Cross-sectoral interactions of adaptation and mitigation measures

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Abstract Adaptation and mitigation are complementary strategies for addressing the impacts of climate change, yet are often considered separately. This paper examines the literature for evidence of the interactions of adaptation and mitigation measures across the agriculture, biodiversity, coasts, forests, urban and water sectors, focusing on Europe. It found that often adaptation and mitigation synergies and conflicts were not explicitly mentioned within a sector, let alone between sectors. Most measures, however, were found to have an effect on another sector, resulting in neutral, positive (synergies) or negative (conflicts) interactions within and between sectors. Many positive cross-sectoral interactions involved biodiversity or water and thus these could represent good starting places for the implementation of integrated, cross-sectoral strategies. Previous studies suggest that adaptation and mitigation are undertaken on different time and geographical scales; this study found many local scale measures which could facilitate integration between both adaptation and mitigation. It is important that cross-sectoral interaction of adaptation and mitigation measures are explicitly recognised if they are to be mainstreamed into policy, so that positive outcomes are enhanced and unintended consequences avoided.

Keywords: Climate change, adaptation, mitigation, interactions, synergies, conflicts

1 Introduction

Given the projected changes in climate, both means and extremes, adaptation and mitigation will continue to be important responses for addressing the causes and impacts. Traditionally viewed as two separate actions within climate impacts science, and often dealt with by two different sets of policy makers, their interaction has largely been ignored (Biesbroek et al. 2009). This could, potentially, lead to further adverse consequences, for example, where there are short term benefits of adaptation, but long-term adverse consequences for mitigation. The interrelationship between adaptation and mitigation is, therefore, complex, with a number of differences including spatial, temporal, and administrative scales (see Biesbroek et al. 2009 for a discussion).

We define adaptation as ‘an action which avoids the unwanted impacts of climate change, and can also be a means of maintaining or restoring ecosystem resilience to single or multiple stresses’ (Convention on Biological Diversity 2005). Mitigation was considered as any actions seeking a net reduction of greenhouse gas (GHG) emissions or involving the protection and promotion of carbon sinks, through land use and habitat management. However, the two are inherently linked, for example, a high level of mitigation could require less adaptation and conversely with sufficient adaptation, there is a possible reduced need for mitigation (Wilbanks et al. 2007), although scale differences in the implementation of these actions has been suggested, with adaptation viewed as local and mitigation as global.

Increasingly it is recognised in practice and policy that adaptation and mitigation need to be addressed by all sectors, for example the EU Adaptation Strategy (COM (2013), 216), but their interrelationship needs to be well understood to maximise potential synergies, avoid conflicts and consider trade-offs (Tol, 2005; Smith and Oleson, 2010; VijayaVenkataRaman et al. 2012). This requires a holistic approach (Walsh et al. 2010; Harry and Morad 2013) and thus creating combined frameworks of adaptation and mitigation to assess climate change strategies is essential (van Vuuren et al. 2011; Viguié and Hallegatte 2012); there being no place for an adaptation and mitigation dichotomy in future climate policy (Bosello et al. 2013). Further research to improve understanding of the links between these measures would help the construction of such frameworks and greatly improve policy, as win-win solutions are much more efficient than those with adverse effects (Laukkonen et al. 2009; Walsh et al. 2010; Smith 2012; Viguié and Hallegatte 2012).

A review was undertaken to gather evidence from the literature on cross-sectoral interactions of adaptation measures within the agriculture, biodiversity, coasts, forestry, urban and water sectors. The review was targeted to support the modelling work within the CLIMSAVE project on impacts, vulnerability and adaptation to climate change (Harrison et al. this volume). However, it was extended to include mitigation, so that three key questions related to the knowledge gaps identified above, and their importance for future effective climate change responses and policy, could be addressed:

1) What is the nature of, and evidence for, cross-sectoral interactions between adaptation and mitigation measures?

2) Which measures are synergistic or in conflict?

3) What are the implications for adaptation and mitigation policy?

2 Methodology

To address these questions, a literature search was undertaken to identify, for each sector, relevant papers for a selection of adaptation and mitigation measures. We focused on measures of relevance to adaptation in the CLIMSAVE Integrated Assessment Platform (Harrison et al. this issue) and/or which had a good level of evidence. These measures were used as keywords alongside sector-specific subject terms (Supplementary material Table 1) and input into SciVerse Scopus or Web of Knowledge. The hits were sorted by relevance and with no restriction on year, but preference was given to more recent papers. Given the large number of measures, it was aimed to identify twenty five papers per measure. While this number is arbitrary, it should enable the identification of the main evidence for cross-sectoral interactions. Where the number of hits was high, keywords were combined with sectorally-specific terms. For example, in the coastal sector 'coastal engineering' produced 9049 hits, whilst 'de-embankment' produced only nine hits. For keywords, with greater than 100 hits, a search using the 'AND' function, with an additional relevant term, e.g. "dikes" and "salt marsh", was initiated. Some keywords, e.g. "white-topping asphalt" for urban, were very specialised, and few hits were registered. For keywords with fewer than 25 hits, references were searched for relevant articles (i.e. snowballing), and subsequent citation of articles (i.e. reverse snowballing) were investigated in order to increase knowledge of the measures' interactions. Snowballing was particularly useful when there were few hits, but included an important review article.

The initial search was based on the peer-reviewed literature which has been evaluated by the scientific community, but, when snowballing was undertaken, grey literature also was included. Articles were selected if the adaptation and mitigation measures had been carried out and explicit impacts on one of the six sectors were mentioned. Those with quantitative results, case study examples, plus details on synergies, conflicts and trade-offs were favoured. Data on: sector(s) impacted; nature of the impact; scale of impact; time scale of implementation/impact; and evidence of adaptation affecting mitigation or vice versa were also sought to address the first two questions on knowledge gaps. Primarily, articles relevant to Europe were used, as this is the focus of CLIMSAVE, but excellent, relevant examples from elsewhere were also included where they demonstrated new knowledge and potential learning and application to Europe.

3 Analysis of cross-sectoral interactions

The number of explicit references to cross-sectoral interactions was low, as often they were not the focus of a paper, so they had to be inferred from knowledge of sectoral adaptation and mitigation options. Explicit examples tended to be found in more multi-disciplinary studies. Also, there was a lack of clarity in how the terms synergies and conflicts were used. The main confusion concerned whether the synergy/conflict was between an adaptation or mitigation measure and a climate change impact, or only between the measures themselves. Here we propose a set of definitions to overcome this confusion.

Cross-sectoral interactions are the ***effects*** that an adaptation or mitigation measure in one sector has on another sector, but the measure does not affect adaptation or mitigation in that other impacted sector. These interactions, however, could have various outcomes for adaptation and mitigation in the affected sector**: neutral** (no impact)**, positive** (beneficial impact) **or negative** (detrimental impact). If the adaptation or mitigation measure enhances adaptation or mitigation in the same, or another sector, it is defined as a **synergy**, while if it adversely affects adaptation or mitigation within the same, or another sector, it is defined as a **conflict** and leads to the need to consider trade-offs. A range of interactions (neutral, positive or negative), and the synergies and conflicts identified in this review are summarised in Table 1 (for a fuller version see Table 2, Supplementary material) and a selection are discussed below to illustrate the types of interactions identified.

Insert Table 1 near here.

3.1 Neutral Interactions

The neutral category is the smallest, as it is rare that adaptation or mitigation measures have no effect on other sectors, although there are, of course, within-sector impacts. Most of those identified concerned adaptation in the urban sector to reduce temperatures, where strategies, such as white topping or building measures (e.g. Greece, Synnefa et al. 2011; the Netherlands, Kleerekoper et al. 2012), have no recorded direct effect on other sectors, although by decreasing temperatures they may reduce the need for other urban adaptation and/or mitigation measures. There were few other neutral measures, although some biodiversity adaptation measures, many of which are site-based, such as habitat restoration have minimal impact outside the sector (Hannah et al. 2010). This would not apply to protected area expansion or new sites, as they would take land from other uses.

3.2 Positive Cross-sectoral Interactions

This category had about 50% more recorded cross-sectoral interactions in terms of the sectors involved compared with negative interactions and nearly twice as many impacts from adaptation and mitigation measures, with many of them involving biodiversity or water (Supplementary material Table 2).

Those identified in this review only concerned water quality, with many of the examples related to coasts in the Netherlands and UK, where evidence was found for saltmarsh restoration leading to improvements in local water quality (e.g. Blackwater Estuary, UK, Chang et al. 2001; Shepherd et al. 2007), providing treatment of stormwater runoff, as well as a sink for contaminants and nutrients (Humber Estuary, UK, Andrews et al. 2008; Essex estuaries, UK, Garbutt and Wolters 2008). Shepherd et al. (2007) quantified the benefits of managed realignment for the Blackwater Estuary as an additional annual storage of 200-795 tonnes of nitrogen and 146-584 tonnes of phosphorus. Biodiversity strategies, such as the corridors being created in the Netherlands as part of the de Doorbraak project, have also led to improvements in water quality (Waterschap Regge en Dinkel 2011). Similarly for forestry it was found that planting on former agricultural land may restore water quality (especially nitrate levels) and recharge to pre-agricultural levels (Plantinga and Wu 2003).

3.3 Negative cross-sectoral interactions

As with the positive cross-sectoral interactions, negative ones only were found which impacted the water sector. For example, in agriculture, a lack of soil mixing in no-tillage systems caused greater herbicide concentrations in run-off water (Stevens and Quinton 2009), whilst in Denmark delayed sowing of winter cereals resulted in reduced autumn and winter nitrogen uptake by crops, leading to higher nitrogen leaching (Olesen *et al.* 2004). For coasts, wetland creation can lead to a short-term decline in water quality due to increased concentrations of heavy metals and increased nutrient levels (Georgia, US, Loomis and Craft 2010).

3.4 Synergistic interactions

No explicit within sector synergies were identified, but some potential synergies can be proposed since adaptation measures in the same sector are often aimed at addressing different, but related issues. For example, crop breeding may seek to reduce climate stresses while maintaining/increasing yields or addressing climate-related increases in pests or diseases. Synergies within a sector, however, may be complementary or alternative measures for dealing with the same issue. For example, there are several stormwater management options in urban areas through the use of different types of greenspace, such as green roofs (Mediterranean, Fioretti et al. 2010), Sustainable Urban Drainage Systems (SUDS) (Wise et al. 2010) and urban trees (Greater Manchester, UK, Gill et al. 2007).

Most potential synergies between adaptation measures in different sectors, while being implicitly synergistic were not promoted as such, thus opportunities for enhancing adaptation co-benefits were not realised. It is likely that many synergies with biodiversity will become more explicit, given its role in a range of adaptation and mitigation measures and the increasing interest in ecosystem services, including climate regulation (e.g. Balvanera et al. 2006) and in ecosystem-based adaptation (Munang et al. 2013). Synergies identified included various urban green infrastructure measures which have a range of within-sectoral and cross-sectoral synergies. SUDS, for example, whilst aiding adaptation for the water sector, can restore some ecosystem functions in urban areas, through habitat restoration (e.g. green roofs), and soil moisture replenishment (New York, US, Spatari et al. 2011). SUDS, greening measures and wetland creation all can have synergies with biodiversity, providing both feeding and habitat areas for birds and insects (e.g. London, UK, Chance 2009).

The greatest numbers of explicit synergies recorded were between adaptation and mitigation, whether in the same or a different sectors. For a number of measures there were both within and between sector synergies and in order to avoid this division of the synergies associated with a measure, they are discussed together. Given the carbon content of biomass, any measure that increases biomass will enhance carbon sequestration, while adaptation measures which conserve, enhance or restore carbon-dense ecosystems, like peatland and forest, will similarly contribute to mitigation. A number of the coastal adaptation measures affected mitigation positively, although carbon sequestration mostly was considered a co-benefit, rather than the reason for implementing a scheme. Saltmarsh creation, for example, provides a natural coastal defence and is an effective carbon sink (England, Luisetti et al. 2011). Urban adaptation, especially green infrastructure, can contribute to mitigation through avoided emissions and carbon storage (Leicester, UK, Davies et al. 2011).

3.5 Conflicts

As with synergies, almost no conflicts explicitly mentioned the impacts of an adaptation or mitigation measure on adaptation or mitigation in the impacted sector, thus conflicts only could be inferred. There are a number of implicit examples of adaptation conflicts, especially in relation to biodiversity. For example, increases in biofuel production and some forestry plantings and operations (Nabuurs et al. 2007). Additionally, coastal hard-engineering could prevent coastal ecosystems migrating inland in response to sea-level rise. Also, in the water sector agriculture can conflict with adaptation measures related to water supply to other users through increased demand (Giannakopoulos 2009).

Almost all examples of adaptation conflicting with mitigation concerned the agricultural or coastal sectors. For example, tidal barriers can degrade intertidal habitat leading to loss of a carbon sink (Oosterschelde, Netherlands Schekkerman et al. 1994), whilst the carbon storage benefits of saltmarsh creation *may* be more than offset by methane and nitrous oxide releases (Southern Sweden, Thiere et al. 2011). Very few explicit negative mitigation impacts on adaptation were identified and these mostly occurred in the agriculture, urban and forestry sectors. For example, plantations can decrease biodiversity adaptation through reducing diversity and habitat quality (Brockerhoff et al. 2007) and some conservation agriculture practices lead to increased nitrous oxide emissions (Carlton et al. 2012).

Almost no examples were found of conflicts between mitigation measures, although there were several examples of trade-offs resulting from measures which increase emissions of other GHGs, such as the wetland creation mentioned above (Thiere et al. 2011).

4 Discussion

This paper is one of the first to address the cross-sectoral interactions, synergies and conflicts between adaptation and mitigation measures. For some measures the level of explicit evidence of their impact is limited, thus suggesting that cross-sectoral interactions currently are not seen as important to take into account. Nevertheless, it has identified some common themes which can be used to suggest possible effective responses to climate change and their implications for policy.

In terms of the first question posed in the introduction to this paper on the nature of, and evidence for, cross-sectoral interactions, the review found a lack of information on some measures or little explicit reference to and analysis of within-sectoral and cross-sectoral impacts of measures. This is despite high level calls for action on adaptation and mitigation and for their mainstreaming into policy (e.g. European Commission 2013a), and suggests a continuation of the past pattern of adaptation and mitigation being considered independently (e.g. Klein et al. 2007). Thus many synergies (and conflicts) are unrecognised or not explicitly acknowledged and are under-represented in the literature and, as was found in this review, even those with such information, often lacked evidence on their effectiveness and wider impacts. This is partly due to little long-term monitoring of the strategies (Adger et al. 2005) and to the time taken for the success of some measures to become evident (Louters et al. 1998). Also, in the case of biodiversity, there is not always a clear distinction between good management practice and specific climate change adaptation, since resilient ecosystems are more likely to be able to adapt autonomously and require less intervention (e.g. Tompkins and Adger 2004; European Commission 2013b).

Secondly, while some neutral cross-sectoral interactions were found, most measures resulted in (usually implicit) synergies or conflicts, with examples primarily demonstrating how adaptation could contribute to mitigation, rather than vice versa. The majority of interactions were positive, although there is a danger in assuming that the frequency of mention, or evidence of an interaction, represents the significance of a particular category of interaction. More importantly it found that the effect on the impacted sector could often be considered consistent with adaptation measures for that sector, as shown by the green typeface in Table 2 (Supplementary material).

In terms of the second question posed in the introduction, many of the positive cross-sectoral interactions and synergies involved biodiversity or water and those for biodiversity could also be considered to represent ecosystem-based adaptation (or mitigation). A number of interactions with biodiversity involved habitat restoration or creation by other sectors (e.g. coasts, urban) and potential benefits included biodiversity conservation, carbon sequestration, and sustainable water management. The identified negative interactions and conflicts mostly concerned water quantity and quality or biodiversity and competing land uses, which will lead to trade-offs. For example, Daccache et al. (2012) suggest that given competition for water, and existing conflicts (e.g. between irrigation and public water supply and environmental protection) trade-offs are inevitable. Numerous trade-offs are also present in long-term coastal management, however, these can be overcome by developing more coherent cross-scalar approaches to planning and increasing collaboration during the decision-making process (Few et al. 2004). The number of adaptation and mitigation measures for which trade-offs can be identified (whether implicitly or explicitly) highlights the importance of more integrated management.

A number of other factors should be taken into account when considering adaptation and mitigation measures, their impacts and interactions (Berry et al. 2009). Firstly, it is possible that while measures in one sector may not contribute to adaptation or mitigation in another sector, nevertheless they can improve environmental conditions, such as water and soil quality, in the impacted sector. Measures such as these increase adaptive capacity by increasing resilience and robustness both to climate and other changes (Tol 2005). They are, therefore, often seen as low, or no-regret measures, as their benefits are realised regardless of the uncertainties surrounding future climate projections (Hallegatte 2009). For example, in urban areas rainwater harvesting and greywater re-use decentralise water supply, reduce potable water use, and increase regional resilience to drought by improving security (Graddon 2010). In the absence of synergies, such actions should be preferred, as they are likely to produce overall environmental benefits and be more cost-effective. This review found that few authors explicitly included such opportunities, or showed how the impact could vary depending on circumstances.

Previous studies have often suggested that adaptation and mitigation occur on different scales, with adaptation being mostly local, small scale; whereas mitigation is more global, dealt with by national governments and international agreements (Tol 2005; Biesbroek et al. 2009; Jarvis et al. 2011). Preston et al. (2013) tested the heuristic that “adaptation is local” and found 59 % of adaptation documents analysed endorsed this view. This review, focusing more on implementation, found that many measures were undertaken at similar scales. For example, mitigation actions such as, tree planting (Leicester, UK, Davies et al. 2011), green roofs (Brenneisen 2006), and low energy residential developments (London, UK, Chance 2009) in urban areas; local saltmarsh and floodplain restoration schemes and conservation agriculture (Six et al. 2004), are all implemented at small, often local scales. Adaptation options, such as SUDS (Andersen et al. 1999), building measures (Artmann et al. 2008), testing genetic diversity (Singh and Reddy 2011), changing seed sowing dates (Tubiello et al. 2000) and the construction of low-crested structures (Lamberti et al. 2005) again all occur at local scales. This is not to say that local projects will individually achieve reductions in global GHG concentrations, or to neglect the fact that some mitigation projects are much larger in scale, however, the review found most mitigation actions in Europe seemed to be locally implemented. Mitigation has rarely been considered in this way (e.g. Wilbanks and Kates 1999; Lutsey and Sperling 2008), thus this review adds support to the suggestion of Wilbanks and Kates (1999) and Schreurs (2008) that adaptation and mitigation actions occur at similar, local scales, while benefits may be experienced at different scales.

Differences in temporal scale for adaptation and mitigation were also found, although mitigation actions often led to long-term benefits, and adaptation to near-term benefits (Dessai and Hulme 2007). Many adaptation measures, such as changed sowing times, building measures, and rainwater harvesting schemes, can be implemented (relatively) quickly (Czech Republic, Trnka et al. 2004). However, the review also found evidence of adaptation occurring over much longer timescales, for example, the creation of ecological networks and new protected areas to facilitate species migration responses to climate change, and afforestation using more climate-resilient genotypes. Similarly, many mitigation efforts, such as saltmarsh creation for carbon storage (Choi et al. 2001), or reforestation for carbon sequestration purposes (SW Spain, Caparrós et al. 2010), take place over longer timescales and require longer to become effective. These findings show that, in addition to potential match in terms of spatial scale, the temporal scale of mitigation and adaptation measures also can be similar. Past literature has often emphasised the temporal and spatial mismatch of scales as posing a barrier to the integration of mitigation and adaptation, and the successful evaluation of trade-offs (Tol 2005; Howden 2007). Results from this review, however, suggest that there are many cases in which the scales are comparable, thus providing support for arguments to change this perceived barrier and to integrate adaptation and mitigation (e.g. Preston et al. 2013).

It is important that these within-sectoral and cross-sectoral interactions are taken into account in any mainstreaming of adaptation (or mitigation) in sectoral policies to enhance positive outcomes and to avoid unintended consequences (Klein et al. 2007). The largest category of synergies identified was between adaptation and mitigation within a sector. Often these synergies (and conflicts) were not explicit and, if adaptation and mitigation are to be more successful, these need to be stated explicitly and the benefits of measures quantified, in order that greater effectiveness can be achieved or trade-offs dealt with (see Stoorvogel et al. 2004; Jarvis et al. 2011). This would require greater cross-sectoral working and integration across relevant policies at all levels of governance as advocated by the EU White Paper on "Adapting to Climate Change" (European Commission, 2009) and the recently adopted EU "Strategy on adaptation to climate change" (European Commission, 2013a). Thus it is recommended that all interactions, whether synergistic or conflicting, and trade-offs should be part of any formal assessment of the impacts of adaptation and mitigation measures, in order to achieve integrated and efficient responses to climate change. One example of potential cross-sectoral integration is ecosystem-based adaptation which increasingly is being promoted by the UNFCCC[1] and by the EU. The Impact Assessment accompanying the EU Strategy on adaptation to climate change suggests that "there is growing recognition of the importance of ecosystem-based approaches by other sectors, particularly in relation to coastal protection, urban planning and water management" p33 (European Commission 2013c). Such an approach also is advocated in the EU Biodiversity strategy to 2020 as a cost-effective way to address climate change adaptation and mitigation while offering multiple benefits beyond biodiversity conservation (European Commission 2011). It is further stressed in the Communication on Green Infrastructure (European Commission 2013d) and this review found evidence to support this, for example, green infrastructure, including green roofs, urban trees, and SUDS (e.g. Wise et al. 2010; Fioretti et al. 2010). It is interesting that biodiversity adaptation measures appeared to have little or no direct impact on other sectors or were synergistic, thus further supporting the ecosystem approach to environmental management.

Moving forward it is logical to favour strategies involving a high number of synergies to avoid unsustainable pathways or lock-in and promote cost effectiveness (Bosello et al. 2013; Skourtos et al. this volume). However, the flexibility of schemes and the extent to which they offer no-regret solutions and increase resilience, are also important to consider (Adger et al. 2005; Hallegatte 2009), as they can substantially reduce climate change impact uncertainties. Several of the measures reviewed are no-low regret and have synergies with mitigation and/or adaptation and mitigation in other sectors, but other factors may influence their effectiveness. For example, habitat and wetland creation both have synergies with mitigation, but while the latter is a very effective carbon sink, the extent of mitigation provided by habitat creation is highly dependent on habitat type. Similarly, the strength of mitigation provided by afforestation with climate-resilient genotypes depends on the ability of new species to sequester carbon and their vulnerability to other drivers of change. Taking the above factors into consideration, it appears that some of the most favourable options are those which work across sectors, restoring and enhancing the natural capacity of biodiversity to provide ecosystem services. For example, SUDS options and green infrastructure options

[1] http://unfccc.int/resource/docs/2013/sbsta/eng/02.pdf

benefit adaptation in the water and urban sectors, as well as contributing to mitigation through carbon storage, reduction of the heat island effect and providing habitat for biodiversity (Greater Manchester, UK, Gill et al. 2007).

5 Conclusions

This paper is one of the first to address the cross-sectoral interactions, synergies and conflicts between adaptation and mitigation measures. It found that there are knowledge and/or reporting gaps on the cross-sectoral interactions between the measures, with many synergies and conflicts not explicitly recognised. Nevertheless, some explicit and more implicit evidence of the highly cross-sectoral nature of many of these measures was identified, with many of those examined having synergies with other sectors. The need for cross-sectoral integration is acknowledged in current international adaptation policy, and given the number of interactions identified by this review involving biodiversity and water, actions like ecosystem-based adaptation or mitigation and blue/green infrastructure seem promising as they involve a high number of synergies and benefit multiple sectors. Realisation of these synergies will require cross-sectoral working which presents the challenges of collaboration across sectors, as well as engagement with multiple stakeholders. Also, it will require appropriate metrics for the standardised assessment of which measures are the most effective. It will, however, assist the mainstreaming of adaptation and mitigation into policy and provide opportunities for more efficient, cost-effective adaptation and mitigation to be undertaken.

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	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
Agricultural irrigation	*Decrease supply to other water users*; **water saving irrigation techniques could reduce demand**	*Reduce water in rivers and lakes can adversely affect biodiversity, especially wetlands*					**Possible increased soil C storage; water saving techniques could reduce energy demand**; **reduce CO_2 emissions**; **decrease CH_4 emissions by intermittent irrigation of paddy rice**
Habitat restoration	**Peatland/coastal restoration increases water storage**; **decrease flood risk** ; increase water quality					**Improve coastal defence**; *increase tidal prism/ erosion*	**Wetlands/coastal habitats restoration will increase carbon sequestration**
Coastal managed realignment	Long-term improvement in water quality; *short-term may be negative*	**Increased habitat**; **benefits most species**	**Increase**/*decrease* **urban protection**		*Loss of agricultural land*		**Increase carbon sequestration**; *increase in CH_4 and N_2O emissions*
Afforestation/reforestation	**Can reduce (peak) river flow**; restore water quality; *groundwater recharge; increase water demand from trees; Drainage ditches increase peak*	**Increase diversity and habitat availability**; *habitat loss/change; species loss due to chemical*			*Loss of agricultural land*		**Increase C storage (on newly planted land**; *subsequent thinning and management can reduce C storage*

	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
	flows in early stages of plantations	*inputs and forest management*					
Urban trees and greenspace	**Runoff reduction**; improve air quality by reducing particulate pollution	**Habitat provision**; **increase biodiversity**; *increase allergens and invasive species*					**Carbon sequestration; reduce energy demand through decreasing temperatures**

Table 1: Examples of adaptation measures identified in this review (both implicit and explicit), and their cross-sectoral interactions and effects on mitigation. Text in bold indicates a synergy between the measure and adaptation or mitigation in another sector; italics indicates a negative interaction or conflict between the measure and adaptation or mitigation in another sector; normal type indicates a neutral effect between the measure and adaptation or mitigation in another sector, but can represent an overall environmental benefit, such as an improvement in water quality. NB this is based on evidence found from the review and a fuller version of the Table and the sources of the information can be found in Table 2, Supplementary information.

Supplementary Material

Subject	Adaptation	Additional adaptation term	Mitigation	Additional mitigation term
Agriculture				
Agriculture[1]	Cover/catch crops Tillage No till Reduced tillage Spring crop Winter crop Irrigation Drain*		Reduced manure[3]	Mitigation Carbon storage Carbon sequestration
Arable[1]			Nitrogen fixation[3]	
Crop[1]			Fertiliser/fertilizer[3]	
			Tillage[3]	
		Climate change		
Pasture	Breeding			
Grassland	Breeding			
Biodiversity				
	Habitat matrix[2]	Climate change adaptation		
Biodiversity	Protected areas[2]			
	Buffers[2]			
	Habitat restoration[2]			
	Ecological corridor			
Species	Refugia[2]			
	Assisted migration[2]			
Habitat	Stepping stones[2]			
	Restoration[2]			
Coasts				
	Beach nourishment	Climate change adaptation		
Coastal	Wetland creation/Wetland restoration	Adaptation	Wetland creation/Wetland restoration	Carbon storage
	Managed realignment/Managed retreat	Europe		
	Storm-surge barrier	Adaptation		

Subject	**Adaptation**	**Additional adaptation term**	**Mitigation**	**Additional mitigation term**
Salt marsh			Salt marsh[3]	Mitigation Carbon storage
Coastal wetlands			Coastal wetlands[3]	Mitigation Carbon storage
Forests				
Forest*	Afforestation		Afforestation[3]	Carbon sequestration Carbon storage
	Reforestation		Reforestation[3]	
	Agroforestry		Agroforestry[3]	
	Thinning		Thinning[3]	
Urban				
Cities	Climate proofing/ Climate-proofing	Adaptation		
	Smart growth	Climate change		
Urban	Green walls/ living walls	Climate change adaptation	Green walls/ living walls	Climate change mitigation
	Green roofs/ living roofs	Climate change adaptation	Green roofs/ living roofs	Climate change mitigation
	Storm water management	Adaptation	Greenspace	Mitigation
	Green infrastructure/ Green-infrastructure	Climate change adaptation		
	Intensification	Climate change adaptation		
Europe			Passive ventilation	Climate change
Europe			Sustainable construction[3]	Climate change mitigation
Europe			Building design[3]	
Subject	**Adaptation**	**Additio**	**Mitigation**	

		nal adaptation term		
Europe			Public transport[3]	
Europe			Retrofitting[3]	
Water				
Runoff / storage[4]	Policy (water management, CAP etc) Floodplain restoration Urbanisation Afforestation / reforestation		Wetland creation Carbon storage Carbon sequestration	
Infiltration[4]				
Flow rate[4]				
Flood impact[4]				
Demand (for water resources) [4]				
	Changing tillage practice[5]	Increased infiltration		
	Extensification[5]			
	Stormwater source control[5]			
	Field Drainage[5]	Reduced run-off / increased storage		
	Afforestation[5]			
	Buffer strips/zones[5]			
	Hill slope connectivity[5]			
	Rainwater harvesting[5]			
	Bypass channels / flood diversion[5]			
	Detention ponds[5]			
	Wetlands and washlands[5]			
	Floodplain / wetland storage[5]			
	Channel restoration[5]			
	Floodplain restoration[5]			
	Drainage channel maintenance[5]	Reduced flow rate		
	Drainage channel realignment[5]			
	Re-open culverted watercourses[5]			
Subject	**Adaptation**	**Additional adaptation term**	**Mitigation**	**Additional mitigation term**
	Temporary defences[5]	Reduced flood impact		
	Land-use planning[5]			
	Dikes and embankments[5]			
	Floodplain restoration[5]			
	Water resource	Demand		

	management[5]			
	Water use management[5]			
Agricultural users[6]			Carbon sequestration Carbon storage Wetland creation	Demand
Domestic users[6]				
Industrial users[6]				
Freshwater wetlands[6]				Habitats
Inland surface waters[6]				
Mires, bogs and fens[6]				
Grasslands and tall forb habitats[6]				
Heathland, scrub and tundra[6]				
Woodland and forest[6]				
Sparsely/unvegetated areas[6]				
Fish[6]				
Birds[6]				
Mammals[6]				
Reptiles / Amphibians[6]				

[1] each of these subjects was searched against each adaptation in the column to the right.

[2] each of these adaptation terms was searched against the additional term Climate change adaptation

[3] each of these mitigation terms was searched against each of the additional mitigation terms

[4] each of these subjects was searched against each adaptation and mitigation term

[5] each of these adaptation terms was searched against the additional adaptation terms

[6] each of these subjects was searched again each of the mitigation and additional mitigation terms

Table 1**:** Literature review sectoral search terms**.**

Adaptation measures	Sectors impacted by adaptation measure						
	Water	Biodiversity	Urban	Forests	Agriculture	Coasts	Mitigation effect
Agriculture							
Irrigation	Decrease supply to other water users[1]; water saving irrigation techniques could reduce demand[2,3]	Reduce water in rivers and lakes can adversely affect biodiversity, especially wetlands[4]					Possible increased soil C storage[5]; water saving techniques could reduce energy demand[6,7]; reduce CO_2 emissions[8]; decrease CH_4 emissions by intermittent irrigation of paddy rice[8]
Crop type		Increase in water levels in wetlands[9]					
Earlier sowing dates	Decrease water requirement and stress in summer[10,11]/ spring crops increase irrigation need[11]						Possible increase in soil carbon storage[12]; spring sown crops could reduce N_2O emissions[13]
Breeding		Loss of genetic diversity[14]					

	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
Conservation agriculture	Improve crop water use efficiency[15]; increase water storage[16,17]; reduce N leaching[13];decrease crop water use efficiency[18,19]; no-tillage can increase pesticide concentrations[20]	Increase soil fauna, including earthworm numbers; better habitat for micro-organisms[21,22]; possible weed and pest control problems[23,24]					Possible increase in soil C storage[25,26,27], reduce energy inputs[28,29]; decrease/increase GHG emissions depending on measure & its implementation[30.31]
Targeting amount and timing of fertiliser application	Improve water quality through reduced nitrogen leaching[32]						Decrease GHG emissions[25]
Biodiversity							
Assisted colonisation				Increase climate change resilient species[33]			
Corridors	Improve water quality[34]						Decrease energy demand in urban areas[35]
Networks				Possible loss of forest and carbon store[36]	Possible loss of agricultural land[36]		Increased C storage likely with replacement of agricultural land[36]

	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
Habitat restoration	Peatland/coastal restoration increases water storage[37]; decrease flood risk[37] ; increase water quality[37,38]					Improve coastal defence [38, 39,40]; increase tidal prism/ erosion [39,41]	Restoring wetlands/coastal habitats will increase carbon sequestration[37,42,43]
Coasts							
Wetland/coastal habitat creation	Decrease flood risk[44,45]; long-term improvement in water quality[46,47]; short-term may be negative[48]	Increased habitat[39] species richness and carrying capacity[49, 50, 51]			Loss of agricultural land[42,50]		Increase carbon sequestration[42, 43, 52]; increase in CH_4 and N_2O emissions[53-5]
Managed realignment	Long-term improvement in water quality[56]; short-term may be negative,[53,57]	Increased habitat[39,58]; benefits most species[59]	Increase/decrease urban protection[60,61]		Loss of agricultural land[50,62,63]		Increase carbon sequestration[42]; increase in CH_4 and N_2O emissions [53,55]
Managed retreat	Possible short-term reduction in water quality followed by overall improvement[64]	Habitat gains[47]/loss[58,65]; benefits most species	Increase/decrease urban protection[60,61]		Loss of agricultural land[62,63]		Increase carbon sequestration[42]; increase in CH_4 and N_2O emissions[64]

	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
Low crested structures		Provision of novel habitat[66-68]; fish nursery ground[69]; increase in algae, but can prevent species settling on structure[67]; coastal squeeze[70]					
Beach nourishment		Change assemblage[71]/loss of species[71-73]					
Storm surge barriers	Improve/decrease (on seaward and landward side of barrier respectively) of water quality and clarity[74]	Habitat creation potential behind barriers; improved water quality can increase phytoplankton productivity; changed species composition[74,75,76]; also loss/ degradation of habitats[36,74,77]	Protection from flooding [74]				Tidal barriers if combined with energy production could reduce fossil fuel demand; lakes behind them can increase local temperatures[74,77]
Forests							

	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
Afforestation/reforestation	Can reduce (peak) river flow; restore water quality; groundwater recharge; increase water demand from trees[78,79]; Drainage ditches increase peak flows in early stages of plantations[78,79]	Increase diversity and habitat availability [80,81]; habitat loss/change[80,81]; species loss due to chemical inputs and forest management[82]			Loss of agricultural land[83]		Increase C storage (on newly planted land[84-7]; subsequent thinning and management can reduce C storage[88]
Urban							
Green roofs	Stormwater, infiltration and flow reduction[89-92]	Habitat provision[93,94], but challenging environment[95]					Carbon sequestration[96,97]; reduce energy demand through decreasing temperatures[98]
Urban trees and greenspace	Runoff reduction[99, 100, 101]; improve air quality by reducing particulate pollution[102]	Habitat provision[103,104]; increase biodiversity[103,104]; increase allergens and invasive species[104,105]					Carbon sequestration[105-7]; reduce energy demand through decreasing temperatures[91, 99 107]
White-topping/cool pavements							Reduce energy demand through decreasing temperatures[108-10]

	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
Rainwater harvesting	Reduces water demand[111-3]; especially domestic; decentralises water supply[112,113]						
Building measures e.g. insulation, air conditioning and passive ventilation							Reduce energy demand through decreasing temperatures[114-7]
Sustainable urban drainage systems (SUDS)	Reduced amount and peaks of runoff[90,118-121]; pervious pavements filter and store runoff; improved water quality via reduced diffuse pollution[122,123]	Can provide habitat[111, 124]; restore certain ecosystem functions[124]					
Urban intensification/ densification	Possible increased runoff[125]	Preserves greenspace (habitat for species) [126]			Can protect agricultural land from development[126-9]		Reduce GHG emissions through reduced travel distances[129,130]; decrease heating demands[131,132]; increase emissions due to traffic congestion[130]
Water							

	Sectors impacted by adaptation measure						
Adaptation measures	**Water**	**Biodiversity**	**Urban**	**Forests**	**Agriculture**	**Coasts**	**Mitigation effect**
Increased infiltration e.g. changing tillage practices; storm water control			Reduce urban flooding[118-121]		Increase soil water availability[16,17]		
Increased storage e.g. reduced drainage; RWHS afforestation; wetland restoration		Ponds can increase biodiversity[124]				Reduce sediment supply[133]; saline intrusion[133]	Ecosystem-based measures could increase carbon sequestration[134]
Reduced flood impact e.g. through defences, planning		Change biodiversity[124]					Ecosystem-based measures could increase carbon sequestration[134]
Flood plain restoration	Improve water quality[135]	Increase in wetland habitat and species[136]					Ecosystem-based measures could increase carbon sequestration[134]
Dams/reservoirs		Gain of lacustrine/ loss of riverine species/habitat; restricted species movement[137]					Reduce emissions from fossil fuel if HEP energy used instead[138]; direct increase in greenhouse gas emissions[138]

Table 2: Overview of adaptation measures identified in this review (both implicit and explicit), and their cross-sectoral interactions and effects on mitigation. Text in green indicates a synergy between the measure and adaptation or mitigation in another sector; red indicates a negative interaction or conflict between the measure and adaptation or mitigation in another sector; black indicates a neutral effect between the measure and adaptation or mitigation in another sector, but can represent an overall environmental benefit, such as an improvement in water quality. NB this is based on evidence found from the review and the sources of the information are indicated by the numbers.

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