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Environmental impacts of climate change adaptation

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ABSTRACT

Climate change adaptation reduces adverse effects of climate change but may also have undesirable environmental impacts. However, these impacts are yet poorly defined and analysed in the existing literature. To complement this knowledge-gap, we reviewed the literature to unveil the relationship between climate change adaptation and environmental impact assessment, and the degree to which environmental impacts are included in climate change adaptation theory and practice. Our literature review showed that technical, social and economic perspectives on climate change adaptation receive much more attention than the environmental perspective. The scarce interest on the environmental impacts of adaptation may be attributed to (1) an excessive sectoral approach, with dominance of non-environmental perspectives, (2) greater interest in mitigation and direct climate change impacts rather than in adaptation impacts, (3) a tendency to consider adaptation as inherently good, and (4) subjective/preconceived notions on which measures are good or bad, without a comprehensive assessment. Environmental Assessment (EA) has a long established history as an effective tool to include environment into decision-making, although it does not yet guarantee a proper assessment of adaptation, because it is still possible to postpone or even circumvent the processes of assessing the impacts of climate adaptation. Our results suggest that there is a need to address adaptation proactively by including it in EA, to update current policy frameworks, and to demand robust and reliable evaluation of alternatives. Only through the full EA of adaptation measures can we improve our understanding of the primary and secondary impacts of adaptation to global environmental change.

1. Introduction

The effects of climate change are tangible and demand actions (Pielke et al., 2007; Klein, 2011). These actions can be mitigation, to prevent greenhouse gas (GHG) emissions or reduce their atmospheric concentration, or adaptation, to adjust to actual or expected climate and its effects (Field et al., 2014). Mitigation and adaptation have been seen as 'mirror images' (Yohe, 2001) or substitutable (Buob and Stephan, 2011). This led to climate policies focus on mitigation (Biesbroek et al., 2010), because adaptation was seen as a substitute (Adger et al., 2005; Klein, 2011; Hallegatte et al., 2011) with local and tangible benefits, in contrast to the global benefits of mitigation (Wilbanks et al., 2007; Klein, 2011). Currently, both mitigation and adaptation are widely accepted as interrelated actions in addressing climate change (Klein et al., 2005; Warren et al., 2012). However, any adaptation measure may have unintended environmental impacts (Adger et al., 2005), which could question its suitability for achieving the desired objectives.

Adaptation to climate change is at the intersection of science, communities and decision-making, with different spatial and temporal scales (Scarlett, 2011), and is influenced by social issues, financial resources, political context, public awareness, politicization of climate change or scientific uncertainty (Carlson and McCormick, 2015). Consequently, different approaches have influence in decision-making, but with a risk of monopolizing the debate, biasing the choice of adaptation. Adaptation is not exclusively linked to climate change, but the effects of 'climate change', due to human influence, or of 'changing climate', due to natural irregularity, are quite similar (Kiem and Austin, 2013). In fact, many climate change adaptations build on traditional measures adjusted to deal with new or increased impacts. Novel vulnerabilities and impacts may need alternative and innovative measures. Adaptation to climate change is the process of adjustment to actual or expected

Abbreviations: EA, Environmental Assessment; EIA, Environmental Impact Assessment; GHG, Greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; SEA, Strategic Environmental Assessment.

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climate and its effects, and may be done through a wide range of actions, structural, institutional, or social (Agard et al., 2014).

The impacts of climate change on human and natural systems and the adaptation to them have been extensively studied, in general (e.g. IPCC, 2014) or by sector (e.g. for agriculture by Wreford et al., 2010; for pastoral systems by Lieffering et al., 2016; for transport infrastructure by Nemry and Demirel, 2012; for winter tourism by Abegg et al., 2007; or for human health by Haines et al., 2006). Guidance about climate change and EA, both Strategic Environmental Assessment (SEA) and Environmental Impact Assessment (EIA), are available for example in the USA (CEQ, 1997, 2010), Canada (CEAA, 2003), the UK (IEMA, 2010a, 2010b) or the European Union (EU, 2013), whose EIA Directive (EU, 2014) explicitly requires the consideration of climate change. According to these documents, EA should assess both the contribution to climate change and the impacts of climate change in the plans, programmes and projects, and propose mitigation and adaptation measures. Nevertheless, they fail to mention the environmental impacts of mitigation and adaptation. The environmental impacts of adaptation are receiving little attention in policy design, EA regulations, academic debate (Fezzi et al., 2015) and decision-making.

The aim of this paper is to analyse the literature to establish whether the environmental approach has been linked to climate change adaptation, and the degree to which environmental impacts are assessed in this context. For this purpose, we reviewed academic and 'grey' literature, selecting documents with specific measures for climate change adaptation, and in particular those that may have significant environmental impacts. In the selected sample, we analyse the sectoral approach of the documents, characteristics of the measures and degree of consideration of environmental impacts.

2. Methodology

Adaptation is a multidisciplinary field with different agents working on it. Consequently, a comprehensive review on the topic should include a wide range of documents from different perspectives and sources, both academic and grey literature. Difference in source format, style and objectives, and the need of searching quite specific concepts, limits the ability of traditional search engines to provide sufficient information, thus requiring an approach that combines both traditional searchers with an individualized search of documents. Once the combined search is conducted, individual documents are analysed in depth both qualitatively and quantitatively. According to Berrang-Ford et al. (2015) our review falls under the method of 'realist review', with mixed qualitative and quantitative components. We have also followed these authors' proposal of components for a review, which includes mentioning the research question/aim, data sources and document selection, and analysis and presentation of results.

2.1. Research questions

Our review assessed how the environmental impacts of adaptation have been addressed in the literature. For this purpose, we have defined questions in three main topics:

a) *Adaptation approaches*. Which are the main approaches to climate change adaptation in the literature? Is the environmental approach important? The objective is to establish the perspectives with which the literature considers climate change adaptation and their weight.
b) *Environmental impacts of adaptation*. Are potential environmental impacts of climate change adaptation mentioned in the literature? The objective is to analyse if the real or potential impacts of adaptation measures are effectively mentioned in the literature, and if so, to what extent.
c) *EA and adaptation*. Is EA integrated into climate change adaptation and decision-making? Is it mentioned in the literature? The objective is to determine to which extent is adaptation accounted for in EA, how does it inform decision-making, at what time in the process does it appear, if an all, and if the scope of assessment is sufficient.

2.2. Data source and document selection

a) *Justification and description of literature sources*. Research on climate change adaptation can be found in academic literature, but policies and practices are mainly described in grey literature (manuals, reports, strategies, case studies, country summaries, etc.). The approach of our review requires the inclusion of both academic and grey literature. We searched in English and focused primarily on the literature of the past ten years, also including earlier sources which we found using forward and backward citation tracking (Berrang-Ford et al., 2015).
b) *Document selection and criteria for inclusion.* We conducted a three-stage process.

- *Primary selection.* Primary selection was based on search terms, with different processes for academic and grey literature. (i) For academic literature search we used Web of Science (WoS), a robust search engine used in other adaptation reviews (Heller and Zavaleta, Berrang-Ford et al., 2015), including the following data bases: Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI) and Emerging Sources Citation Index (ESCI). We used in the searches the topic words "climate change" AND "adaptation" in the "Title" field, and limiting the publishing period to 2006–2015 (all databases cover this period except ESCI, which only has data from 2015), language (English) and document types (Articles or Reviews). As a result, we obtained nearly 1500 results. (ii) For grey literature, we used Google as a general search engine, because it retrieved the greater amount of results on the topic. To delimit the results we searched for "climate change" AND "adaptation", limiting file types only to "pdf" to obtain readable documents. As a result, we obtained 500 results.
- *Secondary selection.* After the primary selection, we decided on in- or exclusion using two criteria. (i) Quality: documents should meet minimum quality requirements. For academic literature we assumed that WoS indexed journals had enough quality for our study purposes, and all the results of the primary search were acceptable without additional quality controls. For grey literature we only accepted those coming from major international institutions (OECD, World Bank (WB), different United Nations (UN) institutions, NATO, etc.), government departments or agencies (Bolivia, Canada, European Union, Spain, United Kingdom, United States, etc.), or recognized or solvent institutions (world associations, academies, universities, research institutions, etc.). (ii) Scope: documents were selected when they focused on climate change adaptation; the occurrence of the primary search terms does not necessarily mean that the document is devoted to this topic. To detect that, we read the abstracts from academic documents, and indexes and introduction from the grey literature.
- *Tertiary selection.* The third selection filter was based on the adaptation measures that the documents included, with three criteria. (i) Documents included specific adaptation measures, and not only generic adaptation without detailing actions. To detect these measures we searched for the term "adaptation" in the documents. We have also sought after the term "assessment" at this stage, to detect references to EA, EIA or SEA. (ii) Adaptation measures were a response to climate change, and not to natural climate hazards; the boundaries between both are unclear (Cox et al., 2015) and measures overlap, but we only included documents where the measures are proposed as an adaptation to climate change. (iii) Adaptation measures may have significant impacts. Although this

criterion may seem subjective, significance is a key concept in EA (Lawrence, 2007; Briggs and Hudson, 2013); in fact, EA applies to plans, programmes and projects with potential significant impacts. To decide whether environmental impacts would be significant or not, we followed EA practice, because all the measures discussed are widely known actions. As we did not know in advance the measures proposed, there were no preliminary inclusion criteria, forcing us to make a case-by-case decision. The information directly extracted from the literature was about the "adaptation measures", their "location", "global change problems" that justify them, "definition" and "environmental impacts". The amount of information retrieved varied greatly per case, as many some references did not include all the data we were seeking. When not explicitly mentioned, the authors filled in data gaps by using their judgement to determine the "main approach" of each document. Also, qualitative analysis was necessary to group into standard categories measures that are similar but that have different names across documents. The field with less directly available information was "environmental impacts", which was completed by the authors to determine if such impacts could be significant, as discussed later in the analysis of selected publications (see Section 2.3).

- *Other selection criteria.* Once we selected the main sample, we completed it with (i) citation tracking, mainly from key papers and extensive reviews like IPCC reports, and (ii) specific searches on websites of important institutions in this topic. For all these documents, selection criteria were applied as described for the tertiary selection.

As a result, we selected 120 documents with 239 mentions to adaptation measures (a single document may have one or several). These documents came from 41 different journals, 4 conferences and 26 institutions or organizations. The complete list of documents and extracted data is provided as supplementary material (SM1).

c) *Error and bias.* We are aware that our search criteria left out documents that would otherwise meet the selection criteria. Searching criteria makes the review not exhaustive, providing only a sample (Berrang-Ford et al., 2015). This type of review requires expert case-by-case selection of documents, with limited use of search terms, so documents could be undesirably excluded. Grey literature availability depends greatly on organizations' transparency and open access culture; while some offer easy access, others do not promote or facilitate access. Using English as search language may bias the selection. Despite these limitations, we think that the search results are a representative sample because (i) the selected documents cover worldwide (see "Location and references" in the supplementary material SM1); (ii) documents from major international organizations, such as UN or WB, provide data even from remote areas, and academic literature is international; (iii) we have wide representation of adaptation measures, and also of sectoral approaches, from climate change research to engineering, economics, health, agriculture or social sciences; and (iv) the research aim is to show whether the environmental impacts of adaptation are included, rather than conduct a meta-analysis of quantitative data. We think that additional documents may change the frequency of occurrence of approaches to climate change adaptation in our results, or the specific percentage of references mentioning environmental impacts, but not the overall trends due to the diversity of sources, relatively large and recent sample size, variety in sectoral approaches and geographical scope, which offer robust results, sufficient for the aim of this paper, and a clear and stable tendency.

2.3. Analysis of selected publications

a) *Adaptation approaches*. First, we classified each document by its adaptation approach, which refers to the dominant sectoral perspective: (i) economic: the focus is on adaptation costs, funding, cost/benefit analysis or other purely economic factors; (ii) technical: the focus is on the proposal and design of measures, and their viability, functionality or effectiveness; (iii) social: the focus is on population wellness, mainly through an increase of the community resilience, food security, influence on quality of life and social acceptance; (iv) environmental: the focus is on natural resources, physical and biological, especially threats to biodiversity, ecosystems, and landscape, and also in environmental concerns such as pollution or contribution to climate change. This compartmentalization is necessary for clarity purposes, but we acknowledge that they are coupled and full separation is virtually impossible. Once the approaches were identified, we calculated the relative representation of each within our sample.

b) *Adaptation measures*. Once a list of adaptation measures has been obtained after the tertiary selection, we filtered adaptation measures according to their potential environmental impacts. Significance is a subjective concept, but fundamental and inherent to EA. A significant effect is defined as an effect that is sufficiently important to require assessment and reporting, so that the decision-maker is adequately informed of the environmental consequences before permitting a project (CIEEM, 2016). Our goal is to analyse adaptation measures, and to determine if an adaptation measure may have significant effects we have applied a conservative approach. To select adaptation measures with potentially significant effects we searched whether this was mentioned in the original text. Then, we only included measures where at least one of the following criteria were met: (i) significant environmental impacts were mentioned in the documents themselves; (ii) the practice of EA has consistently reported significant impacts of such projects, (iii) we found reviews indicating the significance of the specific adaptation measure, especially for unusual or rare activities (e.g. Speybroeck et al., 2006 for beach nourishment, OSPAR, 2009 for coastal defences, Roberts et al., 2010 and Liu et al., 2013 for desalination). As a result, we obtained 32 adaptation measures with potentially significant impacts. The list is not exhaustive because the determination of significance in EA practice is subjective, normative and value-dependent (Lawrence, 2007). The greater the degree of definition of an adaptation measure, and the more similar it is with other known actions, the greater the certainty about the probability of occurrence of environmental impacts. This leads to a dominance of infrastructural adaptation measures in our review, while we are aware that non-infrastructure mechanisms, such as adaptive planning and institutional aspects, also exist. The implications of such dominance are that our review is more on the implications for implementation rather than at the planning or rules domains. We encourage an additional review on those levels, but we question whether the timing is right for such review as less literature exists on the institutional and planning aspects of adaptation.

c) *Global change problems*. Adaptation measures are responses to global change problems, such as climate stressors or impacts. The relationship between measures and global change problems may or may not be defined in the documents. We defined seven major problems, assigning each measure to one of them (although boundaries are often blurred).

d) *Type of adaptation*. Documents do not usually classify adaptation measures, but may refer to them as 'hard' or 'soft'. Firstly, we defined possible adaptation categories according to the literature, attending to intent, timing, temporal scope, spatial scope, form, hardness, strategy, mode of action and effects (Table 1). Secondly, we applied these types to each measure qualitatively, depending on their characteristics and objectives.

e) *Specificity of adaptation*. We defined the level of specificity of adaptation measures with respect to climate change impacts. To do so, we developed a classification scheme where we defined if measures

Table 1
Types of adaptation.

Types		Attributes
Intent[a]		Autonomous or spontaneous (Au); planned, deliberate or intentional (Pl)
Timing[a,b,c]		Anticipatory, proactive or ex ante (An); concurrent (Co); responsive, reactive or ex post (Re)
Temporal scope[a]		Short term (St); long term(Lt)
Spatial scope[a]		Localized (Lo); widespread (Wi)
Form[a,d]	Planning	Spatial and land-use planning (Sp); financial (Fi)
	Behaviour	Institutional (It); informational (In); educational (Ed); behavioural (Be)
	Action	Technological (Te); engineering and construction (En); ecosystem-based (Eb)
Hardness[a]		Hard (Ha); soft (So)
Strategy[e,f,g]		Protection or defence (Pr); retreat or move (Rt); accommodation (Ac)
Mode of action[h]		Reducing the sensitivity (Se); altering the exposure (Ex); increasing the resilience (Rs)
Effects[g,i]		Incremental or preservationist (In), transformational (Tr)

[a] Smit et al. (2000).
[b] Berrang-Ford et al. (2011).
[c] Hallegatte et al. (2011).
[d] IPCC (2014).
[e] Cendrero et al. (2005).
[f] UNFCCC (2006).
[g] Ruhl (2009).
[h] Wreford et al. (2010).
[i] Field et al. (2014).

respond to specific climate change impacts, have multiple uses, are a reinforcement of existing measures, or are similar to other measures already used (Table 2). We then applied these categories to each measure qualitatively. With this classification scheme, we can better understand the variability in adaptation measures in the selected literature.

f) *Environmental impacts*. We defined the main potentially significant impacts that motivated the inclusion of the measures in the review. We used as primary source the reviewed literature, and if impacts were not detailed, the EA practice.
g) *References and location*. For each measure, we included the geographical location where it took place, when specified, and the literature references. This returned a large amount of information, which we provide as supplementary material (SM1).

3. Results

We selected from the literature 32 adaptation measures proposed worldwide with potentially significant environmental impacts (Table 3). A full version of the table, including locations and references, is included as supplementary material (SM1).

3.1. Approaches to climate change adaptation

Adaptation is an ambiguous concept that allows for different disciplinary approaches, responds to different stakeholder's interests (Sovacool, 2011) and is open to manipulation, for example to maintain the *status quo* in development (Ireland, 2012).

In our sample, we found a dominance of the technical approach, with a majority of documents that first analyse the impacts of climate change and then propose adaptation measures (Fig. 1). Documents with a social approach were the second largest group, most of them focused on developing countries. We found an economic approach in about a quarter of the documents, a proportion that may be underestimated because papers with economic focus but without specific measures (e.g. Schweikert et al., 2014a, 2014b; Chinowsky et al., 2015; Twerefou et al., 2015) were not included in our review. A minority of the documents had an environmental approach, usually combined with other perspectives.

3.2. Types of adaptation

There are different classifications for adaptation (Table 1), although not all of them are applicable to all cases. Of the reviewed measures, 94% were planned, 81% hard, 78% reactive and 72% accommodation actions (Fig. 2). This means that in our sample adaptations are mainly hard actions adopted in a reactive manner to accommodate to a situation. According to EA practice, measures that involve more frequent or intense impacts are included in the category 'hard', but we found that 41% of 'soft' measures may also have potentially significant impacts.

3.3. Specificity of adaptation with respect to climate change

A great majority of the measures were intensive (88%), 38% multifunctional, 19% exclusive and 6% multiple. This implies that the analysed adaptation measures consisted mostly in reinforcing existing practices, with well-known environmental impacts. The exclusive measures were not actions hitherto unknown, but the application of known

Table 2
Specificity of adaptation with respect to climate change impacts.

Adaptation	Definition	Examples
Exclusive (Ex)	Actions applied exclusively for climate change adaptation	Adaptation to sea level rise, permafrost thawing
Multiple (Mu)	Actions used as adaptation but with multiple goals	Dams for water supply, irrigation and hydropower
Intensive (In)	Actions used more intensely due to climate change pressures	River defences, increase dams height and reservoirs capacity
Multifunctional (Mu)	Similar actions used as adaptation or for other purposes	Groundwater extraction, irrigation

techniques to solve impacts associated with climate change (e.g. raising the vertical alignment of a road to adapt to sea level rise; Table 3).

3.4. Environmental impacts of adaptation

Only 15% (36 out of 239) of the references to adaptation measures mentioned environmental impacts, most of them superficially, despite our focus on actions with potentially significant impacts. The only case where impacts are widely mentioned is the use of air conditioning in relation to energy consumption. There is little or no consideration of impacts associated with measures that require land occupation (relocation, extensification) and may potentially be highly impactful.

3.5. Environmental assessment and climate change adaptation

We have detected a general lack of attention to EA in the context of climate change adaptation. The 5th IPCC report, devoted to impacts, adaptation and vulnerability, does not take into account the role of EA; as striking examples, it is neither included in the decision making chapter (Jones et al., 2014) nor cited among the tools used for adaptation planning in Africa (Niang et al., 2014). In the UK, RAE (2011) considers the constraints set by the environmental agencies as legal, administrative and institutional barriers to adaptation, instead of an inherent part of the adaptation design process. Although we did not register whether those specific actions should be subjected to EA processes according to national regulations, we found that in a global context EA is not a process-integrated tool for decision-making on climate change adaptation or, at least, for strategic decisions, which are essential in this area.

EA is highly variable across scales. The scope of a project and whether it is subject to EA is determined by governments, and nations define thresholds, screening processes, or both of them. However, what is often lacking is the assessment of cumulative impacts of individual projects promoted by governments, NGOs, donors, etc., to reduce vulnerability from various perspectives. Such integration is necessary in the close future, and some analysis at regional scales and multisectoral are emerging (Thorne et al., 2014).

4. Discussion

Adaptation, although reducing adverse effects of climate change, may also have undesirable environmental impacts, and our results show that this aspect is being poorly treated in the grey and academic literature. The main approach to adaptation in the literature is technical, followed by social and economic criteria. This seems to be influenced by the type of sectors, stakeholders and professional groups involved in climate change adaptation. For example, civil engineers pay attention to infrastructure adaptation, with numerous publications from researchers, working groups, professional associations and governments analysing actions and costs. In developing countries international donors, who fund most adaptation actions as development aid, tend to have a stronger focus on the social component. We did not find any stakeholders' group focused on the environmental effects of adaptation, maybe because currently the main environmental concerns are mitigation and direct impacts of climate change, but not adaptation impacts.

Our results also show the scarce inclusion of environmental impacts of adaptation across all types of documents. This is worrying as we only analysed adaptation measures with potential significant environmental impacts, and most of them are reinforcement of actions already implemented or similar to other well-known actions. There may be several explanations for this situation. The first would be an excessively sectoral approach to adaptation, focusing on specific themes and without a global vision. Although climate change science is interdisciplinary, it is mainly managed by specialised sub-units, which makes cross-sectoral coordination difficult (Larsen et al., 2012). Secondly, there may be confusion between primary impacts of climate change, solved by adaptation, and secondary impacts, caused by it. The first are currently evident, causing great concern, while the second may go unnoticed due to the lack of attention and detailed models for assessing potential adaptation impacts under different climate change scenarios. This is worrying, because the environmental effects of certain adaptation measures may be greater than the corrected climate change impacts; for example McEvoy and Wilder (2012) indicate that desalination in the U.S.-Mexico border can reduce vulnerability related with water supply but can also introduce new ones such as a water-energy nexus, GHG emissions, urban growth, brine discharge, chemical pollutants, changes in geopolitical relations related with water security, increase of water prices, and it is likely to exacerbate existing social inequalities. Finally, there is a tendency, explicit or implicit, to consider adaptation as good in itself. We found no references to environmental impacts of adaptation, and even an emphasis on positive impacts, in documents such as 'white papers', strategies or national plans (OECC, 2006; EC, 2009, 2013; EuropeAid, 2009). Other examples are the Danish climate change plans (Kørnøv and Wejs, 2013) or the UK emergency plans, including measures to minimise the effects of disasters (Swain and Therivel, 2014), both exempt of SEA. A first step in adaptation would be to assess whether measures follow a no-regret or low-regret strategy, are efficient in the current situation and require lower investments, replacing a more robust adaptation with greater uncertainty. However, a risk of no-regret strategy is to postpone adaptation, making it always reactive and not anticipatory, as it should be. In these cases, EA will have a limited utility; useful to propose mitigation measures but not to evaluate real alternatives. Different adaptation pathways should be considered according to climate change scenarios and with suggestions on how to move from one to the other. Although pathways might be uncertain, through EA we may know in advance the potential consequences of each path.

We also observe preconceived positive or negative ideas about some adaptation measures. Desalination has significant environmental impacts and large energy consumption (Roberts et al., 2010; McEvoy and Wilder, 2012; Liu et al., 2013) but may be an alternative to options with larger impacts, like transboundary water transfers (e.g. in the Arab Gulf Countries; Verner, 2012). Energy consumption is usually associated with desalination and air conditioning, but not with groundwater extraction, also energy dependent. In large dams (proposed as an adaptation) environmental impacts are sometimes cited, but not in small dams or ponds, presented as a good soft adaptation. However, they also have impacts, which can be cumulative; depending on the pond size and number in the same watershed, they may produce significant flow reductions. Therefore, qualifying a measure as 'good' or 'bad' should be the result of an adequate environmental assessment and not from a priori opinions, neither for nor against it; EA is a key tool for this analysis.

Environmental impacts are frequently associated with 'hard' measures, such as construction, but we also found a big number of 'soft' measures with potential impacts. Moreover, the concepts 'hard' and 'soft' are not clear. For example, beach nourishment is proposed in The Netherlands as a soft alternative to coastal defences (PRC, 2009; Hewitson et al., 2014), but may have severe impacts on aquatic life of seabed, both in extraction and supply areas (Speybroeck et al., 2006). On the other hand, coastal defences generate unwanted changes in coastal morphology (OSPAR, 2009) but can prevent land occupation from relocations or coastal retreat. Autonomous soft measures adopted to face scarcity periods may have important environmental effects (exploitation of wild lands, deforestation, overgrazing, etc). Measures implying land use change or occupation (coastal retreat, relocation, farm extensification, etc) may have significant impacts usually ignored, or are even considered soft alternatives. Consequently, 'soft' does not means 'free-of-impacts'.

We found examples of 'hard' measures not mentioned in developed countries but explicitly cited in regions with major threats and less income. For example, in The Netherlands, with massive coastal defences, adaptation programmes highlights beach nourishment, while in

Table 3
Global change problems, adaptation measures, type, specificity and potential environmental impacts.
Note: Abbreviations are in Tables 1 and 2. A full version of this table is included as supplementary material (SM1).

Global change problem	Adaptation measure	Definition	Type of adaptation	Specificity to climate change	Environmental impacts
Sea level rise, aggressiveness of coastal phenomena	Coastal defences	Works to protect coastal areas and stop erosion as sea-walls, levees, groynes or breakwaters	Pl, An-Re, Lt, Lo, En, Ha, Pr, Rs-Ex, In	Ex (sea level rise); In (coastal aggressiveness)	- Inhibit the adaptation of mangroves, salt marshes, seagrass and seabeds to rising sea levels, and the migration inland - Interruption of natural movement of sand, loss of beach areas - Disturb of sediment balance, resulting in erosion in other areas - Encourages further development
	Beach nourishment	Supply of sand to offset the losses by coastal erosion, natural or due to defences	Pl, Re, St, Lo, En, Ha, Ac, In	Ex (sea level rise); In (coastal aggressiveness)	- Impacts in sand extraction - Impacts in beach ecosystem components
	Artificial islands	Gain land from the sea to offset the loss of land by sea level increase	Pl, An, Lt, Lo, En, Ha, Tr	Ex (sea level rise)	- Alteration of coastal dynamics - Destruction of seabeds - Damages to marine biodiversity
	Elevation of infrastructures	Elevation of roads, streets or railways to avoid flooding due to sea level rise	Pl, An-Re, Lt, Lo, En, Ha, Pr, Rs-Ex, In	Ex (sea level rise)	- Land occupation - Landscape impacts - Need for quarries or borrow pits
	Coastal retreat	Move settlements and infrastructure inland to avoid coastal damage	Pl, An, Lt, Wi, En-Eb, Ha-So, Re, Ex, Tr	Ex (sea level rise)	- Land occupation affecting biodiversity, agriculture, landscape - Changes in runoff with hydrological consequences
River erosion and floods	River defences	Channelling, breakwaters, walls or ridges to stabilize rivers and prevent flooding	Pl, An-Re, Lt, Lo, En, Ha, Pr, Ex, In	In (flood frequency)	- Increase of flooding downstream - Changes in river flows and loss of naturalness - Water quality alteration - Damages to riparian vegetation
	Floodplains retreat	Move settlements and infrastructure out of floodplains to avoid damages	Pl, An, Lt, Wi, En-Eb, Ha-So, Rt, Ex, Tr	In (flood frequency)	- Similar to coastal retreat
	Remove river sediments	River dredging to increase hydraulic capacity to allow navigation with lower flows	Pl, An-Re, St, Wi, En, Ha, Ac, Ex, In	In (flood frequency); Ex (lower flows)	- Destruction of river bed, benthonic fauna and spawning areas - Alteration of river dynamics - Impairment of water quality
	Bridge extension and reinforcement	Reinforcement of foundations and increase of bridges section to withstand greater flows	Pl, An-Re, Lt, Lo, En, Ha, Pr, Rs-Se, In	In (flood frequency)	- Water quality alteration - Damages to river bed and riparian vegetation
Drought, reduction in rainfall, flows and freshwater availability	Dams and reservoirs	Construction of reservoirs for water storage or increase their capacity by dredging or heightening the dams	Pl, An-Re, Lt, Lo, En, Ha, Ac, Rs, In	Mu (water consumption, irrigation, hydropower); In (flood frequency)	- Hydro-dependency and threats to community resilience - Sediment retention, evaporation - Land occupation in flooded areas - Flow regulation and reduction - Barriers for fishes (dams) and terrestrial wildlife (reservoirs)
	Small dams and ponds	Construction of small dams for water storage, usually for irrigation	Pl, An-Re, Lt-St, Lo, En, Ha-So, Ac, Rs, In	In (drought frequency)	- Land occupation in flooded areas - Flow reduction - Fish barriers
	Water transfers	Detraction of water from a basin for transfer to another, where it is used	Pl, An-Re, Lt, Wi, En, Ha, Ac, Rs, Tr	Mu (water consumption, irrigation); In (drought frequency),	- Impacts in donor basin: flow reduction, river degradation, vegetation and wildlife disappearance, water table lowering, loss of recreational and hydropower use, degradation of estuaries …
	Groundwater extraction	Groundwater extraction, by drilling or wells, for human consumption or irrigation, to offset the reduction of freshwater availability	Pl, Re, St, Lo-Wi, Te, Ha-So, Ac, Rs, In	Mu (water consumption, irrigation); In (drought frequency)	- Overexploitation, salinization and water table lowering - Consumption of resource with slow renewal rate - Reduction in contributions to rivers - Impacts on phreatophyte vegetation - Land subsidence and increased damage in earthquakes
	Desalination	Desalination plants to obtain freshwater from seawater	Pl, Re, Lt, Lo, En-Te, Ha, Ac, Rs, Tr	Mu (water consumption, irrigation); In (drought frequency)	- Energy consumption and GHG emission - Brine and pollutants discharge - Water-energy nexus - Water price increase
	New hydropower projects	Construction of new hydropower plants to offset the loss of production due to the reduction in river flows	Pl, An-Re, Lt, En, Ha, Ac, Rs, In	In (lower flows)	- Flow reduction between water diversion and discharge points - Barriers for fishes (dams or weirs) - Fish damages in the turbines

Global change problem	Adaptation	Definition	Type of adaptation (Table 1)	Specificity to climate change (Table 2)	Environmental impacts
Increase in summer temperatures and heat waves	Changes in road and airport pavements	Change bituminous pavements to other less sensitive to heat (such as concrete) or reduction in maintenance frequency	Pl, Re, Lt, Lo, En, Ha, Ac, Rs, In	In (higher temperatures)	- Noise increase due to the use of concrete pavements - Increased consumption of resources and energy and waste production by shortening replacement period
	Air conditioning	Increased use of air conditioning in residential, commercial or industrial uses, and transport stations	Pl, Re, Lt, Lo, Te, So, Pr, Ex, Tr	In (higher temperatures)	- Increase of energy demand and GHG for generation - Increase the need for energy transport infrastructure
Loss of agriculture and livestock production, reduction of food security	Crop irrigation	Irrigation of rain-fed crops or increase water supply in irrigated crops to offset the reduction in rainfall and prevent loss of production	Pl, Co—Re, St, Wi, Te, Ha, Ac, Se, In-Tr.	In (lower rainfall); Mu (irrigation of rainfed crops)	- Disease transmission for water storage - Groundwater salinization; wetland degradation - Impacts in water biodiversity - Impacts from water obtaining (dams and reservoirs, groundwater extraction, water transfer, desalination …)
	Increased use of fertilizers and pesticides	Using greater doses of fertilizers to offset the loss of productivity, and pesticides by increased incidence of pests	Pl, Co, St, Wi, Te, Ha, Ac, Se, In-Tr	In (lower production); Mu (fertilization of non-fertilized crops)	- Hazards to human and ecosystem health - Increased emission of N_2O from fertilizers
	Terracing	Terracing hillsides to improve water harvesting, offsetting lower rainfall and runoff	Pl, An, Lt, Wi, En, Ha, Ac, Rs, Tr	In (lower rainfall and runoff); Mu (greater harvest)	- Landscape impacts - Changes in runoff
	Farm extensification	Expansion of farms to offset the lower production	Pl, Re, Lt, Wi, Sp, Ha-So, Ac, Rs, Tr	In (lower production)	- Decrease in eco-efficiency - Occupation of uncultivated land: potential effects on biodiversity
	Relocation of farms or graze areas	*Re*-location of exhausted farm or grazing areas, looking for more productive alternatives	Pl, Co—Re, St, Wi, Sp, Ha-So, Ac, Rs, Tr	In (lower production)	- Impacts on vegetation due to farming and livestock - Occupation of uncultivated land affecting biodiversity
	Change livestock type	Change in livestock species, to find those most suited to the conditions, often goats	Pl, Re, St, Wi, Eb, So, Ac, Se, In	In (lower production, pasture changes)	- Damages on natural vegetation, especially with goat introduction
	New species in marine farming	Change species in marine farming, to find those most suited to the new conditions	Pl, Re, St, Lo, Te, So, Ac, Se, Tr	In (lower production); Mu (market changes)	- Risk of introduction of foreign species and parasites
	Increase fishing catches	Improvement of fishing fleets to increase captures, offsetting the lowest amount of fish	Pl, Re, St, Wi, Te, Ha, Ac, Rs, In	In (lower production); Mu (market changes)	- Depletion of fisheries - Imbalances in the marine ecosystem
	Hunting wild animals	Hunting wild animals to offset lower livestock production	Au, Co, St, Wi, Be, So, Ac, Se, In	In (lower food availability and income); Mu (usual hunting)	- Risk for threatened species, if hunting is not selective - Imbalances in the ecosystems
	Changes in land use	Changes in land uses looking for the most profitable, due to a loss of agricultural income	Pl, Re, Lt, Wi, Sp, Ha-So, Ac, Rs, Tr	In (lower production); Mu (market changes)	- Changes in ecosystems, affecting wildlife - Changes in the landscape
	Charcoal production	Charcoal as alternative source of income to agriculture and livestock	Au, Co, St, Wi, Fi, So, Ac, Se, In	In (lower income); Mu (usual charcoal production)	- Deforestation due to slow acacia regeneration
Shorter and milder winters: reduction in snowfall and permafrost thawing	Snowmaking and glacier skiing	Artificial snowmaking in ski resorts, and expansion into glacier areas to ensure enough snow for skiing	Pl, An-Re, Lt, Lo, Te, Ha, Ac, Se, In	In (lower snowfall); Mu (expand ski area and season)	- Affection to vegetation, wildlife, soils, hydrology and landscape in sub-alpine and alpine areas - Glaciers recession due to their use as ski slopes - Consumption of water and energy, and GHG emissions - Noise from snow cannons
	River flow regulation	Change river flow regulation due to a reduction of base flows for lower snowfall	Pl, Re, Lt, Wi, En, Ha, Ac, Se, Tr	In (lower flows)	- Flow reduction - River degradation and vegetation and wildlife disappearance - Water table lowering - Loss of recreational uses and hydropower potential
	Infrastructure relocation	Relocation of infrastructure out of permafrost areas and permanent works replacing ice roads and bridges	Pl, Re, Lt, Wi, En, Ha, Ac, Se, Tr	Ex (global warming)	- Land occupation, which may affect biodiversity or landscape
Reduction of food security, increased frequency of disasters and social unrest	Migration	Population displacement, temporal (scarcity, seasonal activities) or permanent (unbearable living conditions)	Au, Co—Re, St-Lt, Wi, Be-Fi-Sp, So, Rt, Ex, Tr	In (lower food availability and income); Mu (disasters, wars, droughts...)	- Rapid growth of urban areas - Formation of slums without sewage or waste collection systems - Increased human pressure on the environment in receiving areas - Occupation of uncultivated land: potential effects on biodiversity - Social conflicts, human tragedies

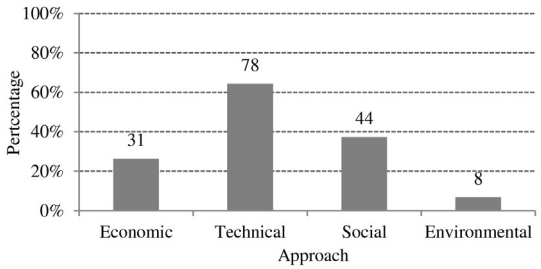

Fig. 1. Frequency of occurrence of approaches to climate change adaptation in the reviewed literature.

sensitive island states like Kiribati, Maldives or Samoa defences are openly proposed (World Bank, 2010a; Sovacool, 2012; Donner and Webber, 2014). River defences to avoid flooding, common worldwide, are mainly mentioned as an adaptation in Southeast Asia (Jacobs, 1996; World Bank, 2010b, 2010c). Crop irrigation and water extraction, frequent everywhere, are only openly mentioned as adaptations in countries with severe droughts, especially in Africa (Table 3). Failing to mention impactful measures that could be necessary, leads to a partial and incomplete assessment; it is necessary to analyse the whole set of adaptation options, more or less hard, for different projections and scenarios, so that there can be a reasonable prediction of the environmental effects that each adaptation path would have, and its associated uncertainties.

EA regulations require that plans, programmes and projects with significant environmental impacts undergo SEA or EIA. However, adaptation measures may do so at a later stage, with few or no alternatives, or even circumvent EA due to impact undervaluation, project splitting or urgency in acting. An appropriate environmental assessment should address the adaptation in an anticipatory form, with a genuine evaluation of alternatives. As noted by Wende et al. (2012), SEA should not be used just to introduce some isolated measures in plans or programmes, but can also contribute to the development of alternative approaches. There are several possibilities for applying EA processes to analyse the environmental impacts of adaptation measures, which depend on their attributes, and are greatly influenced by timing. In Table 4 we propose environmental assessment possibilities for each type of adaptation.

EA is linked with planning and thus it only applies to planned measures and not to spontaneous or un-programmed actions. Many adaptation measures require EA, SEA for those mainly related with land planning or EIA for construction options. However, EA does not apply to some cases, like financial or behavioural adaptation, because regulations do not include them. In practice, the inclusion of adaptation in EA is scarce, as noted for example in Denmark (Larsen, 2014), Austria and Germany (Jiricka et al., 2016) or Spain (Enríquez-de-Salamanca et al., 2016).

Timing determines the type of EA process applicable, and even the possibility of not following anyone. When adaptation is anticipatory, it may be submitted to SEA or EIA, and different alternatives can be analysed. By contrast, the application of EA to concurrent or responsive measures is restricted because there would be either limited or no alternatives, and when they require quick decisions, the urgency may waive the need for assessment. For example, if a bridge collapses, the priority will be to rebuild it and not to evaluate adaptation alternatives such as changes in watershed management; Swain and Therivel (2014) indicate a similar problem, the exemption of SEA in emergency plans. Also, progressive adaptation without prior overall assessment leads to project splitting, that could circumvent EA by failing to reach the minimum thresholds or could underestimate the global impact (Enríquez-de-Salamanca, 2016), as for example in successive works along an infrastructure or a coastal section.

5. Conclusions

Our key message is that the environmental impacts of adaptation are frequently ignored, undervalued or considered superficially, without a true environmental assessment. This can be attributed to several causes, such as an excessively sectoral approach to adaptation, with greater weight given to technical, social and economic perspectives, major or unique consideration of primary impacts of climate change rather than to secondary impacts of adaptation measures, or a tendency to consider adaptation as good in itself. Such undervaluation of the environmental effects of adaptation may have negative implications in decision-making.

We also want to draw attention to preconceived ideas about some adaptation measures that are either considered good or bad without proper evaluation: the association 'hard-bad' and 'soft-good' is not necessarily true; the impacts of adaptation can only be established through a case-by-case assessment. The decision to select a more or less intensive adaptation measure should integrate all approaches, social, environmental, technical and economic, in a multi-criteria analysis. This analysis should value, inter alia, social and environmental sensitivity, benefits and drawbacks or trade-offs with climate, including all the adaptation options, among them the 'no action' alternative. The application of EA processes to adaptation is possible, providing an effective and proven tool to include the environmental considerations into decision-making.

Although EA is widely implemented worldwide, the regulations by themselves cannot ensure a proper assessment of adaptation. EA might be circumvented by impact undervaluation, project splitting or urgency in acting, or might be applied at a late stage, with few or no alternatives. Adaptation should be addressed in an anticipatory form, where possible, evaluating actual alternatives rather than justifying

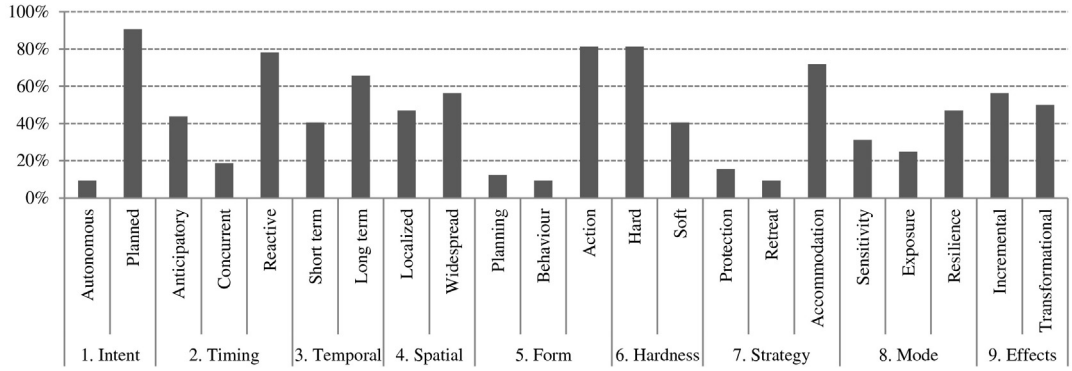

Fig. 2. Types and attributes of the analysed adaptation measures in the reviewed literature.

Table 4
Environmental assessment possibilities of adaptation.

Types		Attributes	Environmental assessment possibilities
1. Intent		Autonomous	Not possible
		Planned	Possible through SEA or EIA
2. Timing		Anticipatory	Possible through SEA or EIA
		Concurrent	Possible through a limited EIA, or not possible in urgent actions
		Responsive	Possible through a limited EIA, or not possible in urgent actions
3. Temporal scope		Short term, long term	Possible; no influence in EA
4. Spatial scope		Localized, widespread	Possible; no influence in EA
5. Form	Planning	Spatial and land-use planning	Possible, through SEA
		Financial	Difficult; lack of mechanisms for EA
	Behaviour	Institutional, informational, educational, behavioural	Difficult; not clear mechanisms for EA
	Action	Technological, engineering and construction,	Possible, usually through EIA
		Ecosystem-based	Possible, but not clear mechanisms for EA
6. Hardness		Hard, soft	Possible, but more clear EA mechanisms for hard adaptation
7. Strategy		Protection	Possible, usually through EIA
		Retreat	Possible, through SEA or EIA (if anticipatory and planned)
		Accommodation	Possible, usually through EIA
8. Mode of action		Reduce sensitivity, alter exposure, increase resilience	Possible, through SEA or EIA
9. Effects		Incremental, transformational	Possible, through SEA or EIA

predefined solutions, and should provide a comprehensive understanding of both direct and indirect impacts. We have everything needed for the EA of adaptation, enough knowledge and verified tools, but we should also become aware of the major flaws of the current approaches.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eiar.2017.03.005.

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