenance[40] or intergenerational problems, such as long-term biodiversity conservation.
2. Two-way interdependence. Providers and beneficiaries are the same group of actors. A typical example is the use of a CPR, such as a shared aquifer, forest or network infrastructure. Both the public goods and commons literature address this challenge.

The second dimension refers to another aspect of interdependence between provider and beneficiaries, and describes whether collective good provisioning is dominated by 'supply-side' or 'demand-side' measures[1]:

1. Supply-side provisioning consists of measures that supply a public good, or otherwise increase or maintain the productivity of a CPR. Examples of the former in the adaptation domain include dike building to reduce risks from sea-level rise[41], and of the latter irrigation system restoration to increase water supply[42].
2. Demand-side provisioning only applies to rival collective goods (for example, CPRs or congestible public goods) and consists in measures that reduce the (negative) impact of resource appropriation on the availability of collective goods. A typical example consists in multiple actors maintaining a CPR, such as a common pasture or a shared groundwater aquifer, through reducing their resource use.

The third dimension refers to the interdependence between the provisioning actors only, and is determined by the technology and geography of collective good provisioning. Following Nordhaus[43], we distinguish between the following two situations:

1. Additive adaptation, which is when any contribution of a provisioning actor will lead to some increase in the level of collective adaptation goods provided. For example, each individual private homeowner greening roofs in urban areas will incrementally reduce the risk from stormwater run-off.
2. Joint adaptation, which is when there is a threshold in the number of actors that must contribute to the provisioning in order for the collective adaptation good to be provided[44]. For example, farmers may convert portions of their crop land to maintain dispersal corridors for threatened species to conserve biodiversity under changing climate conditions. The corridors are only effective if they are connected, which in turn requires a sufficient number of farmers to contribute[45].

Table 1 | Six types of adaptation dilemma.

Adaptation	One-way	Two-way	
		Supply side	Demand side
Additive	Any upstream actor's contribution to the collective good leads to incremental adaptation benefits for downstream actors. (For example, rural farmers allowing riverine flooding to reduce urban flood risk[60])	Any actor's contribution to the collective good leads to incremental adaptation benefits for all actors. (For example, urban property owners greening roofs to reduce urban heat island effect[55])	Any actor's reduction of CPR use leads to incremental adaptation benefits for all actors. (For example, farmers reducing water use to reduce water scarcity[31])
Joint	All upstream actors must contribute to the collective good to produce adaptation benefits for downstream actors. (For example, farmers providing species dispersal corridors to maintain biodiversity[45])	All actors must contribute to the collective good to produce adaptation benefits for any actor. (For example, coastal dwellers flood proofing redevelopment to reduce storm surge flood risk[57])	All actors must reduce CPR use to produce adaptation benefits for any actor. (For example, power plants reducing water use for discharge to avoid impacts on salmon population[48])
Type of good	Public goods and CPRs	Public goods and CPRs	CPRs

An example and key reference for each type are provided. CPR, common pool resource.

Combining these three dimensions of interdependence results in six types of social dilemma (Table 1). Note that the distinction between the supply and demand sides does not apply to situations of one-way interdependence, when all provision is, by definition, supply-side. Each type of dilemma provides different material incentives for the involved actors to engage (or not engage) in adaptation, which can be used as a helpful indication for finding appropriate governance arrangements and policy instruments for overcoming the dilemma.

There is, however, no one-to-one relationship between dilemma type and policy instrument, because material incentives are further mediated through a range of contextual variables that differ depending on their relevance to different dilemmas. Understanding the effectiveness of policy instruments hence requires in-depth contextual analysis, as pointed to by not only the commons literature but also other prominent branches of adaptation governance literature that emphasizes the 'wicked' nature of climate-change-related problems[46]. To illustrate this, we elaborate each dilemma type in the context of a specific adaptation case study. For each case, we describe material incentives arising through interdependencies, indicate policy instruments, and explain how incentives and indications on policy instruments are mediated through contextual variables. We thereby focus on those contextual variables that alter material incentives and that the commons literature has found to be most relevant for a given type of dilemma, acknowledging that other branches of governance research emphasize other contextual variables beyond the material ones.

Governing two-way interdependence

The incentive structures in two-way dilemmas vary depending on both of the other two dimensions of interdependence.

Additive demand-side provisioning, such as adapting to increasing water scarcity in a shared aquifer. An example of an additive demand-side provisioning dilemma comes from the Spanish Guadiana river basin. Agriculture is vital to the region and although large-scale irrigation is present, water shortages are projected to become frequent by 2030 because of climate change[31]. Guadiana farmers thus need to reduce their groundwater extraction to maintain the shared aquifer. This is an additive dilemma because any water not extracted by a farmer will contribute incrementally to aquifer replenishment. Currently, however, many farmers pump groundwater illegally. Climate change is likely to exacerbate this dilemma through pressure on groundwater replenishment.

It is widespread in the literature to consider the incentive structure arising from interdependencies in the form of various games. Additive demand-side provisioning dilemmas may be described by the 'prisoner's dilemma' game. A farmer can always improve their short-term pay-offs by extracting more water, while imposing social costs on the long-term sustainability of the resource. The socially optimal solution for actors to choose low extraction rates is not stable because the individual gains from high appropriation rates increase when others lower theirs.

For the choice of policy instruments, the contextual variable of heterogeneity of actor endowments is particularly relevant. At high levels of heterogeneity (that is, when one actor is responsible for most CPR appropriation), the actor does not depend on others for maintaining the CPR, which means that this actor has an incentive to reduce appropriation rates. This is a so-called Olsonian actor, who derives more benefits from the resource than their costs of providing it and thus may provide the collective good alone. Nevertheless, an Olsonian actor making a purely financial decision will not provide the collective good to socially optimal levels[47]. Therefore, policy instruments may focus on providing non-monetary incentives that motivate the Olsonian actor to increase their level of provisioning. An example of such an instrument would be a government launching a publicity campaign, for example, conferring awards to recognize efficient water use by a large farm, and thus communicating the farm's practices to the wider community.

Moderate levels of heterogeneity, as found in the Guadiana, make solving the demand-side provisioning dilemma particularly difficult because Olsonian solutions are unlikely[1]. Even when one actor is able to appropriate considerably more resources from a CPR than others, they do not have strong incentives to conserve the CPR, as it can still be destroyed by the appropriation of others. Targeting only large appropriators with economic incentives is thus not sufficient. Instead, all appropriators should be targeted by policy instruments such as, for example, market-based policy instruments through which each actor bears the full cost of their own resource appropriation.

Joint demand-side provisioning, such as water temperature thresholds for salmon populations. An example of a joint demand-side provisioning dilemma is the one between Germany and the Netherlands, who both committed under the 'Rhine 2020' programme to the re-introduction of a sustainable salmon population into the Rhine. The survival of the salmon population critically depends on water temperature, which in turn is affected by the discharge of high-temperature cooling water from electricity generation plants in the two countries[48]. Under current conditions, Rhine waters can accommodate both the salmon policy and the energy production needs of each country. However, climate change is projected to bring lower flows and higher maximum temperatures, and thereby introduces a dilemma for the two riparian countries: they will need to reduce high-temperature discharge from electricity

generation to maintain the collective good of salmon populations. If water temperature is too far from the thresholds for salmon migration (23 °C) and survival (27 °C), this is an additive dilemma similar to the water resource case discussed in the previous section. Close to the thresholds, however, the water temperature remains a joint dilemma, because all actors must reduce simultaneously high-temperature water discharge to provide the collective good of salmon populations in the Rhine.

In joint dilemmas, the CPR is destroyed (or not provided) if one actor does not contribute, which provides a strong incentive for individuals to cooperate. In general, 'jointness' leads to an 'assurance game'[49], which has weaker free-riding incentives and stronger co-operation incentives as compared to the prisoner's dilemma, which describes additive dilemmas[50]. In a prisoner's dilemma, co-operation necessarily means the sacrifice of individual gains. In an assurance game this is not the case. On the contrary, the highest pay off for an individual is achieved if all contribute. Hence the preferred strategy in an assurance game is to co-operate, if the other players are expected to do so. A dilemma nonetheless exists because of the risk of getting a lower payoff while co-operating, when others instead defect. It should be noted that jointness does not always lead to an assurance game; a prisoner's dilemma may also be reached. The type of game depends on the relative benefits from the collective goods (for example, salmon population) and individual goods (for example, energy production) involved[51].

As co-operation is limited mainly by expectations that others will also co-operate, policy instruments that promote information sharing, such as making information publicly available on the volume and temperature of power plant discharges, are promising. CPR research shows that transparency regarding actions increases trust in others[25,50].

For the same reason, the contextual variable 'uncertainty in resource levels' is important for the Rhine case in particular, as well as for joint dilemmas in general. If uncertainty is high, then information sharing may not suffice. In the Rhine, the resource level is the availability of river water to absorb heat discharged from electricity generation. The amount of heat the river can absorb is uncertain because it depends on precipitation, snow melt and air temperatures. Therefore, whether salmon populations can be maintained in the future is uncertain. This reduces the incentives for riparian countries to sacrifice individual goods (that is, discharging heat) for the collective good. Climate change further reduces these incentives by increasing the likelihood of high water temperatures and low flows to levels beyond those at which salmon can migrate or survive, thus increasing the uncertainty that the collective good will be provided. Establishing joint regulation through an international body, such as the International Comission for the Protection of the Rhine, could help overcome this dilemma.

Additive supply-side provisioning, such as adaptation to stormwater run-off risk in European cities. An example of an additive supply-side provisioning dilemma faced by property owners in European cities is the reduction of risk from stormwater run-off. Climate change is likely to increase heavy precipitation events throughout northern Europe (in all seasons) and continental Europe (all seasons except summer), which leads to increased urban pluvial flood risk[52]. Urban property owners can reduce these risks by investing in greening roofs, as they provide temporary rainwater storage and reduce surface water run-off and sewage overflows from increased precipitation rates[53]. This is an additive dilemma as each individual green roof has an incremental effect on flood risk and expected property damage levels.

The source of the social dilemma in supply-side provisioning is the incentive to free-ride on the provisioning of others[1], which parallels the reasoning in the public goods literature[38]. Incentives for free-riding depend on several factors, including the technology and geography of provisioning[1] and the costs of provisioning relative to the value of the collective good. The latter is particularly important in supply-side dilemmas as opposed to demand-side dilemmas, as the costs of provisioning do not necessarily depend on the value of the collective good. For example, the cost of greening roofs does not depend on the value of a reduction in urban flood risk, whereas in contrast, the cost of reducing water use in a shared aquifer does depend on the value of water. Due to this independence of costs and benefits of collective good provisioning, there may be different intensities of free-riding incentives, and so the supply-side provisioning dilemma can be described by either an assurance game or prisoner's dilemma depending on these incentives[54].

In additive supply-side dilemmas, the contextual variable of high heterogeneity has a similar effect as in the additive demand-side dilemmas: an Olsonian actor may find it in their interest to make the supply-side investment unilaterally, if they can reap enough profit from it. In many European cities, heterogeneity in terms of property owners is moderate. The building stock is owned by a mix of public bodies and private firms, for example, real estate development firms and owner-occupants[55], but no property owner is large enough to constitute an Olsonian actor.

Given moderate levels of heterogeneity — which, as noted above, makes dilemmas particularly difficult to solve — communication instruments are unlikely to be effective on their own. Policy instruments based on regulations or economic incentives are required. For example, providing economic incentives to real estate developers may reduce the costs of provisioning sufficiently to encourage investments in green roofs. Indeed, this is already occurring, for example in Basel, London, Stuttgart and Rotterdam, where municipalities charge lower fees for stormwater drainage or allow higher density of developments for real estate developers that include green roofs in new buildings[55]. The municipalities favour such economic incentive instruments, as building regulations are decided in these settings at a federal level.

Joint supply-side provisioning, such as adaptation to sea-level rise in coastal communities. An example of a joint supply-side dilemma that coastal communities in the northeastern US are facing, following the damage caused by Hurricane Sandy, is to either invest in hard coastal protection measures such as dikes and seawalls, or in soft measures involving natural habitat regeneration and relocation of build-sites to outside of the flood zone. Climate change is likely to further exacerbate the dilemma by increasing the risks of storm surge flooding largely through sea-level rise[56]. The dilemma is joint: for hard measures, building and maintenance of sea defences require full completion in order to produce any benefits, whereas for soft measures, it is necessary that all actors coordinate their relocation for natural habitat regeneration[57].

Jointness means that there are no free-riding incentives, in contrast to the additive dilemma discussed in the previous section, because solving joint supply-side dilemmas requires the cooperation of all actors. Thus, joint supply-side dilemmas are best described as an assurance game, where trust in or expectations about the behaviour of others are key to solving the dilemma.

In general, policy instruments to promote joint supply-side provisioning of adaptation may thus focus on communication instruments. In the case of the northeastern US, such instruments are already on their way. For example, several communities have integrated flood risk reduction plans into urban development through public consultations[58]. This dilemma could, however, be mediated through the contextual variable of 'site specificity[33]'. For instance, coastal resorts derive their value almost entirely from their specific geographical location at the coast. Adaptation measures that require changing the site of an activity, such as relocating a coastal

community out of the flood zone, may meet resistance from actors that refuse to move, and thus improve their bargaining position, in order to secure their vested interests. Communication instruments may not be sufficient in this context, and economic incentives may be required as socially optimal, when such actors otherwise refuse to participate in collective adaptation[59].

Governing one-way interdependence

Generally, the incentive structure of one-way dilemmas differs radically from that of the two-way dilemmas discussed in the last section, because providers and beneficiaries are not identical, which means that providers have no direct material incentive to contribute to the adaptation measure. Internal solutions through collective action are thus less likely to occur.

Additive provisioning, such as upstream farmers providing flood buffers to reduce downstream flood risk. An example of a one-way additive provisioning dilemma involves upstream rural farmers in Scotland allowing flooding on their farmland to reduce flood risk for downstream urban areas[60]. The adaptation dilemma is additive because any contribution by an upstream farmer will incrementally contribute to downstream flood risk reduction. Climate change is likely to exacerbate this dilemma across Europe, because riverine flood risk is likely to increase[52].

Because providers and beneficiaries are different actors, communication policy instruments are not likely to be effective and regulations or economic incentives should be applied. For example, the urban municipality may pay upstream rural farmers for flood risk reduction measures. One contextual variable particularly relevant in this case is whether the assets in the floodplain are largely public or private, because reducing flood risks increases the value of these assets. When the assets are largely privately held, such an instrument may meet social resistance because other actors may not want their tax money to be spent in this way[8]. Design of the finance for such an instrument must take this into account, for instance, by funding the instrument through a property tax. In contrast, if flood risk reduction mostly benefits public infrastructure, payments to upstream farmers by the municipality may be effective regardless of their funding source[61].

Joint provisioning, such as farmers providing corridors for biodiversity conservation. An example of a one-way joint provisioning dilemma is Finnish farmers adjusting land use to maintain dispersal corridors for species to migrate with climate-change-induced shifts in habitat. These corridors have been largely closed off through the conversion of natural habitats during agriculture intensification in Finland[45]. Re-establishing and maintaining these corridors to conserve biodiversity is a one-way dilemma, because its beneficiaries are largely future generations. This adaptation measure is joint, because a minimum threshold of adjacent parcels of land must be set aside to maintain contiguous areas: if any farmer fails to contribute, the remaining unconnected habitats will not form an effective corridor.

Similarly to the additive one-way dilemma, provisioning actors have no direct material incentive to contribute to the adaptation measure, and policy instruments based on regulations or economic incentives are important. Compared to the additive one-way dilemma, the joint one-way dilemma increases the relative bargaining power of upstream farmers, because any single farmer can destroy the collective good by holding out. An important contextual variable is thus the existence of potential alternative additive measures, which reduce the bargaining power of the farmer holding out, and thus the cost of economic instruments. In the Finland case, for instance, such an additive measure for biodiversity conservation would be species translocation. In the absence of such alternatives, regulation instruments may be preferable.

Perspectives for adaptation practice and research

The six types of dilemma presented above, together with the contextual variables, offer categories for understanding and addressing adaptation that are complementary to those of the existing literature. This includes, for example, 'autonomous/planned', 'anticipatory/reactive' and other contextual variables, which have largely emerged from a perspective of climate impact modelling prominent in the IPCC[62]. We argue that if interdependence between actors is high, the former categories developed from a materialist perspective on institutions are more meaningful for understanding and enabling adaptation than those in the existing literature. Our categories also complement the description of barriers found in the adaptation literature with an explanation of why institutional barriers emerge and how they can be overcome through self-organization and policy instruments.

For adaptation practice, these social dilemma categories can play a similar role to 'adaptation tipping points' in the now prominent adaptation pathways approach[63]. Adaptation tipping points occur when a shift in adaptation measures is needed because existing measures are no longer effective[64]. Distinguishing dilemma types according to the categories provided here enables the identification of when climate change either introduces new social dilemmas or shifts existing dilemmas from one type to another. In both cases, shifts in internal institutional arrangements and/or external policy may be needed, and the categories provided here can help to identify these.

For adaptation research, the dilemma types developed here provide entry points for well-structured comparative case study research to deepen the understanding of how context influences adaptation governance processes. This paper focused on a small number of contextual variables that can influence material incentives and explain underlying mechanisms that promote or hinder the collective provisioning of adaptation goods. Using the dilemma types and associated knowledge of underlying mechanisms provides a basis for rigorous comparative research on the wider range of contextual variables that is analysed in the commons as well as other branches of governance literature. These include biophysical variables (such as resource mobility[65]), community attributes (such as market access, demographics and poverty levels[14,66]), and institutional variables, such as networks[67], social capital[2] and dominant discourses[68]. For CPRs, this approach has been notably successful and is prominently represented by the Ostrom social-ecological systems framework[16].

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Author contributions

A.B. initiated the planning of the project and conducted systematic literature reviews. Both authors contributed equally to the intellectual content and the drafting, revision and editing of the text.

Additional information

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Competing financial interests

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