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# National Borders Impede Collaboration on Climate Adaptation, Yet Conducive Factors Exist: A New Framework and Network-Analytical Evidence

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**Abstract:** Climate change requires concerted action, often across national borders. Yet, so far, climate adaptation occurs mostly within nation-states, and past conceptual work on cross-border collaboration has focused on a specific constellation of downstream risk transmission. This study offers a broader theoretical framework that also covers situations where climate-change impacts happen simultaneously on both sides of a border, suggesting potential benefits of joint or coordinated responses. Empirically, we examine this constellation in the Danish-German border region, where rising temperatures, declining frost days, and shifting precipitation are challenges on either side. Using a community-detection algorithm, we analyze original social network data containing collaborative ties between stakeholder organizations from various sectors that work on climate adaptation. Results show that the national border indeed constitutes an impediment as collaboration clusters within the two countries. However, actors who are used to communicating in a bridge language (English) and have systemic incentives for cooperation, rather than competition, show increased levels of cross-border collaboration. Since these two factors are relevant in border regions worldwide, they may substantially influence the capacity to adapt to climate change.

**Key words:** climate crisis, adaptation, social network analysis, cross-border collaboration

**Word count:** 9,600 + 4th figure (=300 words) = 9,900

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## Competing interests

The authors are employed at organizations that are represented as stakeholder organizations in the social network under study. This does not involve any financial conflicts of interest.

## Data availability statement

An interactive version of the network is available here [URL will be added after peer review]. The raw data can be obtained from the corresponding author upon request.

## Author credits

Conceptualization: ED, ST, DJA, SM; Data curation: ST, ED, KG, SM; Methodology: ED, ST, KG, SM; Formal analysis and investigation: ED, KG, SM; Visualization: KG, SM; Writing - original draft preparation: ED; Writing - review and editing: ED, ST, SM, KG, DJA; Funding acquisition: SM, DJA, ED.

## Ethics Approval and Consent to Participate

Not applicable.

## Consent for Publication

All authors whose names appear on the submission made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; drafted the work or revised it critically for important intellectual content; approved the version to be

published; and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

## 1. Introduction

Global warming and the transgression of most planetary boundaries (Planetary Boundaries Science, 2025) demand swift collective action (IPCC 2022). Increasingly, mitigation efforts—due to their insufficient decisiveness and scale in the past—must be complemented[1] by adaptation measures (Howarth & Robinson 2024). One observer has even argued that "adaptation" has become *the* central theme of society today (Staab 2026), but climate-adaptive work remains slow, underfunded, and fragmented (Burke et al. 2024; Tomej et al. 2026). In the context of the climate crisis, adaptation means the "adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC 2022: 2898). In addition to national adaptation strategies, collaboration between neighboring countries can be a decisive factor for finding adequate solutions (Lin et al. 2025; Yu et al. 2024), not least because the physical and societal challenges are often the same on either side of a border. As a Kenyan scientist remarked using a poignant local example: "droughts don't recognize borders—so our solutions must cross them too." (Mohamed et al. 2025, cited in Ferreira 2025: 6).

The idea that climate change and other ecological problems do not stop at state borders has long been recognized in the social sciences (e.g., Beck 1992) and in policy circles. For instance, in June 2025, at an event to mark the 10-year anniversary of the Paris Agreement, UN Climate Change Executive Secretary Simon Stiell stated: "The prognosis was – and remains – clear: without cooperation between nations, humanity was on a crash course for self-destruction." (UNFCCC 2025). Despite the frequent recognition that tackling the climate crisis requires concerted action by multiple groups of societal actors across national borders, policy documents do not usually take the influence of borders in structuring collaboration patterns into account (Tinning & Andersen 2022). Scientific knowledge remains limited too since past studies have focused mostly on *intra*national collaboration networks or relatively specific cross-border transmission scenarios, as we will demonstrate below. The study at hand

[1] Game-theoretical calculations show that when adaptation *crowds out* mitigation efforts, expected welfare declines, but when adaptation *complements* mitigation, expected welfare increases (Elgersma 2025).

aims to contribute to filling this gap by presenting a novel, more comprehensive theoretical framework on climate-adaptation-related cross-border collaboration and empirically examining fine-grained actor networks in the Danish-German border region to find out (a) to which extent such a national border constitutes an impediment to collaboration with regard to climate adaptation, and (b) which factors are conducive to cross-border collaboration.

The Danish-German border region constitutes a relatively open EU-internal border region. Since 1999, border control in the region has been regulated by the Schengen agreement, which allows for the free movement of goods, services, and people across it. Accordingly, Denmark and Germany ranked 5th and 6th out of 49 countries, respectively, on the World Economic Forum's Open Border Index 2017 (World Population Review 2026). However, even in the Schengen area, authorities can temporarily introduce selective controls, which Denmark has done since 2016 and Germany has followed suit in 2024, mainly due to political sentiment against irregular immigration.[2] Based on the Border Permeability Dataset (Deutschmann et al. 2023), the Danish-German border ranks 64 out of 312 land borders globally (21st percentile) in terms of the density of cross-border transport infrastructure (roads, cycleways, footpaths, etc.). Within Europe, it ranks 41 out of 82 (50th percentile) on this index and is thus quite representative of the average European border.

Furthermore, Denmark is considered one of the global leaders in terms of climate action: It is the highest-ranking country on the Climate Change Performance Index 2026 (still ranked 4th with ranks 1-3 left empty to signal that all countries, including Denmark, are doing too little; Burck et al. 2025: 7). Germany currently ranks 22nd on this index.[3] Hence, this is a clear case where cross-border collaboration is, in theory, highly desirable: it appears that Germany could learn from one of the world's most advanced country in terms of climate adaptation efforts and Denmark could try to export some of its successful strategies. Moreover, qualitative interviews with Danish and German stakeholders have revealed that "[o]n both sides of the border and across sectors, the green transition is perceived as a major opportunity for regional development requiring reinforced cross-border collaboration." (Andersen & Tinning 2026: 282). In global perspective, a study focusing on this border can thus be considered close to a *most-likely case design*: actors in this region have very good

[2] There is also a wild boar fence that covers part of the border (constructed solely by Danish authorities despite concerns from the German side) which led one team of researchers to classify the border as a "fortified border" (Taubenböck et al. 2023; personal communication with two of the authors, 18/03/2026).

[3] Similarly, on the Notre Dame Global Adaptation Initiative's (ND-GAIN) 2023 Readiness Index, Denmark ranks 2nd globally (after Singapore), while Germany ranks 13th (ND-GAIN 2026).

conditions for successful collaboration, including amicable relations, well developed cross-border infrastructure, and high ambitions with regard to tackling climate change.

Methodologically, we draw on fine-grained meteorological data from AWS (Automatic Weather Stations) on temperature, precipitation, and frost day trends, as well as original network data that covers collaborative ties between different types of stakeholders who work on climate adaptation in the region. The latter data is explored using social network analysis (SNA) and a well-established community detection algorithm. While SNA is increasingly used to studying climate adaptation patterns, most past analyses have focused on actor networks within countries (e.g., Braunschweiger 2022; Ingold & Balsinger 2015; Joseph et al. 2016; Locatelli et al. 2020; Mondal et al. 2024; Nagel 2020). Investigations of climate adaptation in border regions, and thus across state borders are still rare. One notable exception is Hamilton & Lubell (2018, 2019), who studied East Africa's Lake Victoria region, involving Kenya, Uganda, and Tanzania. To the best of our knowledge, we provide the first network analysis of collaborative climate adaptation ties in a European border region.

In addition to this empirical contribution, this article also presents a theoretical innovation. Past frameworks on cross-border climate adaptation have put emphasis on a relatively specific constellation, where a climate-change impact occurs on one side of a border, the risk travels across it, and the response happens on the other side (Carter et al. 2021). We find that this scenario, while certainly important, does not capture well what is happening in the Danish-German border region (and presumably in many other places worldwide). Rising sea levels or temperatures for instance take place simultaneously on both sides of the border; increasing or declining precipitation occurs to similar extents in areas on either side. To include these alternative constellations, we propose an expanded theoretical framework that indeed covers cases where the impact unfolds (a) in the entire border region (making a joint response seem reasonable) or (b) in similar ways in spatial pockets on either side of the border (rendering knowledge exchange and cooperative responses sensible).

The rest of the article proceeds as follows. The next section presents this expanded theoretical framework and hypotheses regarding differences in expected network structure between three types of actors: public sector, private sector, and research institutions. Next, the data and methods are described. Then, we demonstrate that the changing climatic conditions – temperature, frost days, and precipitation – present a joint challenge (or similar impact pockets) in the Danish-German border region, in line with our theoretical considerations. Afterwards, we present the result of the network analysis, focusing first on the overall

network structure, then on differences between type-specific subnetworks, and finally on the role of bridging actors. The study ends with a discussion and conclusion.

## 2. A novel theoretical framework for cross-border climate adaptation

Climate adaptation aims to tackle collective socio-ecological risks (Mandelli et al. 2024) and has been conceptualized as a *multilevel public good* with domestic, transboundary, and global dimensions (Banda 2021). Here, we focus on the transboundary aspect, specifically in terms of collaborative ties regarding adaptation across a state border, when climatic conditions and challenges are similar on either side. The definition as a public good means, as Maria Banda has laid out, that "Everyone is better off in a resilient community that can withstand and continue to thrive despite climate impacts, whether they contributed to resilience or not" (Ibid.: 1030). This characteristic implies that the provision of such a public good is not trivial and unlikely to emerge automatically via the market alone (Ibid.). Instead, institutional regulations are necessary and, according to the IPCC (2022: 658), there is high agreement that "[p]articipation, cooperation and bottom-up engagement are critical to optimal adaptation". Therefore, a comprehensive framework will have to take both state and non-state actors into account (cf. Talebian et al. 2021). Here, we include the public sector, the private sector, and research institutions such as universities and think tanks.

### 2.1 Broadening existing frameworks to cover common-impact constellations

Carter et al. (2021) offer an important theoretical framework for cross-border climate-change impacts, which they define as "consequences of climate change that occur remotely from the location of their initial impact, where both impacts and potentially also responses to those impacts such as adaptation are transmitted across one or more borders" (Carter et al. 2021: 2). This is an important advancement compared to the conventional perspective of only focusing on national responses to "national" climate-change impacts (see panels A and B in Figure 1, which are adapted from Carter et al. 2021). However, like similar work (Hedlund et al. 2018; Benzie & Persson 2019; Talebian et al. 2021; Groundstroem 2023), this downstream model mainly focusses on a relatively specific case, i.e., a situation where the impact takes place on one side of the border and the response is organized on the other side because the risk cascades across the border. This is certainly an important constellation that occurs, e.g., when rivers dry out and the consequences are felt in another country downstream. However, it is

certainly not the only relevant situation. In Figure 1 we offer a broader framework, which adds further constellations that are perhaps even more common.

One such constellation is constituted when the risk and impact itself occur on either side of the border simultaneously (*common impact*, panels C and D). Examples would be rising sea levels at the coast, flood risk in river basins or global-heating-induced draughts, affecting entire border regions equally. In such cases, cross-border collaboration would be useful not because the risk "travels" downstream, but rather because challenges are common and could potentially be tackled more effectively by cooperating and coordinating efforts (as depicted in panel D). As the IPCC (2022: 658) put it regarding water adaptation: "transboundary cooperation is essential." All too often, however, responses remain nationally restricted even in the common impact scenario (panel C). A further constellation occurs when similar impacts of the climate crisis occur in separate places on either side of a border. Even though it is not a common impact in the sense that it cuts across border, it can have common causes and consequences that make cross-border collaboration worthwhile (panel E).

***Figure 1 about here

Empirically, a qualitative case study on the Alpine regions demonstrated a failure to create joint or co-operative responses in such situations (Cattivelli 2021). At the same time, two cases have been highlighted as exemplary for successful collaboration: a cross-border early warning system established in the Karamoja Cluster, where Uganda, Kenya, South Sudan, and Ethiopia meet, and a flood-risk management project in the Drin river basin, which involves Albania, Montenegro, North Macedonia, and Kosovo (Ferreira 2025). Overall, however, climate adaptation is still overwhelmingly understood in national terms (Benzie & Persson 2019). Academically, even the innovative network analyses of the Lake Victoria region by Hamilton & Lubell (2018, 2019) have not explicitly examined the effect of the administrative borders. To the best of our knowledge, there are no quantitative network analyses yet on the effect of national borders on collaboration patterns regarding climate adaptation.

Drawing on network analyses of collaboration in other thematic areas, however, makes a dividing effect of borders highly plausible. For instance, it has been shown that network clusters of patent co-inventors coincide almost perfectly with nation-states in Europe (Cerina et al. 2014) and that administrative borders inhibit knowledge spillovers (Tang et al. 2022). One study found that intranational cooperation in science is 10-50 times more likely to occur

than cooperation beyond state borders (Hennemann et al. 2012). Between software developers, international collaboration was reduced by a more modest 16 percent (El-Komboz & Goldbeck 2024). With regard to governance networks, an OECD study on West Africa found evidence for a preference of actors to connect with other actors with the same nationality (but also a lot of cross-border collaboration when zooming in on micro regions such as the Liptako-Gourma region connecting Mali, Burkina Faso, and Niger; Walther 2017). Human mobility networks clearly cluster regionally (Deutschmann 2022). Across topics, there is thus strong evidence for a separating effect of national borders. We thus assume a similar pattern here, which is schematically visualized in Figure 1, panel C:

> $H_1$: The national border between Denmark and Germany has a separating effect in the region's network of collaborative ties with regard to climate adaptation.

### 2.2 Factors conducive to cross-border collaboration on climate adaptation

At the same time, the separation will likely not be absolute (potentially making the ideal-typical visualization in panel C an exaggeration). What factors are conducive to cross-border collaboration on climate adaptation? The literature on this issue is, as mentioned, still limited, yet it is worth taking more general experiences of cross-border collaboration into consideration when answering the question. Research emphasizes that cross-border collaboration is a highly context-dependent enterprise; what is in some contexts considered to be a barrier to collaboration may in other contexts appear as a driver (Souza 2013; Sohn 2014). On this backdrop, it would constitute a simplistic approach to cross-border collaboration to understand it as a matter of working to overcome differences manifested on either side of a state border, such as differences in legal frameworks or institutional set-up. Instead, differences should be considered likely resources and motivation for collaboration across borders (Sohn 2014). In the case of climate adaptation this could be *exchange of know-how* across state borders. We also know that the benefits of exchange based on differences are especially evident in regions that are considered peripheral in their respective kin-state (Martinez 1994), something which is the case for the Danish-German border region. Moreover, the importance of *bridging actors* as intermediaries who facilitate exchange has been highlighted, also in relation to cross-border collaboration on climate adaptation (Hamilton & Lubell 2019).

Not all of these factors can be tested empirically in this study since our data focuses on *existing* collaborative ties (i.e., we cannot analyze their emergence, e.g., via encounters and knowledge exchange) and only one border region at one point in time (i.e., we cannot test the effect of varying institutional setups, etc.). However, we shed light on two factors whose role has not been studied systematically so far in the context of climate adaptation. To do so, we create a novel comparative axis by distinguishing between three types of actors: public sector, private sector, and research institutions. These three types differ in their (a) interorganizational logic and (b) communication pathway (cf. Table 1). The *interorganizational logic* concerns the relations towards other actors in the same environment and can vary between "highly cooperative" and "highly competitive." This factor is important not least because "[t]he degree to which these actors pursue cooperative versus self-interested objectives in policy settings will profoundly shape adaptation outcomes" (Hamilton & Lubell 2019: 314). *Communication pathway* in turn refers to the openness to communicate in a language that is understood on both sides of the border (here: English) or not (here: dominance of Danish/German). We can use this comparative axis to analyze whether these two factors can contribute to more cross-border collaboration (and thus a situation more akin to panels D and E rather than C in Figure 1).

***Table 1 about here.

The *public sector*, i.e., administrative and governmental actors, is clearly relevant due to its power to implement wide-ranging adaptation measures and to build formal agreements and joint institutions. Since *multi-level* governance and the inclusion of local stakeholders and communities is important (Neltoft & Arevad 2022; Talebian et al. 2021), we take local, regional, and national public-sector stakeholders into account. Regarding the interorganizational logic, it needs to be considered that public-sector actors can officially cooperate only within legal and administrative frameworks, which are still very much bound by the nation-state (Beck 1992; Cai et al. 2025; Smith & Winterman 2022). In our case, the governance systems also differ between federal Germany and a more centralized Denmark (Lijphart 2012). With respect to the communicative pathway, German is the mandatory language for administration and legal acts in Germany. While Denmark has no law prescribing an official language, Danish is the de facto administrative language there. Even when a German-speaking minority is recognized in Denmark and vice versa, the different languages do likely present a non-negligible hurdle in addition to the different governance

structures of the two countries. As a result, we expect cross-border collaboration in the public sector to be relatively low in comparison to the other two actor types (despite high intranational levels of collaboration).

In market economies like Denmark and Germany, the *private sector* will also have an impact on the success of climate adaptation (cf. Greenhill et al. 2026). Private-sector actors mostly operate under competition and uncertainty in markets where their survival may depend on getting ahead of competitors. Trustful relations and free knowledge exchange are structurally harder to build under such conditions. Language-wise, many companies and interest organizations still have national audiences with whom they communicate in their respective national languages. Furthermore, research shows that even employees of international players in Denmark that have adopted English as their corporate language prefer to speak Danish (Barfod 2018). Due to these conditions, we expect cross-border (and intra-national) collaboration to be relatively low within the private sector, even among actors who work on climate adaptation.

*Research institutions and think tanks* represent another important actor type due to the central role of information exchange (early warning systems, climate data sharing, etc.; Ferreira 2025). Despite being embedded in the competitive system of "academic capitalism" (Münch 2014; Holtz et al. 2017) and administrative hurdles at universities, there are strong incentives for scientists to cooperate, e.g., due to division of labor among highly specialized researchers, career incentives that reward co-authorship, and the higher impact of co-authored, international publications. Globally, the share of all scientific papers that are internationally co-authored has more than doubled in the last decades (Wagner et al. 2015). In Germany, this share went from 15 to 31 percent between 2002 and 2013, while it stagnated in Denmark at already very high levels (36-39 percent, Aman & Botte 2017: 853). At the same time, pressure to publish in English increased dramatically. In Denmark, the share of publications in English is over 60 percent (Kulczycki et al. 2018: 474) and 58 percent of all researchers publish exclusively in English (Kulczycki et al. 2020: 1375). In Germany, the share of publications in English increased from 42 percent in 2002-2004 to 71 percent in 2011-2013 (Aman & Botte 2017: 851). We therefore expect cross-border collaboration to be high among research institutions. From these considerations, we can delineate the following hypothesis:

$H_2$: Cross-border collaboration is higher among research institutions than among the public and private sectors.

Furthermore, we need to consider the role of bridging actors, who can link distant parts of a network and spread information (cf. Granovetter 1973). In the public sector, national-level authorities are predestined for such a role due to their superordinate position (cf. Braunschweiger 2022). And as English serves as a *bridging* language for non-native speakers, actors most likely to use it (here: research institutions) are also predestined to be bridging actors in this cross-border network. Therefore, we assume that:

$H_3$: National-level public-sector stakeholders and research institutions are particularly likely to occupy bridging positions in the collaboration network on climate adaptation.

# 3. Data and methods

## 3.1 Climate data

To assess whether the climatic conditions and their change fit one of the constellations outlined in the theoretical framework (Figure 1), we compiled observational daily meteorological data from 2011 to 2023 on near-surface air temperature (2-m temperature, measured 2 meters above the ground), frost days (i.e., days on which the minimum 2-m temperature drops below 0°C), and annual precipitation (in mm), from 43 AWS operated by the Danish Meteorological Institute (DMI) in southern Denmark and 18 AWS located in northern Germany, in total 61 AWS. Only stations with at least 99 percent completeness of daily data for each month were included in the analysis. This completeness threshold was chosen to maximize spatial coverage while minimizing uncertainties in trend estimates associated with reduced data availability (Gleason et al., 2008). None of the AWS have been relocated since 2011, and all stations provide continuous records extending back to that year.

For stations with missing observations, data infilling was performed following the procedures described by Liston and Elder (2006). Specifically, (a) missing data segments shorter than 24 hours were filled by averaging values from 24 hours before and after the gap in order to preserve the diurnal cycle, and (b) missing segments longer than 24 hours were reconstructed using an autoregressive integrated moving average (ARIMA) model (Box and Jenkins, 1976; Walton, 1996). In the latter case, the model was used both to forecast into the missing segment using data preceding the gap and to hindcast into the segment using data following the gap, with data spans equal in length to the missing period. The two estimates

were subsequently linearly interpolated and weighted across the data gap (Liston and Elder, 2006).

Standard descriptive statistics, including the mean, standard deviation, minimum, and maximum, were calculated to evaluate records, variability, and trends for the period since 2011. While we acknowledge that the post-2011 period does not constitute a full climatological normal (i.e., 30 years), the available dataset nevertheless allows for a robust assessment of recent climate conditions and short-term tendencies. Spatial patterns in temperature and precipitation were examined by mapping AWS-derived metrics to illustrate regional variability.

### 3.2 Social network data

To collect information on collaboration patterns, we conducted the survey *Climate adaptation in the border region: collaboration networks* via the online platform LimeSurvey. Invitations to participate were sent via email to 146 contact persons of relevant stakeholders who work on climate adaptation in the Danish-German border region. They had been identified through previous desktop research [REF TO BE INSERTED AFTER PEER REVIEW], qualitative interviews, and feedback from the [PROJECT NAME REDACTED FOR PEER REVIEW] project network and advisory board. The invitees cover representatives of five types of organizations: Public sector, private sector or interest organization, research institution or think tank, knowledge dissemination or network, and cross-border collaboration. Since only few respondents self-identified via the last two types (only 4 knowledge dissemination actors and 2 cross-border collaboration actors took part), the analysis of type-specific subnetworks concentrates on the first three actor types, who we also focused on in the theory section. All five types of actors are, however, part of the analysis of the overall social network. For full transparency, the additional two subnetworks are visualized in Supplementary Figure S3, but we consider them non-representative and refrain from a closer analysis.

The fieldwork period was 8 December 2025 to 31 January 2026. Up to five reminders were sent to improve the response rate. At the end of the fieldwork period, 70 persons had filled in the survey (after excluding invalid or empty responses), there was no response in 66 cases, eight persons had actively opted out, and two email invitations had bounced. Taking only the 144 people invited without technical issues into account, the response rate is 49 percent. For comparison, a meta-analysis of >1,000 studies based on online surveys reports a median response rate of 39 percent (Wu et al. 2022). Ours is thus clearly above average.

The main task of the survey was to indicate with which other organizations their organization collaborates with regarding climate adaptation (cf. Supplementary Material Figure S1). To do so, respondents went through five lists of stakeholders (corresponding to the five actor types) and selected one of the following answer options: “frequent contact,” “sporadic contact,” “no contact,” or “do not know” (cf. Supplementary Material Figure S2). The lists comprised:

- 7× cross-border collaboration, e.g., Common Wadden Sea Secretariat, Interreg Project Posseidon,
- 16× knowledge dissemination and networks, e.g., Danish Water Forum, Det Nationale Netværk for Klimatilpasning (DNNK),
- 24× research institutions and think tanks, e.g., Alfred Wegener Institute for Polar and Marine Research, Klimatorium,
- 34× private sector or interest organization, e.g., DI - Dansk Industri, Bauernverband Schleswig-Holstein,
- 66× public sector, e.g., Landesamt für Umwelt SH, Guldborgsund Kommune.

In addition, respondents had the opportunity to name further stakeholders and their degree of cooperation with them in open fields below each list (cf. Supplementary Material Figure S2). Several respondents made use of this option, resulting in further stakeholders being added to the network and a more complete overall picture of relevant actors. We excluded additionally named stakeholders that were not located in Denmark or Germany to keep the analysis geographically restricted and balanced. In addition, we deleted a small number of repeats, i.e. stakeholders that were already listed in the survey, and a few that could not be tied to a specific location (e.g., “Alle danske større rådgivervirksomheder - hyppig kontakt” / “All major Danish consulting firms - frequent contact”). After this cleaning procedure, 62 such additional stakeholders remained. Since they had not been invited to participate in the survey, they are only part of the network as passive “recipients” of incoming collaborative ties.

To turn the string-formatted answer categories into a valued network graph, the category “frequent contact” was given a tie strength of 2, “sporadic contact” a value of 1. Some respondents didn’t specify the contact frequency for organizations that they named additionally in the open fields, requiring a pragmatic decision. In these cases, we assigned a tie strength of 1.5 to simply represent “contact.” “No contact,” “Don’t know,” and missing

values[4] were given a value of 0. In a small number of instances, two (in one case three) respondents from the same stakeholder organization answered the survey. Since the nodes in the network are the stakeholder organizations, not the individual persons who answered the survey, we combined these responses by computing the mean. Furthermore, to reduce illegibility issues in the network visualizations due to multiple actors sharing the same geolocation, we decided to simplify the network by merging sub-divisions of organizations. For example, we combined responses to "CAU Economic Geography Working Group, Department of Geography" and "CAU Coastal Risks & Sea-level Rise Research Group, Dep. of Geography" under the common label "Universität Kiel" (Kiel University), always keeping the maximum tie strength.

These steps reduced the network to 64 concrete stakeholder organizations who answered the survey and provided information on their collaborative ties to 218 stakeholder organizations. Self-referential ties within the same organization were ignored. As a result, the final cleaned network has a maximum potential of 64 × 217 = 13,888 ties. Empirically, there are 830 collaborative ties with frequent contact, 1,412 ties with sporadic contact, 42 ties with "contact" (frequency unspecified in open fields), and 20 ties with a value of .5 (resulting from one respondent answering "sporadic contact" and the other "no contact" in cases where there were multiple respondents from the same stakeholder organization). The density of the full network is thus $D_{narrow}$ = 2,304 / 13,888 = .166 (the network-analytical measure density is defined in a way that $D = 0$ indicates an empty network without connections, whereas $D = 1$ means that all possible connections are present). In other words, one out of six possible connections actually exists, pointing to a substantial amount of collaboration in the region.

In theory, there are even more potential relations, namely 217 × 216 = 46,872. This maximum would hold if all 217 stakeholder organizations participated in the survey. If we consider this theoretical maximum, the observed density is much lower at $D_{broad}$ = 2,304 / 46,872 = .049. For computational simplicity, we draw on this broad definition when reporting densities below. Since the purpose here is to compare the densities of the full network and type-specific subnetworks with each other, this approach works fine. It is important to remember, though, that the factually reachable maximum in $D_{broad}$ is < 1.

[4] To save time while going through the comprehensive lists, it seems that some respondents skipped selecting "no contact" or "don't know" and only actively clicked when actual collaborations exist. It would thus be wrong to treat all empty fields as missing values in the strict sense. However, since "no contact" and missing values are treated the same (both being assigned a value of 0), this (understandable) behavior of some interviewees has no practical consequences for the results of the network analysis.

In terms of demographics, participants were asked to state the name, town, postal code, and country of their organization. In case the organization had multiple offices, respondents were asked to name the location where they worked. The geolocations of stakeholders that were originally planned to be part of the survey were obtained from Google Maps, where they had been collected on an interactive map. To fill in missing information with regard to geolocations, categorization, and country (e.g., for organizations that had been added via open fields), artificial intelligence (OpenAI's GPT-5.3 Instant) was used, followed by thorough manual checks for accuracy. The result is a complete attribute dataset where each stakeholder is assigned to a specific geolocation and one of the five actor types.

### 3.3 Methods

To analyze the social network, we draw on a modularity-based community detection algorithm (Blondel et al. 2008; Newman 2006). This density-based algorithm, also called the Louvain method, detects clusters of nodes that are densely connected with each other. Here, it partitions the network into communities of stakeholder organizations that are more densely interconnected via collaboration, while organizations that are more sparsely linked to each other are placed in separate communities. The algorithm proceeds iteratively, starting with as many communities as there are nodes and then repeatedly merging pairs of communities in sequence, based on the associated gain in modularity ($Q$). $Q$ can range from −1 to 1, with higher values indicating a better quality of the partitions (Blondel et al. 2008). The communities were computed based on a resolution of $\gamma = 1.1$ in Gephi 0.10.1 (Bastian et al. 2009). This was done after experimenting with higher and lower resolutions from .8 to 1.2 (results available upon request) and noticing quite stable results with only minor shifts between $\gamma = 1.1$ and neighboring resolutions. Subsequently, the information was exported to QGIS 4.0 where the networks were visually combined with an administrative-geographical map of the border region.

To examine the role of bridging actors, we follow Calliari et al. (2019) and draw on the network-analytical measure of betweenness centrality ($BC$). $BC$ measures how strongly a node lies on the shortest paths connecting other nodes. Formally, it can be defined as

$$BC(i) = \sum_{s \neq i \neq t} \frac{\sigma^{st}(i)}{\sigma_{st}}$$

where $\sigma_{st}$ is the total number of shortest paths between nodes $s$ and $t$, and $\sigma_{st}(i)$is the number of those paths that pass through $i$. Nodes with high *BC* occupy structurally important positions by connecting otherwise distant or weakly linked parts of the network, capturing their potential to act as an intermediary or broker (Freeman 1977).

# 4. Results

## 4.1 Climatic conditions and climate-change impact in the border region

Topographically, the Danish–German border region is part of the North European Plain and characterized by a uniform, low-lying landscape with a north-south ridge on the Jutland peninsula that transgresses the national border. This situation leads to highly similar climatic conditions on both sides of the border. There are only minimal elevation differences from north to south and most of the region lies below 100 meters above sea level. No major natural barriers exist, and a defining feature is the strong maritime influence from the North Sea (to the west), and the Baltic Sea (to the east). Because the terrain is relatively flat and open, air masses move freely across the state border, and moist maritime air is distributed quite evenly across the region. Figure 2 shows the climatic conditions and climate-change impact in the Danish-German border region for the period 2011 to 2023, focusing on temperature, frost days, and precipitation. All indicators point to a constellation of joint impact across the border and/or similar impact on either side of the border in line with our theoretical framework (Figure 1).

***Figure 2 about here.

The mean annual air temperature (Figure 2, panel A) varies closely around 9.7 ± .3°C (mean ± standard deviation) throughout the year, illustrating this climatic uniformity. The amount of heating over time (panel B) is also similar on both sides of the border with a significant ($p < .01$) average rise of 1.3 ± .3°C from 2011 to 2023. In little more than a decade, this region has thus warmed almost as much as the world as a whole over a much longer time period, namely since the second half of the 19$^{th}$ century (cf. Rohde 2026) – a dramatic shift. Intraregional variation is minor with clusters of higher-than-average (denoted in red in Figure 2) and lower-than-average (blue) temperatures/increases occurring *on either side of the border*, in line with panel E in Figure 1.

The number of frost days (Figure 2, panel C) varies somewhat more depending on local conditions with an average of 20.2 ± 3.4 days across the region, but there are no meaningful differences between the two sides of the border. On both the German and the Danish flank, there are areas with just 15 frost days and others with >24 frost days. The decline in the number of frost days over time due to anthropogenic heating is statistically significant ($p < .05$) and considerable in the entire region (panel D). In little more than a decade since 2011, almost a month (26.5 ± 3.6 days) of frost has been lost on average. Apart from one outlier (Eckernförde bay with "just" 12 frost days lost, which might be a bias in the dataset), the impact is again relatively uniform throughout the whole region, regardless of the national border.

Precipitation exhibits pronounced spatial heterogeneity, even over short distances, reflecting its strong sensitivity to local topography, surface roughness, and land-surface characteristics. This leads to systematic variance in the region, but the gradient runs *orthogonal* to the national border (panel E). There is one cluster of high rainfall, often exceeding 900 mm per year, in the west (south central part of Jutland and northern Germany), and another cluster of lower rainfall, around 600 mm per year, in the east (around the Great Belt region), with intermediate levels of precipitation in between. This pattern is due to westerly winds carrying moist air from the North Sea eastwards. Between 2011 and 2023, precipitation strongly increased in some areas (up to +170 mm) and heavily declined in others (up to −170 mm) due to local variability in topography, surface conditions, and roughness. But there are pockets with increases on both sides of the border and others with decreases on either side as well.

All this demonstrates that Southern Denmark and Northern Germany face similar climatic challenges, either because the impact is common and transcends the border or because similar impacts occur in clusters on both sides of the border. In the coming decades, temperatures are projected to rise further, frost days to decline more, and precipitation to keep shifting according to data and projections from EU Copernicus and IPCC Interactive Atlas.[5] While not visualized, the same holds for rising sea levels, which are relevant for coastal communities both south and north of the border. Accordingly, in line with our theoretical framework, cross-border collaboration could be beneficial when tackling these problems via climate adaptation.

[5] See https://interactive-atlas.ipcc.ch/ and https://atlas.climate.copernicus.eu/atlas (accessed 19/06/2026).

### 4.2 A nationally divided social network

Turning to collaboration on climate adaptation, Figure 3 shows the full social network composed of all five types of stakeholders. The community detection algorithm found two large clusters, which split the network almost perfectly along the national border between Denmark (blue cluster) and Germany (red cluster). Notably, this clear-cut separation occurs even though the algorithm does not know about the geolocation of the actors or the existence of the border. Other network statistics further reinforce this picture. The modularity is $Q$ = .37, indicating a meaningful community structure with some cross-cluster connections ($Q$ = 0 would indicate no community structure, $Q$ = 1 a perfect separation without any ties between clusters).[6] The density of collaboration is similarly high within the Danish ($D_{broad}$ = .081) and German (.091) subnetworks (based on actual location in these countries, not the two detected clusters), but much lower in the full network (.049). There is thus strong evidence that while there are some cross-cutting ties, the national border *does* constitute a structural impediment for collaboration on climate adaptation. This barrier effect is mainly due to social factors, since, as shown above, the climatic conditions do not point to any meaningful divide along the border.

***Figure 3 about here.

### 4.3 Subnetworks reveal different structural logics

To get further insights into factors conducive and detrimental to cross-border collaboration, we now move to the comparison between the three main types of actors (Figure 4). The public sector network (panel A) features a high density ($D_{broad}$ = .089; almost twice as dense as the overall network). Here, the algorithm detected three clusters that coincide quite perfectly with the administrative regions of Syddanmark (red), Sjælland (blue), and the state of Schleswig-Holstein (purple). Hence, this network, which mainly contains the Danish *kommuner* and the German *Kreise* and *Städte* as small-scale administrative units, is structured even more regionally than the overall network. While the two Danish regions are also physically separated by the water strait of the Great Belt as a potential natural barrier, it seems plausible that the division into separate *administrative* regions has a visible effect here. This happens even though both regions speak Danish and despite the relatively centralized Danish

[6] Using the alternative measure of modularity *with resolution* (which takes the chosen γ parameter into account) leads to even higher values in this network and all subnetworks (cf. Supplementary Material Tables S1 and S2).

governance system. With a high modularity of $Q$ = .49, the separation into clusters is even more marked than in the overall social network. Collaboration on climate adaptation within the public sector happens predominantly within relatively clear-cut administrative containers.

***Figure 4 about here.

The private sector network (panel B) is composed of fewer actors but is also sparser in relative terms ($D_{broad}$ = .027, only a third of the public sector network's density), in line with our theoretical considerations about the collaboration-impeding logic of market competition. Consequently, there are more isolates (i.e., actors with no collaborative ties). The two larger clusters that do exist again divide the network along the state border, with a red Danish cluster in the north and a blue German cluster in the south. Once more, the modularity is quite high ($Q$ = .49), indicating that the division into these clusters is substantially meaningful.

Finally, the research institutions and think tank network (panel C) is also comparatively small, but its actors are quite well-connected with each other ($D_{broad}$ = .062). Fitting our expectations, this subnetwork is more border-crossing than the other two. There are no Danish and German clusters. Instead, communities cut across the border. For example, a red cluster links Europa-Universität Flensburg (EUF) in Germany with SDU Sønderborg, SDU Kolding, and other institutions in Denmark, and a blue one connects, inter alia, TU Hamburg, the Geomar Helmholtz Centre for Ocean Research Kiel, and the North German Coastal and Climate Office with SDU Odense and GEUS (Geological Survey of Denmark and Greenland) in Copenhagen. While it is important to remember that this network does not cover academia per se, but rather research actors who explicitly work on climate adaptation in the region, this subnetwork is clearly less nationally bound than the other two (confirming $H_2$).

### 4.4 Bridging actors

Table 2 shows twenty actors with the highest *BC*. In line with $H_3$, a national-level public sector stakeholder, the Kystdirektoratet (Danish Coastal Authority, the government agency responsible for managing and protecting Denmark's coasts) and a research actor (SDU Odense) rank highest. A look at Figure 4 reveals that the Kystdirektoratet mainly links Danish municipalities of different regions whereas SDU Odense also bridges across the state border. The list also shows that apart from further research institutions (CONCITO, SDU Sønderborg, etc.) the top 20 also contains regional (Ministry for Energy Transition, Climate Protection,

Environment and Nature Schleswig-Holstein, Landesamt für Umwelt Schleswig-Holstein) and local (Slagelse Kommune, Stadt Lübeck, etc.) public sector stakeholders, private sector (Tourismusverband Schleswig-Holstein e.V.), knowledge dissemination (Det Nationale Netværk for Klimatilpasning [DNNK]), and cross-border actors (Region Sønderjylland–Schleswig, Common Wadden Sea Secretariat). This shows that while the strongest bridging positions in the top 10 are indeed occupied by public sector (7) and research institutions (3), the role of bridging actors is not per se restricted to organizations from these two sectors. Rather, any type of stakeholder can – at least to some extent – occupy such a brokering position.

***Table 2 about here.

## 5. Discussion and conclusion

In this study, we proposed a novel theoretical framework for investigating cross-border collaboration on climate adaptation that goes beyond the relatively specific case of downstream risk transmission that had been the focus of past research. Instead, we put scenarios of common impact on either side of a national border into the spotlight. We then tested its utility empirically via a network analysis of the Danish-German border region. The results showed that climatic conditions and climate-change-related challenges are, despite local variability, overall similar on either side of the border – pointing to a situation where cross-border collaboration could be beneficial. However, the social network of stakeholders working together on climate adaptation is divided by the national border (confirming $H_1$). All this points to a certain mismatch between the patterns of the climate-change-induced challenges and the structure of the social collaboration network of climate adaptation. Policy-makers and stakeholders might use analyses like this one to build more complete networks, benefit from resulting economies of scale, and tackle climate adaptation more efficiently.

The comparison of actor-type-specific subnetworks demonstrated that cross-border collaboration is higher among research institutions than among the public and private sectors (in line with $H_2$). This pattern fits our argument that an easy communication pathway (here: English as a working language) paired with strong systemic incentives for cooperation are conducive to cross-border collaboration. These factors seem to be missing in the other two sectors, where national languages prevail and administrative/legal frameworks (public sector)

and market competition (private sector) seem to impede higher levels of collaboration across the border. While discrepancies in institutional procedures and regulations can also be a hurdle for collaboration between research institutions, the relatively strong cross-border ties in this sector could point to individual researchers managing to build connections *despite* these formal obstacles. Furthermore, our analysis suggests that in line with previous literature (Braunschweiger 2022) and $H_3$, national-level public-sector stakeholders and research institutions are particularly likely to serve as bridges in the collaboration network on climate adaptation. However, we also saw that actors from all sectors can, in principle, occupy such connecting positions.

Several limitations should be noted. First, while our findings are indicative of a substantial role of administrative borders, working language, and cooperative/competitive structures, such factors often overlap, forming complex amalgamations that are hard to disentangle empirically. For example, in the public sector network, there are two clusters that coincide perfectly with the Danish regions of Syddanmark and Sjælland. On the one hand, this speaks for an effect of administrative borders. On the other hand, the Great Belt strait also constates a more natural obstacle. Similarly, it is difficult to say with precision to which extent the communication pathway or the cooperative incentivizing structure (or unobserved third factors) are driving the high cross-border collaboration in the research sector. Second, we only had data on existing collaborative ties and could not examine how previously existing ones have disappeared and new ones are formed in interaction processes, which would be important to understand how collaboration is impeded and can be increased. Here, more sophisticated research designs are desirable in the future. For example, counterfactual analyses can shed light on the effects of specific policy changes (Druckenmiller et al. 2024).

Overall, this study illustrates that cross-border collaboration plays an important role in climate adaptation beyond specific scenarios of downstream risk transmission. Our approach could, e.g., be used by actors to identify subregions and corresponding actors on the other side of a national border with similar climatic challenges to initiate exchange of potential solutions and best practices. Readers are invited to explore the interactive version of the network for this purpose: [URL to be added after peer review]. The Danish-German case is of course just an example, as border regions worldwide face similar challenges in the rapidly escalating climate crisis, often with a similar need for bridging languages and incentives for cooperation. Our hope is that this analysis may inspire similar work for other regions to increase preparedness and resilience to climatic change within and beyond boundaries.

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867 **Table 1.** Hypothesized differences between sub-networks

| Type | Inter-organizational logic | Communication pathway | Expected cross-border collaboration |
|---|---|---|---|
| Public sector | Cooperation within legal and administrative bounds | Obligatory use of national languages, different legal and administrative frameworks | low |
| Private sector and interest organizations | Competition | Mainly national languages due to focus on national markets, limited information-sharing | low |
| Research institutions or think tanks | Cooperation (within a competitive system) | English as working language | high |

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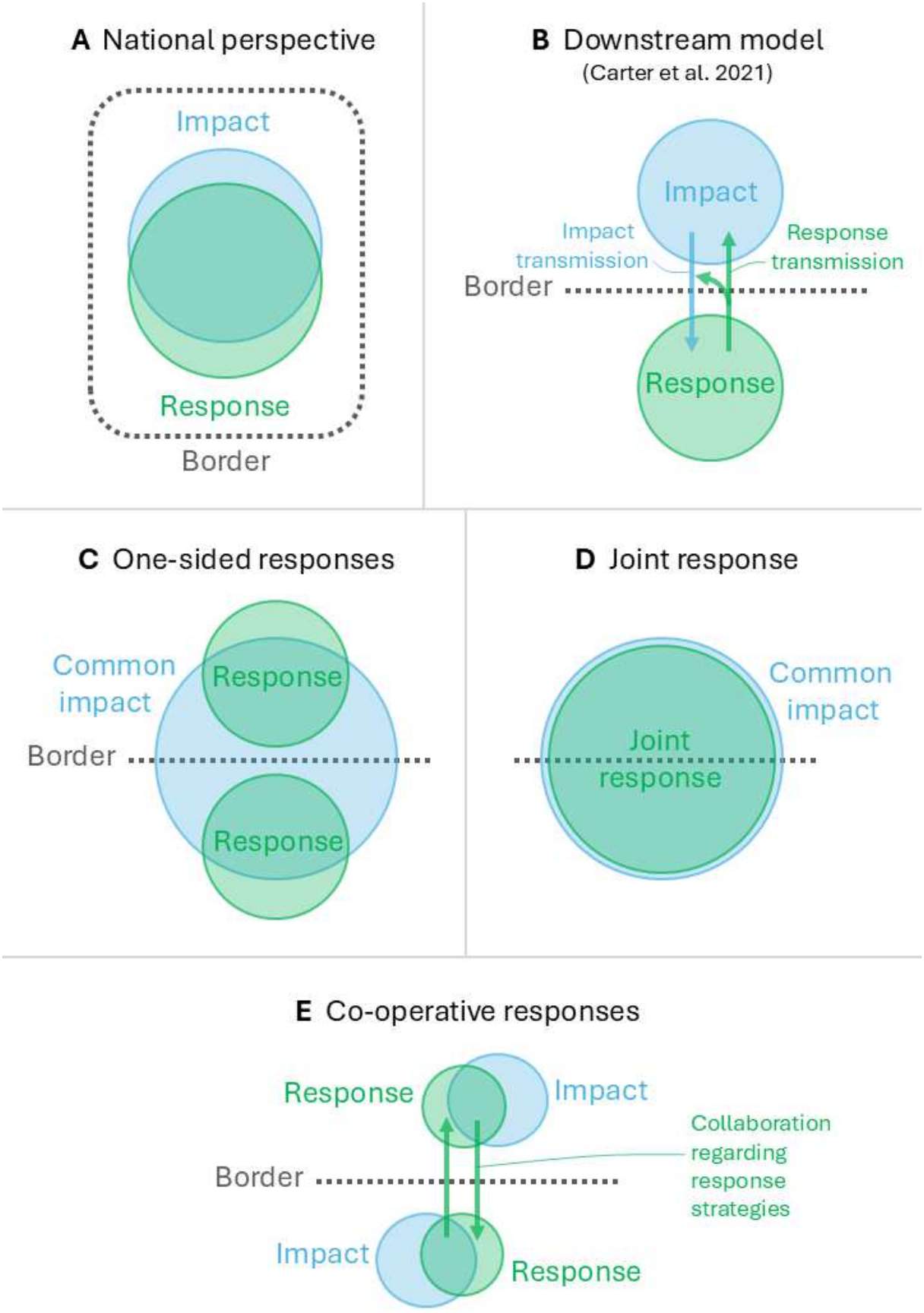
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**Table 2.** Top 20 actors with the highest betweenness centrality

| Rank | Label | Country | Category | Betweenness centrality |
|---|---|---|---|---|
| 1 | Kystdirektoratet | Denmark | Public sector | 2566 |
| 2 | SDU, Odense | Denmark | Research institution | 1981 |
| 3 | Ministerium für Energiewende, Klimaschutz, Umwelt und Natur des Landes Schleswig-Holstein (MEKUN) | Germany | Public sector | 1139 |
| 4 | CONCITO | Denmark | Research institution | 941 |
| 5 | SDU, Sønderborg | Denmark | Research institution | 694 |
| 6 | Landesamt für Umwelt Schleswig-Holstein | Germany | Public sector | 617 |
| 7 | Slagelse Kommune | Denmark | Public sector | 507 |
| 8 | Stadt Lübeck | Germany | Public sector | 502 |
| 9 | Vejle Kommune | Denmark | Public sector | 493 |
| 10 | Kreis Nordfriesland | Germany | Public sector | 448 |
| 11 | Det Nationale Netværk for Klimatilpasning (DNNK) | Denmark | Knowledge dissemination | 447 |
| 12 | Tourismusverband Schleswig-Holstein e.V. | Germany | Private sector | 388 |
| 13 | Universität Kiel | Germany | Research institution | 377 |
| 14 | Technical University of Denmark (DTU) | Denmark | Research institution | 327 |
| 15 | Region Sønderjylland-Schleswig | Denmark | Cross-border | 323 |
| 16 | Odense Kommune | Denmark | Public sector | 296 |
| 17 | Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (LKN.SH) | Germany | Public sector | 293 |
| 18 | Stadt Flensburg | Germany | Public sector | 292 |
| 19 | Aabenraa Kommune | Denmark | Public sector | 244 |
| 20 | Common Wadden Sea Secretariat | Germany | Cross-border collaboration | 240 |

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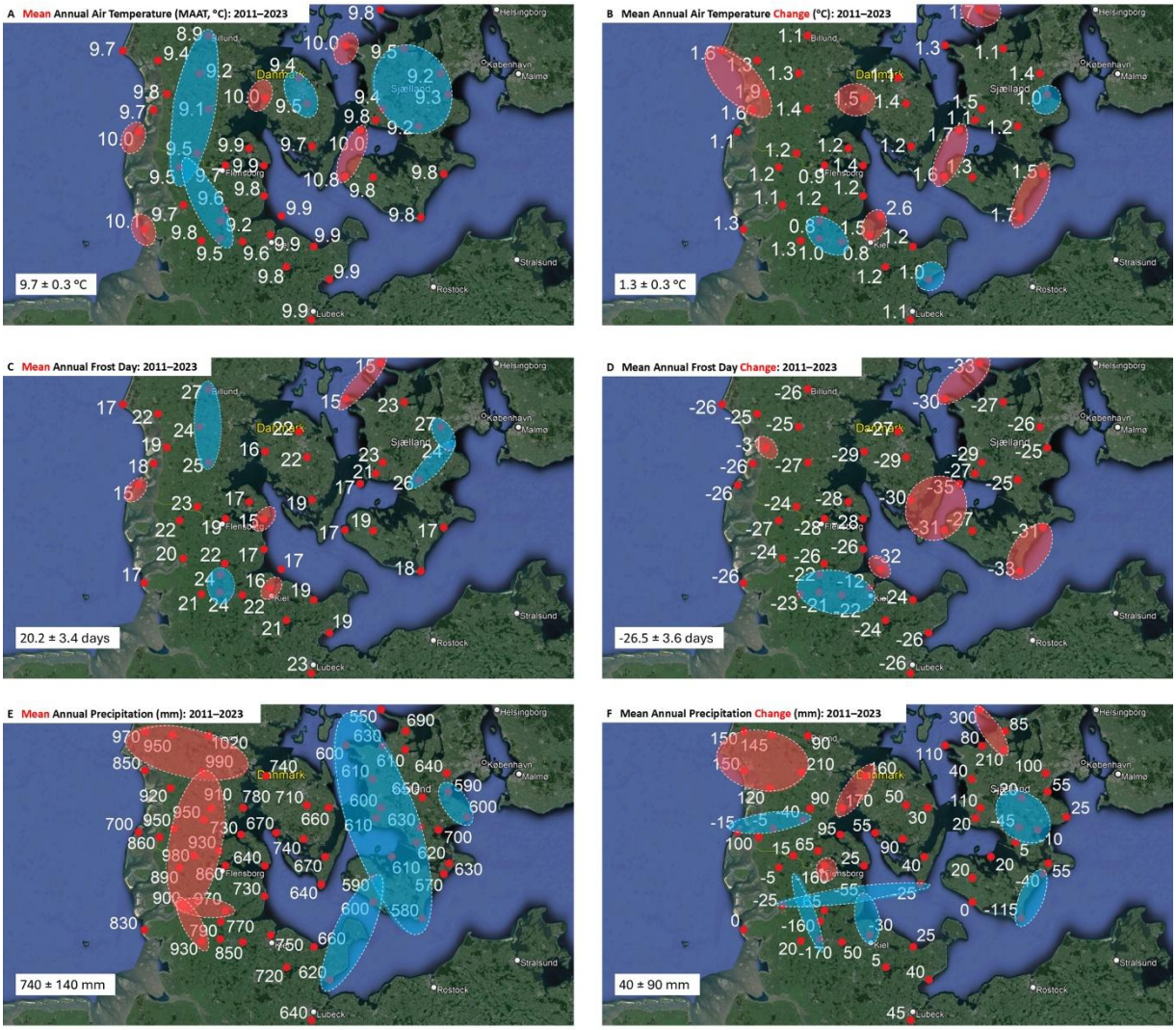
876 **Figure 1.** Theoretical framework for cross-border collaboration on climate adaptation




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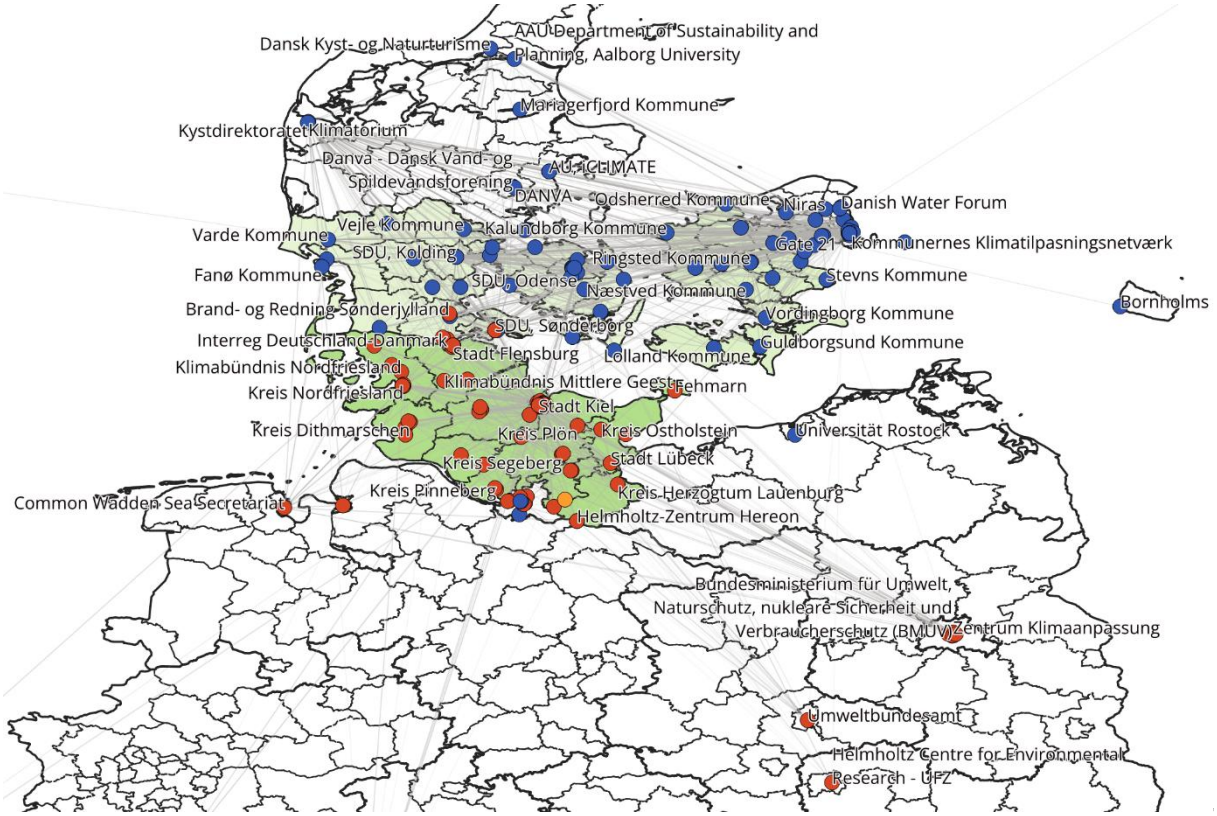
878 *Note:* Panels A and B based on Carter et al. 2021.

**Figure 2.** Climatic conditions and climate-change impact in the Danish-German border region




*Note:* Bottom left figures denote the average and confidence interval across the whole region.

885 **Figure 3.** The complete social network of collaboration with regard to climate adaptation

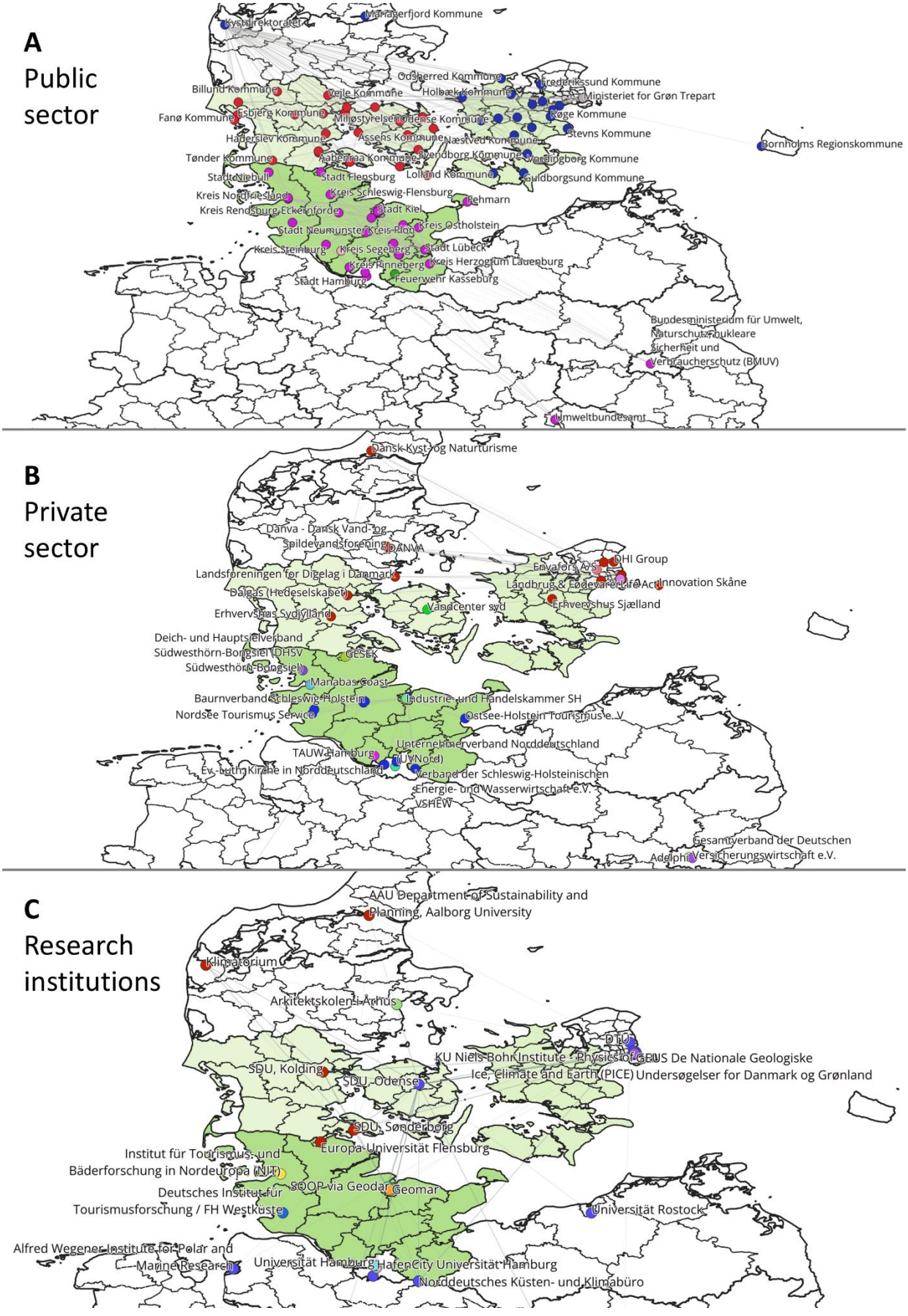



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**Figure 4.** Three type-specific subnetworks of collaboration with regard to climate adaptation



## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.docx