Addressing the climate adaptation tracking gap: an assessment method and its application to the Caribbean region

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ORIGINAL ARTICLE

Addressing the climate adaptation tracking gap: an assessment method and its application to the Caribbean region

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Abstract

This article addresses the climate adaptation tracking gap. Indeed, we still ignore the intensity, nature, spatial distribution, effectiveness, and recent evolution of adaptation efforts at the national, regional, and global scales. We propose a web-based replicable assessment method using key variables to document adaptation efforts: country/territory, location, goal, implementation date, type of action, holder, funding source. Applying it to the Caribbean region, we analyzed 100 coastal adaptation actions. This studies the method while also highlighting the difficulties faced to track adaptation. We found that coastal adaptation efforts are substantial and increasing in the Caribbean, revealing the use of diversified adaptation actions; prevalence of hard protection (51%); increase use of Nature-based Solutions (22%); limited use of retreat (6%); and accommodation (2%). Combined actions (17%) increased over time, due to the failure of single actions and need to find tradeoffs between human asset protection encouraging hard protection and the maintenance of attractive tourist beaches encouraging beach nourishment. Puerto Rico and Trinidad and Tobago fall under the engineering-based "one-size-fits-all" adaptation model, whereas Jamaica and Barbados experiment diversified options and combinations of options. Jamaica, Puerto Rico, Trinidad and Tobago, and Barbados are particularly active in taking adaptation action, while most dependent islands and sub-national island jurisdictions have no adaptation action reported. Considering the advantages and limitations of a web-based method compared to a field-based approach, we recommend the combined use of these two complementary approaches to support adaptation tracking and help structuring communities of practice to the benefits of decision-makers and practitioners and scholars.

Keywords Coastal adaptation · Adaptation tracking · Assessment method · Tropical islands · Caribbean region · Small islands

Introduction

Tropical Islands (TI) are highly exposed to compound risks and their cascading impacts on coastal areas where most of the population, infrastructure, and economic activities concentrate (Glavovic et al. 2022; Mycoo et al. 2022). They experience increasing coastal risks due to the combination of climate change impacts, especially sea-level rise (SLR), climate extremes, and anthropogenic disturbances (Magnan et al. 2019). Climate extremes mainly include extra-tropical and tropical cyclones and El Niño Southern Oscillation (ENSO) events. Whereas the strong swells and heavy precipitations generated by cyclones cause extensive flooding and accelerated shoreline retreat that have destructive impacts on human assets, ENSO events are involved in mass coral bleaching that alters the protection provided by coral reefs (Cooper et al. 2013; Duvat et al. 2019; Eddy et al. 2021). Coastal risks increasingly result from the compounding effects of such events (Bevacqua et al. 2020; Ford et al. 2018). The colonization process amplified these risks through the promotion of highly vulnerable export-driven and climate-sensitive economies and accelerated coastal urbanization (Ferdinand 2019; Pichler and Striessnig 2013).

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Sand mining from beach-dune systems and nearshore areas, the disturbance of physical-ecological processes by coastal development, and maladaptive responses, exacerbated coastal risks (Duvat et al. 2019; Jackson et al. 2012; Klöck et al. 2022). Because coastal risks are likely to make some islands and island coastal areas uninhabitable over this century (e.g., Duvat et al. 2021; Le Cozannet et al. 2021), they increasingly trigger climate adaptation in island countries and territories. This creates a scientific opportunity to better understand coastal adaptation strategies in TI, which this article seizes.

Increasing climate risks call for adaptation which, in human systems, refers to "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC 2022). Adaptation aims at reducing current and future risks, as not addressing short- and long-term challenges in a coordinated manner can lead to maladaptation (Magnan et al. 2016). A wide range of coastal adaptation options exist, which include technical, institutional, ecological, and behavioral actions (Oppenheimer et al. 2019). This paper focuses on technical interventions aimed at reducing coastal climate-related risks, namely coastal erosion and marine flooding. In line with previous studies, these technical interventions include no response, hard protection, accommodation, ecosystem-based adaptation (EbA), retreat, advance with land raising, and de-engineering, which can be used separately or in combination (Duvat et al. 2020; Oppenheimer et al. 2019). No response or "do-nothing" refers to a voluntary absence of action, maintaining coastal risks at their current level and letting them increase in the future (Hoggart et al. 2014). Hard protection consists in reducing coastal risks through the construction of structures (e.g., seawalls or riprap) that fix the shoreline and/or reduce wave impact. Accommodation reduces the structural vulnerability of coastal human assets, including human constructions (e.g., flood-proof buildings). Ecosystem-based adaptation (EbA), which is part of Nature-based Solutions (NbS), reduces climate risk through the protection, improved management, restoration, or creation of coastal and marine buffering ecosystems (Cohen-Shacham et al. 2016). Retreat reduces coastal risks by relocating exposed people, settlements, and human activities, to safer inland areas. Advance with land raising consists of advancing the shoreline through the creation of new and elevated land by reclaiming shallow water areas (Brown et al. 2019). These different actions can be used separately or in combination. For example, the hybrid type combines hard protection and EbA (Nicholls 2018). In line with Duvat et al. (2020: 110), these actions are here referred to as "adaptation-labelled" actions (ALA), since they have not necessarily proven to be effective.

In TI, "there is a consequent need to understand where adaptation takes place and what kinds of interventions are undertaken" (Klöck and Nunn 2019: 3). Whereas numerous scientific studies addressed coastal risks by quantifying hazards (e.g., Giardino et al. 2018) or evaluating vulnerability (e.g., Robinson 2017), limited attention was paid to on-the-ground coastal ALA. Some studies contributed to fill this knowledge gap by providing insights about pilot projects (e.g., Anisimov et al. 2020; Reguero et al. 2018), a given country or territory (e.g., Duvat 2020; Duvat et al. 2020), or a specific type of action (e.g., Betzold and Mohamed 2017; Barnett et al. 2022). Although these studies have improved our understanding of coastal adaptation efforts in TI, we still do not have a comprehensive picture of the technical responses implemented in these settings (Chausson et al. 2020). We still ignore the intensity, nature, spatial distribution, effectiveness, and recent evolution of coastal adaptation efforts in TI. This situation is due to the lack of adaptation tracking at the global and national scales, which makes assessments relying upon available technical reports (e.g., Ferrario et al. 2014) and scattered field investigations (e.g., Duvat 2013). This knowledge gap is exacerbated in archipelagos comprising tens to thousands of islands, due to distance, remoteness, and limited scientific capacities of SIDS compared to continental states (Schultz et al. 2018).

This article thus falls under adaptation tracking research. In line with recent efforts made by scholars (e.g., Magnan et al. 2023), it contributes to the mapping of adaptation efforts in TI through a twofold approach. First, it proposes a methodological protocol aimed at overcoming the limitations of focused studies addressing a specific location or adaptation response. In line with systematic assessments (e.g., Araos et al. 2016), our protocol uses web-based research, following the assumption that this approach allows to cover an entire island region by investigating with the same level of intensity the islands composing it. Key variables are documented for each ALA, including the country/territory concerned, its precise location, main goal, implementation date, type (using the above-mentioned classification) and sub-type, brief description, holder, funding source, and information source. Second, it presents the results of the application of this protocol to coastal ALA in the Caribbean region. Third, based on the lessons learnt from this assessment, which highlight the benefits and limitations of web-based methods, we call for the combined use of web- and field-based approaches to track adaptation.

Context and materials and methods

Study area

This study focuses on 26 Caribbean countries and territories composed of one or several islands, which are part of the Greater and Lesser Antilles and the Lucayan Archipelago (Fig. 1). French overseas territories are not included in this

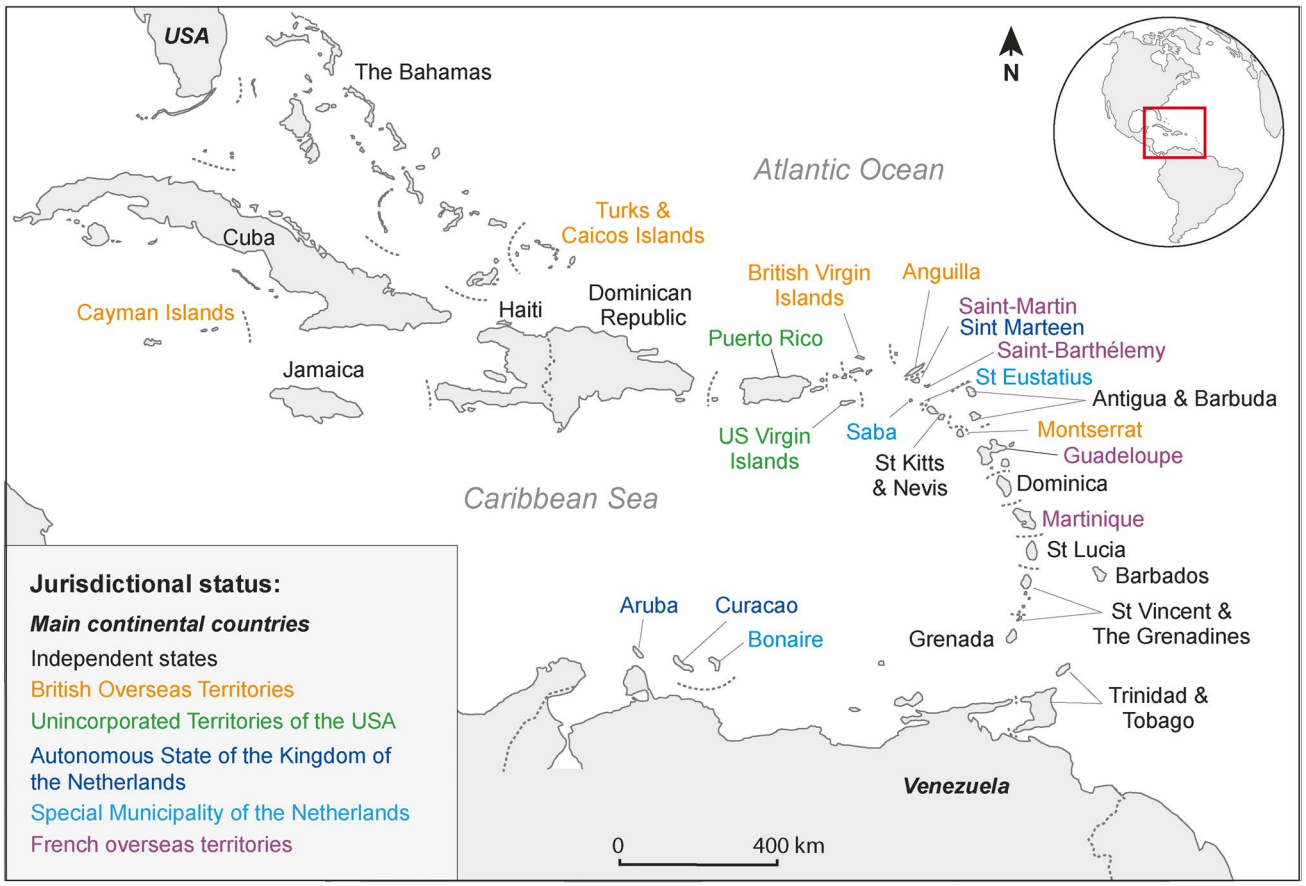

Fig. 1 Study area

study, as they were the focus of another study in preparation. Study islands vary in size, from 13 km^2 for Saba to more than 110,000 km^2 for Cuba. Although most of them are high islands of continental, volcanic, or tectonic origin, several low-lying coral islands are included.

Caribbean TI have a high exposure and vulnerability to climate disasters, especially hurricanes and drought. For example, Hurricane Ivan (2004) affected 79% of Grenada's population (Manuel-Navarrete et al. 2007). Their high vulnerability is driven by a variety of factors, some of which are inherited from the colonial period, including the limited diversification of economic activities, marked societal divisions and inequalities, and widespread environmental degradation (Barclay et al. 2019; Popke and Rhiney 2019; Stancioff et al. 2018). In addition, the small size of Caribbean TI limits available natural and human resources and their coping capacity in the face of climate disasters (Medina et al. 2020; Schultz et al. 2018). Since the mid-twentieth century, coastal urbanization driven by external private investors for beach-oriented tourism and real estate further increased economic vulnerability and population exposure to such disasters (Klein 2018; Scott et al. 2012; Seraphin 2018). Under climate change, Caribbean TI experience an increase in their economic and human vulnerability, especially as their high debt levels challenge their financial capacity to invest in climate adaptation and address adaptation-related governance challenges. This has contributed to maladaptation by constraining the financial resources available at the national level to adapt and encouraging externally driven unsuitable projects (Gheuens et al. 2019; Robinson 2018).

Caribbean TI face increasing coastal erosion and marine flooding. Beach loss was reported in Anguilla, Antigua and Barbuda, St Kitts and Nevis, Montserrat, Dominica, and Grenada, where shoreline retreat reached approximately 0.5 m/year between 1985 and 2000, and it was exacerbated by the 2017 hurricanes (Barreto-Orta et al. 2019; Cambers 2009; Duvat et al. 2019; Pillet et al. 2019). Between 1993 and 2014, relative SLR was greater than average in the Eastern (3–5 mm/year) and North-Western (2.5–3 mm/year) Caribbean (Becker et al. 2019). Hurricanes caused major floods, as highlighted by the 2017 events in Saint-Martin, Saint-Barthelemy, and Cuba (Chew et al. 2020; Rey et al. 2019). In this region, coastal risks are significantly exacerbated by the decline of marine and coastal ecosystems. Seagrasses declined in Bermuda, the Cayman Islands, and the US Virgin Islands, whereas regional-wide bleaching

events caused extensive coral mortality, e.g., in 2005 when 70% of corals were affected (Mycoo et al. 2022). Category 4 and 5 hurricanes are a major risk to population and infrastructure, causing injuries, infectious diseases, and fatalities, especially among vulnerable populations, as well as severe economic loss. For example, Hurricane Maria (2017) caused more fatalities in Puerto Rico's municipalities exhibiting the lowest socio-economic development; it coincided with the first case of *leptospirosis* in the US Virgin Islands; and losses amounted to more than 225% of the annual GDP in Dominica (Eckstein et al. 2018; Mycoo et al. 2022). However, the vulnerability of Caribbean islands varies depending on island size, relative isolation, resources, and socio-economic features, with Haiti being recognized as one of the most vulnerable TI worldwide (Lam et al. 2014; Pichler and Striessnig 2013; Robinson 2017). Coastal erosion is projected to aggravate under accelerated SLR, especially under the RCP8.5 climate scenario (Le Cozannet et al. 2019). In the Caribbean region, where about 22 million people lived below 6 m in elevation in 2017, hurricanes are expected to remain the main driver of flooding (Cashman and Nagdee 2017; Ranasinghe et al. 2021). Even under the optimistic 1.5 °C global warming scenario, SLR would cause the loss of 3100 km^2 of land and be the dominant driver of financial adaptation needs in the region (Mycoo 2018; Tiggeloven et al. 2020).

Identification of coastal adaptation-labelled actions

This study mainly relies on desktop web-based research conducted primarily in English and Spanish, and secondarily in French. It targeted all relevant data sources available online, including scientific and grey literature (mainly technical reports), web media, adaptation program websites, adaptation project brochures, government websites, and climate finance institution websites. We used the search engines *Scopus* and *Google Scholar* to identify relevant scientific publications and *Google* for other sources. The scientific literature search was conducted using keywords associated with the name of the ocean basin (i.e., *Caribbean*). The objective was to collect publications providing information on ALA, either through case studies and pilot projects or through overviews of the situation of study countries and territories. However, this search was not satisfactory, as most collected articles proposed an inventory of risks and recommendations to face them without mentioning concrete actions implemented on the ground. To overcome this limitation, we extended the search to the *Google* engine. First, we focused on a selection of international organizations (i.e., Adaptation Fund, World Bank, Organization of Eastern Caribbean States, Inter-American Development Bank, Caribbean Development Bank, United Nations Development Program, and international NGOs) associated with the name of the ocean basin and keywords related to the topic of interest, including *disaster risk management*, *disaster risk reduction*, *coastal risk reduction*, *coastal protection*, *coastal risk protection*, *climate change adaptation*, *coastal risk infrastructure*, *coastal relocation*, *coastal retreat*, *coastal accommodation*, *coastal ecosystem-based adaptation*, and *coastal nature-based solution* (Fig. 2, step 1). This search allowed us to identify international and regional organizations developing or funding large-scale adaptation programs. These programs were further investigated, either through additional queries on search engines or through the links provided on the web pages visited and the grey literature analyzed. This complementary search allowed us to determine whether ALA were conducted in the TI of interest. If so, the program and related actions were retained. Second, a similar search using the same keywords associated with the name of the ocean basin was run, without entering the name of international organizations (Fig. 2, step 2). This search aimed at completing the first findings by highlighting actions led by less popular organizations and other entities (e.g., public institutions). Third, every program and project retained was searched on *Google* along with the name of the concerned country (Fig. 2, step 3). This allowed us to find concrete cases of ALA. Collectively, these three interrelated steps provided a first sample of ALA. However, for most of them, this search provided more information on risks or governance than on ALA. It mainly served as a basis for the identification of funding programs. A fourth step was then added to the protocol: for each TI, a specific search using the name of the country or territory, and the above-mentioned keywords was run (Fig. 2, step 4). This search mainly led to government websites, including those of ministries and public agencies in charge of environmental matters, planning, and public works. It also directed us to the websites of associations and NGOs holding or implementing projects, and to local press articles. All identified programs and projects were then searched, associated with the name of the country or territory or locality (preferably), to obtain as much information as possible on each ALA (Fig. 2, step 5). Finally, this was completed by a test aimed at checking the relevance of a series of keywords that could potentially improve the inventory already carried out, including *seawall*, *dike*, *levee*, *artificial reef*, *coastal hard defense*, *nature-based solution*, *ecosystem-based adaptation*, *beach nourishment*, *beach restoration*, *coral gardening*, *house on stilts*, *coastal setback*, *coastal managed retreat*, *coastal relocation*, and *coastal managed realignment*. This second list of keywords was used for two territories where no project was found (Anguilla and Curaçao) and for two territories where several projects were identified (the Dominican Republic and Cuba). This last search allowed for the identification of a few additional ALA, but generally it mostly revealed actions that had already been identified.

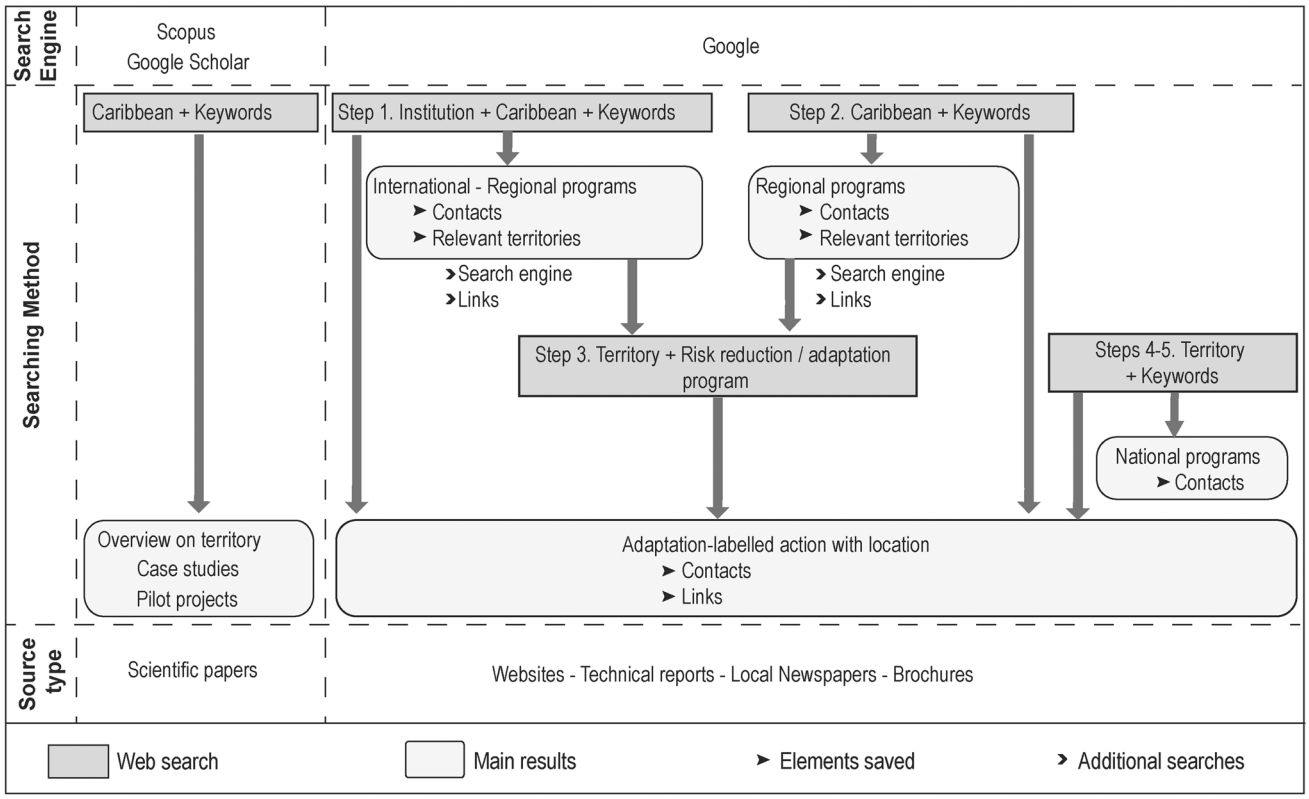

Fig. 2 Web-based search method used to assess coastal adaptation-labelled actions. This flowchart describes the five steps of the search method used to identify and characterize adaptation actions in this study

Database creation

Each inventoried action was entered into an Excel database, with the following attributes filled in: (1) Identification number; (2) Country or territory; (3) Location (from a region to a district); (4) Main goal (reduce coastal erosion, reduce coastal flooding, reduce both coastal erosion and flooding, reduce one of these two risks while also pursuing other objectives, e.g., preserve biodiversity or promote tourism); (5) Implementation date; (6) Action type (e.g., hard protection, following the IPCC categorization described above); (7) Action sub-type (e.g., seawall for hard protection, based on the findings of the search; see sub-types and their definition in Supplementary Material 2); (8) Brief description of the action (see Supplementary Material 2); (9) Holder type (e.g., national public authorities, local public authorities, and NGOs; see full description in Supplementary Material 2); (10) Holder identity; (11) Funding source (national institutions, local institutions, foreign government, NGO, international/regional organizations, private, co-funding; see full description in Supplementary Material 2); (12, 13) Funder type (e.g., hotel company) and identity; (14) Information sources (see Supplementary Material 1). Some of these attributes have predetermined modalities (see Supplementary Material 2 for the full description of the methodological protocol and the definition of the abovementioned modalities). Wherever successive actions were implemented at the same site by the same holder, they were considered as distinct actions and documented as distinct lines in the database, using the same identification number with letters in alphabetical order (e.g., 1a, 1b). For those projects exhibiting missing information, a complementary search was conducted, using photointerpretation of satellite images freely provided by *Google Earth* and contacts with key informants (e.g., project managers or scientists). Thirty-four resource persons were contacted (Supplementary Material 3). The responses obtained provided additional information on actions (27%) and/or new key contacts (21%), who were solicited to collect complementary data. Sixty-two percent of resource persons had invalid email address, did not respond to our request, or could not provide additional information. Those actions for which we were able to document all attributes were kept in the database for processing and analysis. Data were analyzed based on statistical calculations involving flat sorting for each modality and bivariate analysis. Statistical results were reported on maps.

Advantages and limitations of the assessment method

Compared to field-based methods (e.g., Duvat et al. 2020), this protocol had the main advantage of allowing us to cover the whole Caribbean region and to identify a high number of ALA, 143 in total. Among these, we were able to document in full 100 ALA, which constitute the sample used in this study. These ALA were implemented between 1986 and 2021, and most of them over the past decade. Our assessment was constrained by data availability on the web, causing a "reporting bias" (Araos et al. 2016: 4) related to the communication efforts made by project holders. Indeed, ALA implemented on the ground may not be reported on the web. First, this *reporting bias* impacted the visibility of island countries and territories. Overseas territories were found to have limited visibility, since national communication efforts on adaptation generally focus on the mainland. In addition, because we did not conduct any search in Dutch, the Netherlands overseas territories are under-represented in this study. Second, this *reporting bias* led to the over- or under-representation of some types of ALA. We noted over-communication boosting the representation of EbA-NbS and very limited reporting of "do nothing." Likewise, accommodation is under-represented in this study, as it is generally part of national programs upgrading the standard of buildings or addressing the "build back better" challenge. Third, using a web-based protocol makes international and regional organizations and public institutions more visible than local communities and economic actors, since the former undertake communication campaigns highlighting their adaptation efforts whereas the latter do not.

Results and discussion: coastal adaptation-labelled actions in the Caribbean region

As a reminder, 100 ALA were integrated into the database and analyzed. The following sections present the main results obtained. They focus on the main goals of ALA, their type and sub-type, their spatial distribution, their funding, and the risk reduction pathways highlighted by detailed case studies.

Predominance of coastal erosion-oriented actions

Forty-eight percent of ALA aimed at reducing coastal erosion, whereas 28% addressed marine flooding and 21% these two risks (Fig. 3). Although the results may be biased by the inclusion of a high number of erosion-oriented actions implemented in Puerto Rico in our sample, based on the detailed study conducted by Bush et al. (2009), they highlight two key elements. First, the strong economic dependence of Caribbean Islands on beach-side tourism, which pushes public and private actors to take action to maintain or create attractive sandy beaches (Contact No.2, Supplementary Material 3). Second, the role of slow onset erosion accelerated by extreme events in triggering action, compared to rare and temporary flooding (Fabian et al. 2014; Wynne et al. 2016). These results fall in line with observations made in other touristic TI, e.g., in Mauritius (Duvat et al. 2020).

Prevalence of hard protection, Nature-based Solutions, and combined actions

The results reveal the unequal use of the different types of adaptation actions. First, hard protection represents 51% of ALA (Fig. 4a) and is found in most countries and territories. Its use was stable over the past decades. Among hard

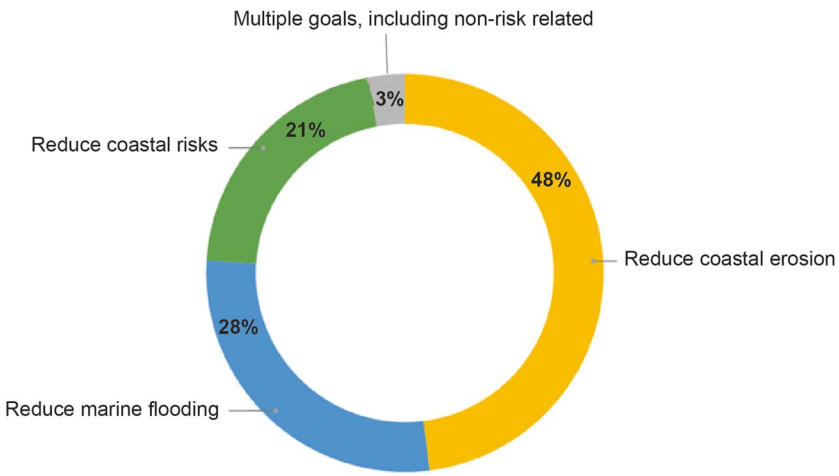

Fig. 3 Main goal of coastal adaptation-labelled actions. Most actions aimed at reducing coastal erosion or marine flooding or both. A very limited number of actions also pursued other goals (e.g., strengthen biodiversity)

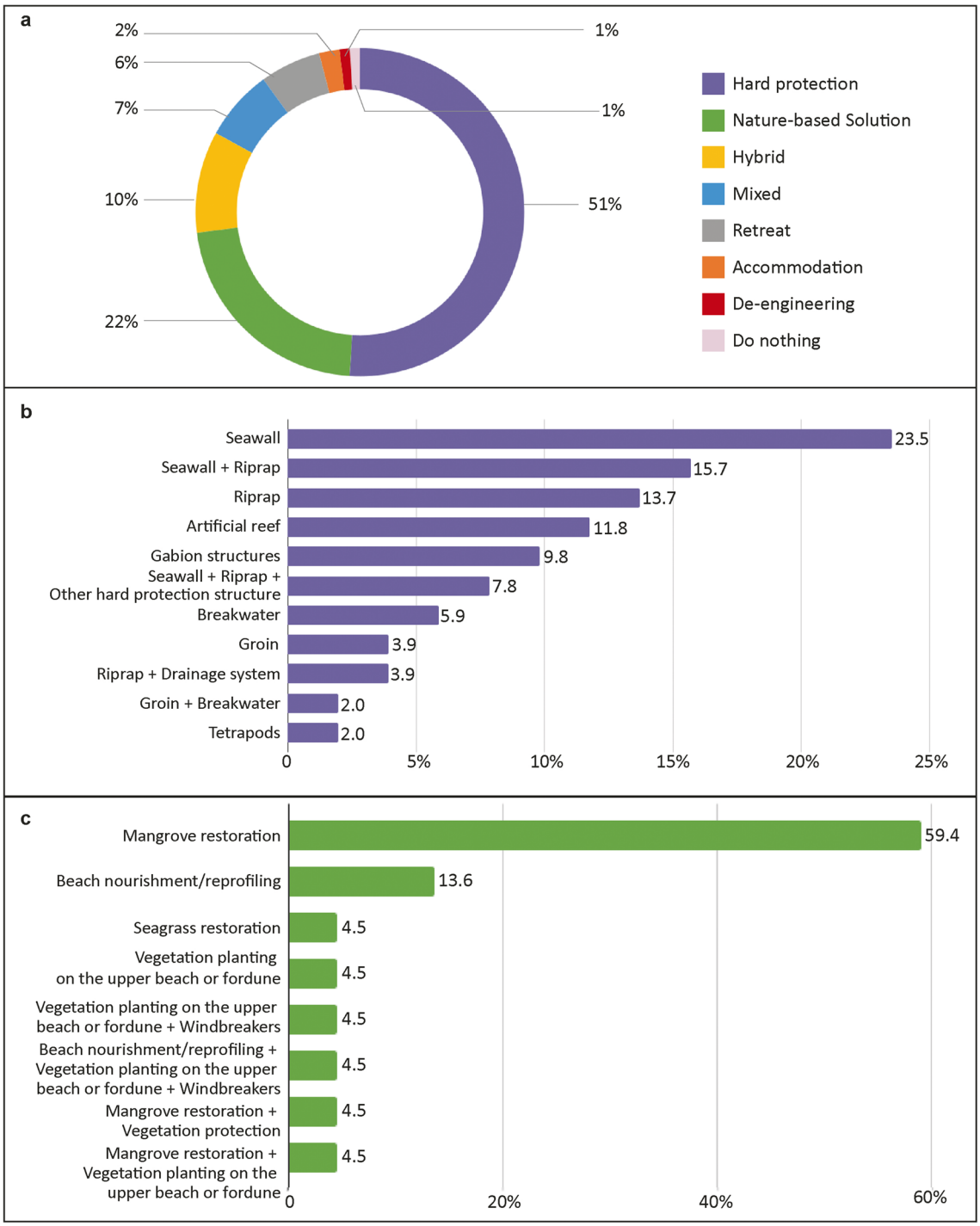

Fig. 4 Distribution of coastal adaptation-labelled actions by type and sub-type. **a** ALA distribution by type; **b** hard protection measures distribution by sub-type; **c** NbS distribution by sub-type

structures, seawalls and riprap prevail, representing 23.5% and 13.7% of these structures respectively, and are often used in combination (15.7%), including with other hard structures (7.8%) (Fig. 4b). These findings are consistent with current knowledge emphasizing the prevalence of hard structures in SIDS, due to the diffusion of the "seawall mindset" from developed to developing countries over recent decades (Banton et al. 2015; Jackson et al. 2012; Klöck et al. 2022). The widespread use of seawalls in Caribbean islands is consistent with observations made in the Pacific Ocean (e.g., Fiji and Kiribati; Duvat 2013; Klöck et al. 2022; Nunn et al. 2021) and Indian Ocean (e.g., Reunion, Comoros, the Maldives;

Betzold and Mohammed 2017; Duvat 2020; Magnan and Duvat 2018; Ratter et al. 2019). This has caused a hard path dependency involving well-established institutional practices, past policies, and former investments, which contributed to its persistence and reinforcement over time, despite the failure and maladaptive character of hard structures at many locations and the emergence of alternative and more promising nature-based options (Morris et al. 2018; Nunn et al. 2021; Parsons et al. 2019; Temmerman et al. 2013).

Second, NbS represent 22% of adaptation actions, 64% of which were implemented over the past decade (Fig. 4a and Supplementary Material 1). The increasing use of NbS worldwide and in TI is due to a variety of factors, including the recognition of the failure of hard protection to reduce coastal risks, the growing international support provided to these alternative options (e.g., by the Convention on Biological Diversity or World Economic Forum), the promotion of community-based adaptation, and the recommendations made by the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) for their wider diffusion (Chausson et al. 2020; Cohen-Shacham et al. 2019; Logan et al. 2018; Nesshöver et al. 2017; Reid et al. 2018; Scarano 2017; Wilson and Forsyth 2018). This strong support relies upon their potentially high effectiveness, low-cost compared to hard measures, "no-regrets" character, and the multiple co-benefits they generate, especially in TI (Beck et al. 2022; Ferrario et al. 2014; Manes et al. 2022; Narayan et al. 2016; Ruangpan et al. 2020). The sustained communication efforts made by NbS funders may have boosted NbS in our sample. In addition, our results reveal that the dominant type of NbS in the Caribbean is ecosystem restoration, whereas we only found a few cases of ecosystem protection and no case of ecosystem creation. With 59.4% of NbS, mangrove restoration is the most common NbS in the region. In contrast, seagrass restoration only accounts for 4.5% of NbS (Fig. 4c), which is in line with the observation made by Wilson and Forsyth (2018: 6) that "Restoration of seagrasses have generally received less attention than [restoration of] mangroves and coral reefs." We found two cases of hybrid actions involving coral gardening and hard protection in Antigua and Barbuda and in the Cayman Islands (Fig. 6a). The limited use of reef-based actions in our sample may be due first, to the high level of degradation of reefs in the Caribbean which negatively affects the protection they can provide, and second, to the challenging character of reef restoration more generally (Duarte et al. 2020; Lirman and Schopmeyer 2016). Cost differences of restoration between marine ecosystems may also explain these results, as seagrass and reef restoration are much more expensive than mangrove restoration (Bayraktarov et al. 2016; Morrison et al. 2019). NbS were mainly found in Jamaica, Barbados, the British Virgin Islands, Haiti, Grenada, the Dominican Republic, and Puerto Rico (Fig. 5).

Third, our results emphasize the use of other adaptation options, although these latter proved rarer (Fig. 4a). Retreat, which mainly consists in the relocation of people in our sample, represents 6% of ALA, with all cases found in Jamaica (Fig. 5). Accommodation is also used in the Caribbean, but to a lesser extent with only 2% of ALA. We only found one case of de-engineering, in Puerto Rico (Figs. 5 and 6), and one case of "do nothing," in Barbados. Advance with land rising was used as part of mixed actions in Jamaica (Fig. 6d). Thus, the various types of adaptation actions listed in the scientific literature are used in the Caribbean region, although their distribution is uneven. The above-mentioned *reporting bias* may contribute to the under-representation of accommodation and "do nothing" in our sample. Because accommodation is generally implemented under national programs through building codes or at individual level by inhabitants, it requires fieldwork to be adequately reported (López-Marrero 2010). Besides, the "do nothing" strategy is rarely reported, as the public authorities in charge of adaptation are supposed to take action, that is, "to do something" to reduce risk.

Fourth, 17% of ALA consist of combined actions. Among these, hybrid actions (combining hard protection and NbS) and mixed actions (other combinations) respectively represent 10% and 7% of ALA (Fig. 4a). Beach nourishment/reprofiling is involved in 90% of hybrid actions, including in association with other NbS. For example, seawalls, vegetation planting, and beach nourishment/reprofiling were implemented together in Anguilla, whereas breakwaters, groins, and beach nourishment/reprofiling were used jointly in Santa Lucia and St Kitts. Mixed actions, which generally involve accommodation, combine up to six technical interventions, as in Annotto Bay, Jamaica, where they associate hard protection, advance, NbS, and accommodation (Fig. 6d). We also noted combinations involving various sub-types of hard structures (joint use of seawalls and riprap; Fig. 4b), and various sub-types of NbS, with combinations representing 18% of the total for NbS (Fig. 4c and Fig. 6). The increasing development of combined ALA is in line with a growing assumption that optimal adaptation requires a combination of measures, preferably "green" and "grey" (Reddy et al. 2016).

Finally, we noted the occurrence of uncoordinated actions implemented at a given location by different stakeholders over time, sometimes with different objectives and without making any reference to former actions (Fig. 6). Six examples were identified, four of which in Jamaica. In Old Harbor Bay, Jamaica, relocation was implemented by the Office of National Reconstruction and followed by the installation of an artificial reef by the National Environment and Planning Agency. Likewise, in Rincon, Puerto Rico, hard structures were built by the local public authorities to reduce coastal erosion, which were later complemented by vegetation

planting by residents. In Telescope, Grenada, two projects of mangrove restoration took place almost simultaneously without coordination (Contact No.34, Supplementary Material 3).

Spatial distribution of coastal adaptation actions

ALA are unevenly distributed across the Caribbean (Fig. 5). Out of the 26 countries and territories considered, eight are missing from the inventory, all of which are either dependent islands (DI) or sub-national island jurisdictions (SNIJ), following the typology proposed by Petzold and Magnan (2019). Although the reporting biases may contribute to the low visibility of these territories, this finding confirms the difficulties for DI and SNIJ to implement ALA due to the lack of local means and human resources and expertise, absence of representation in United Nations negotiations, limited bilateral help, lack of financial and legislative support from mainland, and eviction from international and regional programs (Petzold and Magnan 2019). Moreover, some countries and territories are much more active in climate adaptation and communication than others. Puerto Rico (22 actions), Jamaica (18), and Trinidad and Tobago (10) gather 50% of the actions reported. This is due, first, to the existence of comprehensive data sources inventorying adaptation actions in these countries and territories (e.g., Bush et al. 2009 for Puerto Rico); second, to their strong communication efforts. For example, the Coastal Protection Unit of the Ministry of Work and Transport, Trinidad and Tobago, provides a list of ALA on its website. Likewise, web publications emanating from the government, the local press, and the Adaptation Fund extensively document ALA in Jamaica. The fact that Trinidad and Tobago and Puerto Rico are high-income countries probably contributes to their capacity to both implement and communicate around adaptation actions (Chausson et al. 2020). Among the 18 countries and territories that implemented ALA, 13 implemented less than 5 actions, whereas 3 implemented 6 to 10 actions (Fig. 5).

The unequal spatial distribution of ALA is also obvious at the scale of countries and territories, at which a

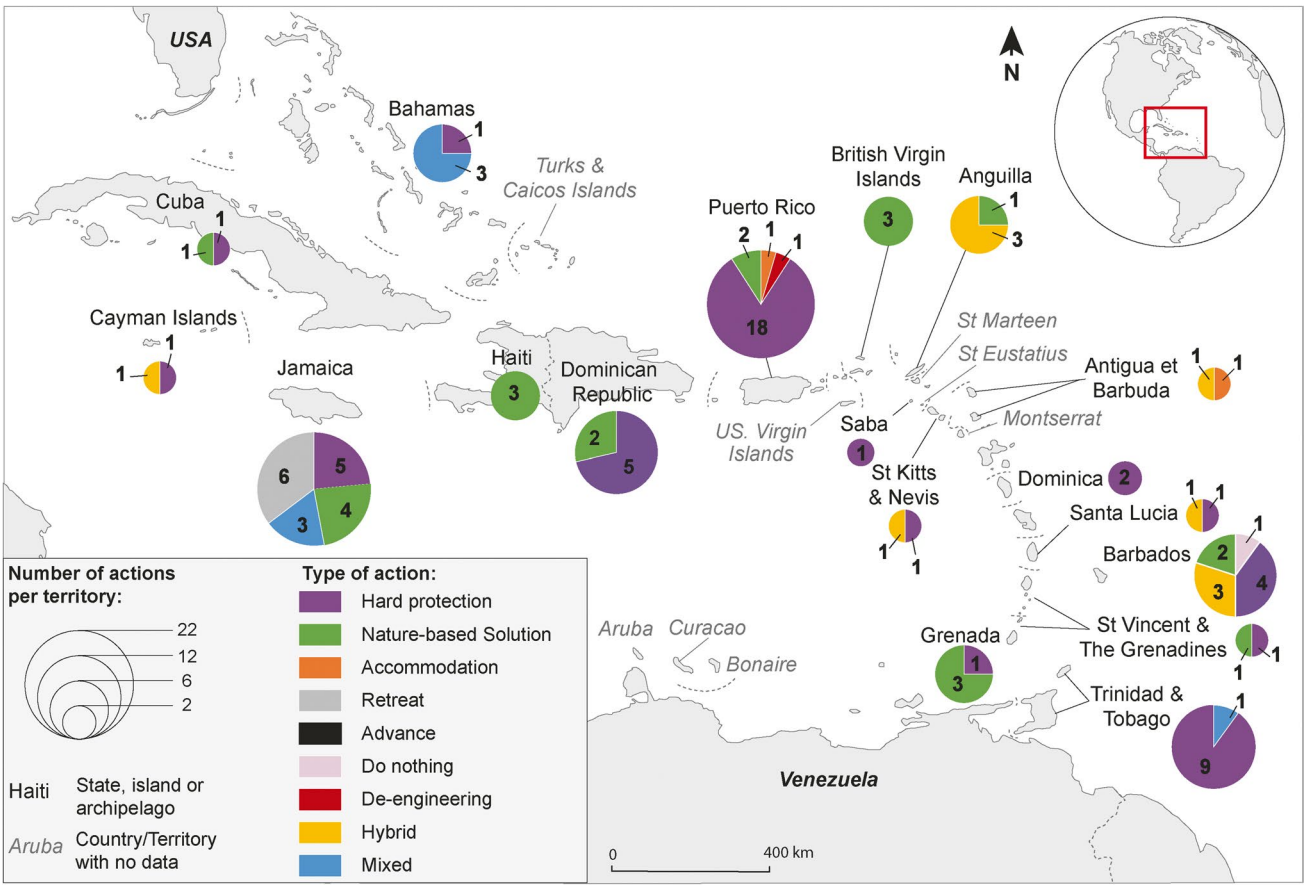

Fig. 5 Spatial distribution of coastal adaptation-labelled actions in the Caribbean region. This map emphasizes the uneven distribution of actions between the 26 countries and territories considered. Whereas eight countries and territories exhibit no action, five countries and territories concentrate most of inventoried actions, including Puerto Rico (22), Jamaica (18), Trinidad and Tobago (10), Barbados (10), and the Dominican Republic (7)

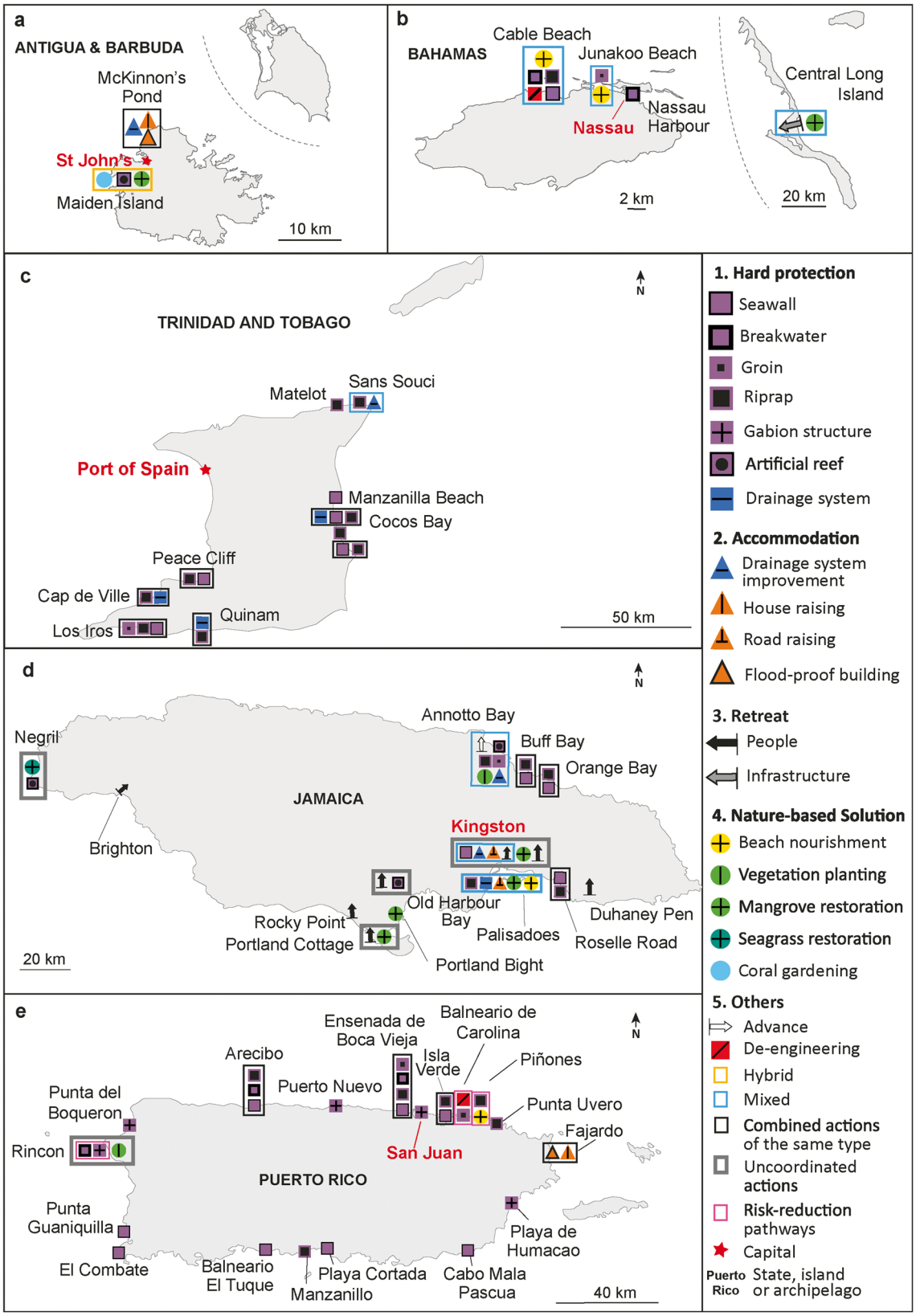

Fig. 6 Selected island examples of coastal adaptation-labelled actions in the Caribbean region. This figure shows the spatial distribution of actions at the island scale. It highlights, first, the high number of actions implemented in Trinidad and Tobago, Jamaica, and Puerto Rico; second, the prevalence of hard protection in some countries (e.g., Trinidad and Tobago, Puerto Rico); third, the extended use of combined options, mostly mixed

core-periphery gradient emerges, with capital islands concentrating most actions, e.g., in the Bahamas, St Kitts and Nevis, Antigua and Barbuda, and Trinidad and Tobago (Fig. 6a, b, and c). This finding is consistent with the assertion made by Klöck and Nunn (2019: 8) that "the core benefits from higher levels of external support and tends to have more and better infrastructure and technical know-how [compared to the periphery]." This statement was since then confirmed by additional studies (Nunn et al. 2021; Klöck et al. 2022). The spatial analysis also revealed the preference of some countries and territories for some ALA. Whereas the coastlines of Trinidad, Puerto Rico, and the Dominican Republic, are largely fixed by hard structures, Jamaica and Barbados show greater diversity of ALA (Fig. 6c, d, and e).

Funding of coastal adaptation actions

First, the major actors involved in coastal adaptation funding are national and local institutions (named public institutions hereafter), international and regional institutions, and the private sector (Fig. 7). In our sample, public institutions funded 40.5% of ALA, with national institutions (23.3%) prevailing over local institutions (17.2%). International organizations (Adaptation Fund, World Bank, and United Nations programs; 10.1%) and regional organizations (Inter-American Development Bank, Caribbean Development Bank; 10.1%), which played an increasing role in coastal adaptation funding since 2010, 20.2% of ALA. This result is in line with the findings of Robinson and Gilfillan (2017). In addition, 14.1% of ALA were co-funded by public institutions and international and regional organizations. The private sector, mainly represented by hotel companies in our sample, funded 20.2% of ALA. Last, minor funding sources include NGOs (3.0% of actions) and foreign governments (2.0%).

Second, these various funders supported different types of ALA (Fig. 7). Public institutions mainly supported hard protection (with 53% of hard protection actions), often used as a "one-size-fits-all" solution in TI because it benefits from an important visibility and provides an immediate sense of protection to residents (Betzold and Mohamed 2017; Logan et al. 2018; Nunn et al. 2021; Ratter et al. 2019). In addition, public institutions supported all retreat projects whereas they were little involved in NbS (10% of NbS funding only). In contrast, international and regional organizations extensively funded NbS, either separately (32% of NbS actions) or through co-funding involving partnership with governments (27%), and most mixed actions (43%). Private actors, especially hotel companies, were mainly involved in hybrid actions aimed at protecting exposed buildings while also supporting the maintenance of threatened beaches (Contact No.2, Supplementary Material 3).

Third, the analysis of ALA funding reveals marked differences between countries and territories. Whereas climate adaptation relies on public institutions in some countries (Jamaica, Barbados, and Trinidad and Tobago), it mainly depends on external funding in others (the British Virgin Islands, Haiti, the Bahamas). For example, in the British Virgin Islands, almost all ALA were funded by international and regional organizations. This situation questions the ability of such countries to bear the cost of these actions over time, which in turn questions the long-term effectiveness of actions requiring maintenance and monitoring, such as hard protection and NbS (Nunn and Kumar 2019).

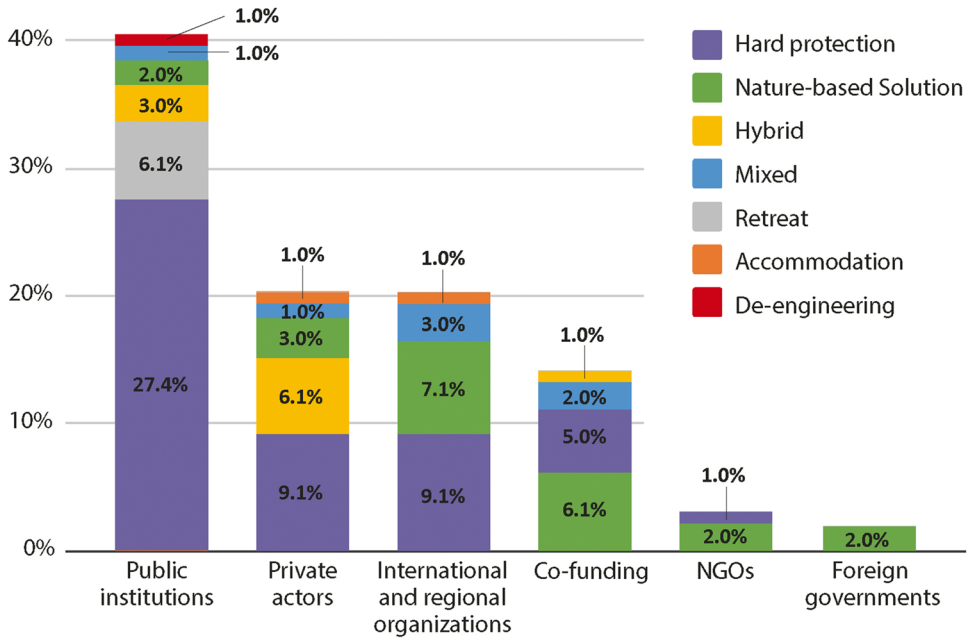

Fig. 7 Funding of coastal adaptation-labelled actions in the Caribbean region. Public institutions include both national and local institutions. Private actors include hotel companies and residents. Co-funding refers to any combination of different funding sources (e.g., regional organization and national government; national government and foreign government)

Past-to-present risk reduction pathways

At six locations, various ALA were successively implemented by the same stakeholder over time to reduce coastal risks (Fig. 8). In line with Duvat et al. (2020), this situation allows to highlight risk reduction pathways. Most cases involved the combination of soft and hard measures. At some locations, stakeholders first used NbS and then shifted to hard or hybrid structures. In Maundays Bay, Anguilla, a hotel company first implemented repeated beach nourishment/reprofiling in the 1990s. Because this action failed in protecting beach villas from wave-driven damages during Hurricane Lenny in 1999, the hotel company installed a seawall while also continuing beach nourishment and replanting vegetation in the 2000s (Wynne et al. 2016; Contact No.2, Supplementary Material 3). Similarly, in Piñones, Puerto Rico, beach nourishment was first carried out in 1986 to rebuild a dune affected by sand mining that protected the coastal road. The artificial dune was destroyed by storm waves and eventually replaced by riprap in the 1990s. In these cases, the successive actions undertaken were motivated by the failure of previous actions in stopping beach erosion and associated damage. In Telescope area, Grenada, to reduce marine flooding, a project was implemented which involved first mangrove restoration and a year later, the installation of four artificial reefs (Reguero et al. 2018). At other locations, adaptation actions shifted from hard to hybrid measures or NbS. At Gran Dominicus Resort, Dominican Republic, artificial reefs were first installed, followed by beach nourishment (Fabian et al. 2014). This second action was motivated by the fact that the reefs did not significantly reduce wave energy. This led to their strengthening by the addition of rock units. These artificial reefs then caused excessive beach accretion and were for this reason moved further offshore (Fabian et al. 2014). The same type of situation occurred at Grand Cayman Marriott Resort, Cayman Islands, where artificial reefs were first installed to promote beach accretion in 2002, and complemented a few years later with new artificial reefs, coral gardening, and beach nourishment (Fabian et al. 2014). In contrast, in one case, the same type of response was maintained over time. This occurred in Rincon, Puerto Rico, where gabions were installed in the early 1990s and replaced by seawalls the next decade to stop beach erosion, with both actions failing. Interestingly, five out of these six risk reduction pathways underline hybridization of actions. The tourism-oriented function of beaches contributed to the choice of NbS, especially beach nourishment, which reinforces the aesthetic value of beaches (Contact No.2, Supplementary Material 3).

Way forward to improve adaptation tracking

We designed and applied to the Caribbean region a web-based methodological protocol aimed at tracking coastal adaptation. This protocol allowed us to map 100 coastal adaptation actions across the Caribbean region and to document them using nine key variables, including the country/territory where the action was implemented, the precise location of the action, its main goal, implementation date, type (using the IPCC categorization), sub-type, brief description, holder, and funding source. This demonstrates that our web-based method (see the "Identification of coastal adaptation-labelled actions" section), which is transferable to non-coastal adaptation actions and to other regions of the world, can provide a valuable support to adaptation tracking and thereby help to build an overall picture of climate adaptation worldwide (Table 1).

However, using the web to document adaptation actions revealed six main limitations. First, whereas the web search allowed us to identify 143 ALA, we were only able to document 100 ALA in full. This is because the actors involved in adaptation actions do not necessarily communicate in detail

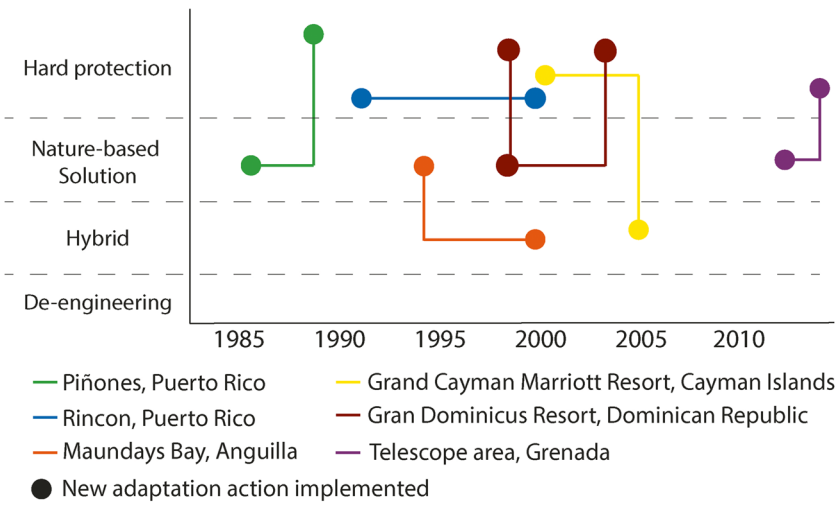

Fig. 8 Examples of coastal risk reduction pathways in Caribbean Islands. These risk reduction pathways highlight shifts in adaptation actions over time and show, although the sample is small, the increased use of hybrid options

about them on their websites and because no inventory effort is made at the country or territory level to report on adaptation. Consequently, the amount and type of information provided on adaptation actions varies significantly from one project to the other. To address this limitation and increase both the number of ALA included in our sample and the amount of information provided on each ALA, we used photointerpretation of satellite images and contacts with key informants (e.g., project managers or scientists). Although this allowed us to strengthen our ALA sample, 62% of the informants who were contacted did not provide additional information (invalid email address, no response, no information to share). Second, information gaps prevented us to determine for each ALA the reasons for its implementation, especially if it was deployed to address climate change impacts and/or pursue other goals (e.g., improve beach condition or support tourism revenues). Third, using the web to track adaptation led to the under-representation of some countries (eight out of the 26 countries targeted are missing in this assessment) and territories (i.e., overseas territories). Fourth, the web-based search also led to the under-representation of some types of ALA for which communication efforts are limited, including "do nothing" (as adaptation actors communicate about "the actions taken") and accommodation. The latter is generally supported by the public authorities through sectoral policies (e.g., housing policies aimed at promoting flood-proof buildings), making it difficult to capture localized accommodation actions (e.g., house on stilts) using a risk-oriented web-based protocol. Fifth, our web-based search led to the over-representation of the actions taken by "visible actors"—i.e., having a website and feeding it (i.e., public institutions, international and regional organizations, and NGOs)—and under-representation of the actions taken by actors who are less visible or "invisible" in the web (e.g., local communities and private individuals) or do not communicate about the adaptation actions they take. Sixth, our web-based method made it difficult to reconstruct risk reduction pathways (only six pathways highlighted), although the latter are crucial to learnt from past experiments to improve the effectiveness of adaptation actions.

These methodological limitations can be overcome by combining a web-based method such as the one used in this study with a field-based approach involving local scientists and adaptation stakeholders at large (Table 2). Local social scientists could, for example, be involved in field visits and semi-structured interviews and focus groups with public institutions, NGOs, and local associations, to collect detailed information on adaptation actions (e.g., Anisimov et al. 2020; Duvat et al. 2020; López-Marrero 2010). This would allow to describe in detail these actions and detect actions that are "invisible" on the web. Additionally, local ecologists and geomorphologists could provide valuable information on the successes and failures of past

Table 1 Benefits and limitations of a web-based approach for adaptation tracking

Variables	Web-based approach	
	Benefits	Limitations
1. Spatial scale	- National - Regional - Global	- No action reported for some countries (dependent islands and sub-national island jurisdictions) and territories (overseas)
2. Temporal scale	- Allows to document a large number of adaptation actions within a limited amount of time	- Makes it difficult to assess adaptation progress through repeated assessments
3. Description of adaptation actions	- Provides information on country/territory, action location, risk targeted, date of implementation, type and subtype of action, brief description, holder, and funding - Allows to reconstruct some risk reduction pathways	- Not exhaustive: major data gaps prevent the consideration of some adaptation actions; actions that are "invisible" on the web are missed - Limited information on the reasons that triggered action - Under-representation of some types of actions (accommodation and "do-nothing" for coastal adaptation) - Under-representation of the actions taken by "invisible" actors (local communities, private individuals, and companies) - Difficulty to reconstruct a large number of risk reduction pathways due to the lack of reporting and high staff turnover, especially in public institutions
4. Information sources	- Allows to identify some adaptation stakeholders (especially public institutions, NGOs, international and regional organizations) - Allows to identify key informants	- Some adaptation stakeholders (especially local communities, residents, hotel companies) and the information they have can be missed - Hazardous and limited contribution of informants

This table is based on the lessons learnt from the present study

Table 2 Benefits and limitations of field-based approaches for adaptation tracking

Variables	Field-based approach	
	Benefits	Limitations
1. Spatial scale	- Local (site) - National	/
2. Temporal scale	- Allows repeated assessments aimed at measuring adaptation progress	- Requires a large amount of time (field visits, interviews…)
3. Description of adaptation actions	- Provides detailed information on adaptation actions, including the reasons that triggered action, the various types and sub-types of actions, actions taken by "invisible" actors - Allows to reconstruct some risk reduction pathways	- Difficulties to reconstruct a large number of risk reduction pathways due to the lack of reporting of actions and high staff turn-over, especially in public institutions
4. Information sources	- Allows to identify some adaptation stakeholders (local communities, private individuals, and companies) - Allows to identify local key informants and collect information among them	- Some adaptation stakeholders (especially international and regional organizations, NGOs, foreign governments) and the information they have can be missed

This table is based on the lessons learnt from a previous field-based study (Duvat et al. 2020)

adaptations actions and help reconstruct risk reduction pathways. The comparative analysis of the specific benefits and advantages of web- and field-based approaches demonstrates that they are resolutely complementary (Tables 1 and 2). Web-based methods allow to cover entire countries and regions (e.g., the Caribbean region in this study) and to detect a large number of adaptation actions (143 actions in this study). This research effort is needed to develop region-wide assessments which, once aggregated, can feed global databases allowing to track adaptation and adaptation progress (through the reiteration of the approach) globally. Moreover, regional assessments are crucial to foster adaptation progress through experience sharing. In addition, field-based approaches can help filling the gaps of web-based methods by providing information on "invisible" countries and territories and detailed information on adaptation actions to document (i) the nine key variables identified to describe actions, (ii) the specific reasons why they were implemented, (iii) actions that are "invisible" on the web, (iv) actions taken by actors that are "invisible" on the web, and (v) risk reduction pathways. On this latter point, a previous field-based assessment completed in Mauritius showed that reconstructing risk reduction pathways based on interviews and locally available grey literature is challenging (Duvat et al. 2020), due to the lack of reporting of adaptation actions and a high staff turnover explaining a limited memory of past actions in public institutions. Beyond this challenge, combining web- and field-based approaches would help creating or structuring communities of adaptation practice through increased networking efforts, which would in turn help designing robust standards for the development of national and global adaptation databases to the advantage of decision makers and practitioners and scholars.

Conclusion

This study provides an overview of coastal adaptation-labelled actions in the Caribbean, based on a sample of 100 technical actions identified using a web-based approach. Although it is not exhaustive and has some limitations that are inherent to the search method used, it demonstrates that desktop research can provide a valuable contribution to adaptation tracking at various spatial scales (including island, national, and regional), and proposes a replicable protocol to address this gap. First, we found that adaptation efforts aimed at reducing coastal erosion (48% of actions) and marine flooding (28%) are substantial in the Caribbean. Second, in line with Pacific and Indian Ocean studies, this article highlights the prevalence of hard protection (51% of actions), especially seawalls (23.5% of hard structures) and riprap (13.7%), over Nature-based Solutions (22% of actions). The latter were more recently implemented, and they mainly consist of mangrove restoration (59.4% of NbS). Retreat and accommodation only represent 6% and 2% of actions, respectively. Combined actions, including hybrid actions involving hard protection and NbS (90% of which involve beach restoration) and mixed actions (other combinations), represent 17% of actions and increased over time. The hybridization of actions is confirmed by reconstructed risk reduction pathways. Combinations of actions and the accumulation of technical interventions over time result from the failure of single actions and the need to protect effectively human assets while also maintaining attractive beaches for tourism. Whereas some countries fall under the engineering-based "one-size-fits-all" adaptation model (e.g., Puerto Rico and Trinidad and Tobago), others (e.g., Jamaica and Barbados) experiment diversified options and

combinations of options to adapt. Third, this study highlights the unequal spatial distribution of adaptation efforts, with Jamaica, Puerto Rico, Trinidad and Tobago, and Barbados being particularly active, whereas most dependent islands and sub-national island jurisdictions have no adaptation action reported. This emphasizes significant differences in island countries and territories capacity to take adaptation action. A core-periphery gradient was also noted. Fourth, coastal adaptation funding mainly relies on public institutions, international and regional organizations, and the private sector. These various actors support different types of actions. Public actors mainly fund hard protection and retreat, whereas international and regional organizations support NbS and combined actions. The latter also have the preference of hotel companies. Some island countries and territories are highly dependent on external funding, which questions their ability to face adaptation challenges over the long run.

We identified six limitations that are inherent to web-based methods, including difficulties to (i) document adaptations actions deployed in some countries (eight out of the 26 countries targeted have no action reported) and territories (especially overseas); (ii) document adaptation actions in full using our nine key variables; (iii) determine the reasons that triggered action (climate-related or not); (iv) report on the various types of adaptation actions equally ("do nothing" and accommodation are under-reported in the web); (v) report on the actions taken by local communities, private individuals, and private companies; (vi) reconstruct risk reduction pathways, due to the lack of reporting of past actions and high staff turn-over, especially in public institutions. We argue that these five limitations could be overcome by combining the web-based method used in this study with a field-based approach. Each of these two approaches has specific benefits and limitations. A web-based protocol allows to identify a large number of actions at the national and regional scales and to provide a first description of these actions. In addition, field-based methods involving local scientists (from social to physical sciences) and stakeholders (especially public institutions, NGOs and local associations, and private companies) would allow to collect in-depth information on actions and thereby help filling the abovementioned gaps. Furthermore, bridging web- and field-based approaches would allow creating or structuring communities of adaptation practice, which would in turn help designing robust standards for the development of national to global adaptation databases to the advantage of decision-makers and practitioners and scholars.

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