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Spatial planning of a climate adaptation zone for wetland ecosystems

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Abstract Here we present a spatial planning approach for the implementation of adaptation measures to climate change in conservation planning for ecological networks. We analyse the wetland ecosystems of the Dutch National Ecological Network for locations where the effectiveness of the network might be weakened because of climate change. We first identify potential dispersal bottlenecks where connectivity might be insufficient to facilitate range expansions. We then identify habitat patches that might have a too low carrying capacity for populations to cope with additional population fluctuations caused by weather extremes. Finally, we describe the spatial planning steps that were followed to determine the best locations for adaptation measures. An essential part of our adaptation strategy is to concentrate adaptation measures in a 'climate adaptation zone'. Concentrating adaptation measures is a cost-effective planning strategy, rendering the largest benefit per area unit. Measures are taken where abiotic conditions are optimal and measures to enhance the spatial cohesion of the network are taken close to existing areas, thus creating the highest possible connectivity with the lowest area demands. Another benefit of a climate adaptation zone is that it provides a spatial protection zone where activities that will have a negative impact on ecosystem functioning might be avoided or mitigated. The following adaptation measures are proposed within the climate adaptation zone: (1) link habitat networks to enable species to disperse from present to future suitable climate zones, (2) enlarge the carrying capacity by either enlarging the size of natural areas or by improving habitat quality to shorten population recovery after disturbances, (3) increase the heterogeneity of natural areas, preferably by stimulating natural landscape-forming processes, to avoid large synchronised extinctions after extreme weather events. The presented approach can be generalised to develop climate adaptation zones for other ecosystem types inside or outside Europe, where habitat fragmentation is a limiting factor in biodiversity responses to climate change.

Keywords Climate change · Biodiversity · Adaptation strategy · Ecological network · Adaptive capacity · Spatial planning

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Introduction

Climate change is considered to have large impacts on biodiversity and the functioning of ecosystems. It is expected to become the greatest driver of global biodiversity loss together with land-use change (Thomas et al. 2004; Lovejoy and Hannah 2005; Millennium Ecosystem Assessment 2005; IPCC 2007). In order to slow down climate change, reducing greenhouse gas emissions is of high importance. However, it has been recognised in policy responses that adaptation measures are also needed to cope with the already unavoidable impacts of climate change (see Brooker et al. 2007 for an overview of policy responses). Even assuming the most optimistic projections of the level of mitigation that can be achieved, we are still going to experience a significant degree of climate change (Pallemearts et al. 2005). The European Union recently published a White Paper on climate change adaptation (Commission of the European Community 2009) in which a framework is set out to enhance the EU's resilience to the impacts of climate change. It is recognised that, although ecosystems are threatened by climate change, they are also part of the adaptation solution as they perform important services for society such as climate regulation, carbon sequestration, flood protection and soil erosion prevention. To safeguard these services for society, resilient ecosystems are needed that are able to cope with impacts of climate change, such as the increased dynamics caused by weather extremes and the shifting of suitable climate zones.

The changing climate is already apparent and relatively strong in the Netherlands (KNMI 2008). Since 1900, the mean temperature has increased by 1.7°C, compared to a worldwide mean increase of 0.8°C. Precipitation in this period also increased by 18%, with more frequent extreme downpours. Future climate change scenarios for the Netherlands are derived from the IPCC scenarios (KNMI 2006) and predict an additional temperature rise of between 1.8 and 5.2°C by 2100 (compared to 1990).

In this paper we introduce a method for the implementation of climate adaptation measures in conservation planning for ecological networks. We first explore the potential vulnerability of ecosystems and species to the impacts of climate change. We then define spatial adaptation measures that will enhance the adaptive capacity to cope with some important impacts of climate change. We illustrate the spatial planning process of our adaptation strategy in an on-the-ground application for the wetland ecosystems in the Netherlands.

Effects of climate change on ecological networks

Ecological networks are a well-known strategy for sustainable biodiversity protection in highly fragmented landscapes (Jongman and Pungetti 2004). In the Netherlands, the National Ecological Network (NEN) was developed in the early 1990s to improve conditions, extend natural areas and enhance functional connectivity. The habitat network concept also plays an important role in building the Natura 2000 network, the European Union system of protected areas. The question has recently surfaced whether the NEN is able to cope with climate change or whether additional measures are necessary to make ecosystems more resilient to the effects of climate change.

Adaptation to climate change refers to an array of approaches that range from natural adaptation at one end of the spectrum to sustainability in coupled human and natural systems at the other (Brooke 2008). Adaptation to climate change is fundamentally linked to the concept of vulnerability, the degree to which a system is likely to experience harm due to exposure to perturbations or stresses (Kasperson et al. 2005). In this paper we focus on adaptation strategies for natural systems. We follow the adaptation definition of Wilson and Piper (2008), who argue that biodiversity adaptation requires a double focus. The first focus is on adaptation measures that reduce vulnerability on the spot by increasing ecosystem resilience to disturbances and by accommodating change. The second focus is on adaptation measures that facilitate the ability of species and habitats to move elsewhere into newly suitable areas.

One of the best documented effects of climate change on biodiversity is the observed shift of species' distributions towards the poles and to higher elevations (e.g. Warren et al. 2001; Green and Pickering 2002; Julliard et al. 2004; Hickling et al. 2006). Bioclimate envelope models predict additional large future range expansions of several hundreds of kilometres during the 21st century, the extent depending on the climate change scenario (Harrison et al. 2006; Araújo and New 2007; Huntley et al. 2007), while ranges are predicted to contract where the climate is no longer suitable. Whether species will indeed be able to colonise this new climate space depends on the land-use pattern. Modelling studies combining projected range shifts with the distribution of suitable habitat predict a further loss of biodiversity because potential habitats are too isolated (Brook et al. 2008; Vos et al. 2008). Warren et al. (2001) found that only those butterfly species capable of dispersing over large distances or using widespread habitats were able to respond to climate change by expanding northwards. These observations imply that range expansion into new climate space depends on both species and landscape characteristics; it is becoming clear that many species are lagging behind in their response to shifting climate zones (Menéndez et al. 2006; Devictor et al. 2008). Thus, spatial responses by species to climate change may be severely hampered or even inhibited by habitat fragmentation (Opdam and Washer 2004; Wilson et al. 2009).

A second important effect of climate change is the increase in extreme weather events, which are expected to become both more frequent and more severe (IPCC 2007). Much less is known of the impacts of increased weather variability on biodiversity, although it is expected that large scale synchronised disturbances, such as flooding or periods of extreme drought, will increase population fluctuations and extinctions. Easterling et al. (2000a, 2000b) point out that not so much the mean trends as the occurrence of weather extremes are the actual driving forces for species responses to climate change. This is supported by the findings of Julliard et al. (2004) during the extreme dry and hot summer of 2003 in France, who found that birds with a northern distribution had relatively low reproduction, while birds with a southern distribution showed a high reproduction success, thus driving range expansion and contraction of species. The effects of extreme drought, heavy rain and heat waves on the species composition of vegetation have also been documented (Jentsch and Beierkuhnlein 2008). A negative interaction with habitat fragmentation is to be expected, as spatially correlated disturbances will shorten the metapopulation time to extinction (Akcakaya and Baur 1996). This effect is illustrated for the blue butterfly (*Cupido minimus*), where local extinctions after the extreme summer heat wave of 2003 were correlated with small population size (Piessens et al. 2008). The recovery time after disturbances also increases with habitat fragmentation. Foppen et al. (1999) showed that sedge warblers (*Acrocephalus schoenobaenus*) in heavily fragmented habitat networks in the Netherlands almost became extinct during periods of population crashes caused by droughts in African wintering areas. The population decrease was smaller and the recovery faster in less fragmented regions. Based on these findings, it is to be expected that the future increase in extreme weather events might lead to regional extinctions more often, especially in fragmented habitats.

Two impacts of climate change therefore come forward that were not taken into account in the original design of the NEN: facilitating range shifts and compensating for additional population fluctuations. The question therefore becomes relevant whether the NEN will be sufficiently robust to compensate for these additional effects. The NEN was originally designed for the sustainable protection of species in habitat networks. Criteria for the size and connectivity of sustainable habitat networks, based on metapopulation ecology (Hanski et al. 1996), were derived for a set of indicator species that represent existing variation in the spatial functioning of target species 'ecoprofiles' (Vos et al. 2001; Opdam et al. 2008). Facilitating range shifts would require the linking of ecosystem networks on a much larger scale between present and future suitable climate zones (Vos et al. 2008). It is also to be expected that larger habitat networks are necessary to compensate for additional disturbances (Verboom et al. 2010).

Facilitating range shifts and avoiding extreme weather-driven extinctions are not only beneficial for the protection of individual species. They are also important in order to maintain a high level of functional biodiversity in ecosystems, thus compensating for unavoidable species losses at the contracting sides of species' ranges. There are indications that a high level of biodiversity is an important prerequisite for the adaptive capacity of ecosystems (e.g. Hooper et al. 2005; Johnson et al. 1996).

Defining an adaptation strategy: climate adaptation zones

We define several adaptation measures to enhance the adaptive capacity of the NEN to cope with climate change. We propose that these adaptation measures should be combined and spatially concentrated to be most effective in a 'climate adaptation zone'. We define a climate adaptation zone as: a focus zone for adaptation measures to enhance the adaptive capacity of the ecological network to cope with climate change and in which activities that would have a negative impact on the functioning of the ecological network, such as urbanisation or road construction, should be avoided.

A first adaptation measure to be implemented within this climate adaptation zone is to improve connectivity over large distances by solving dispersal bottlenecks and thus facilitating range shifts. By linking habitat networks, species will be able to colonise habitats that become suitable as compensation for the loss of habitat at the contracting side of its range.

A second adaptation measure is to increase the carrying capacity of protected areas by either enlarging the size of protected areas or by improving habitat quality. Increasing the carrying capacity provides space for larger populations, thus reducing population extinction probabilities (Verboom et al. 2001) and shortening recovery time after disturbances (Foppen et al. 1999).

A third adaptation measure to be carried out within the climate adaptation zone is to better accommodate natural landscape forming processes such as sedimentation, marshland development, meandering of rivers and freshwater-salt water gradients. By thus increasing the spatial heterogeneity, a strategy is provided for coping with increased weather variability, as large scale correlated population fluctuations can be avoided (Bengtsson et al. 2003; Opdam and Washer 2004; Hodgson et al. 2009). In a heterogeneous habitat, some parts may allow a positive growth rate in very dry years, whereas other parts may be optimal during wet years. This pattern may be reversed due to temporal variation in weather conditions, as was shown for a spatially structured population living in a heathland with dry and wet patches by Den Boer (1986). Piha et al. (2007) also showed that the decline and extinction of common frog (*Rana temporaria*) populations was lower in heterogeneous landscapes in the extreme dry summer of 2003. As the carrying capacity of habitats that are more heterogeneous will be lower compared to patches with optimal habitat quality only, building heterogeneity would be an additional reason to increase patch size.

In the next sections we analyse the NEN for locations where the effectiveness of the ecological network might be weakened because of climate change. We first identify potential dispersal bottlenecks where the connectivity might be insufficient to facilitate range expansions. Secondly, we identify habitat patches that might have a too low carrying capacity for populations to cope with additional population fluctuations caused by weather extremes. We subsequently describe the spatial planning procedure that was followed to determine the best locations for a climate adaptation zone. We illustrate the analysis and spatial planning process for the wetland ecosystem network, one of the main ecosystem types of the NEN.

Identifying dispersal bottlenecks

We analysed the spatial configuration of all wetlands of the NEN to identify dispersal bottlenecks—locations where the distance between wetland areas is considered to be too large for expansion—using the habitat network assessment tool LARCH (Verboom and Pouwels 2004). LARCH delineates habitat networks based on maps of suitable habitat (divided into 25×25 m grid cells) and species characteristics. We used a sample of 42 target species that are characteristic for wetland ecosystems and that represent existing variation in spatial functioning, called 'ecoprofiles' (Opdam et al. 2008). These species vary in their choice of wetland habitat type, individual area requirements, dispersal distance and sensitivity to barriers in the landscape. LARCH delineates wetland networks for each species separately, depending on the specific characteristics. When the distance between suitable habitat patches exceeds the dispersal capacity of a species, or a species-specific dispersal barrier occurs in the landscape, the patches are divided over two separate networks. These locations are regarded as a dispersal bottleneck, as an expanding species with similar habitat choice and dispersal capacity would not be able to cross the distance between these networks. At locations where networks were separated, the route to the nearest network was identified for each ecoprofile. These represent the bottlenecks where networks need to be linked. Of the 42 wetland species that were analysed, 40 % showed one or more bottlenecks, where the distance between wetlands exceeded their dispersal capacity. The distribution of bottlenecks within the NEN is summarised in Fig. 1 in 5×5 km grid cells, indicating

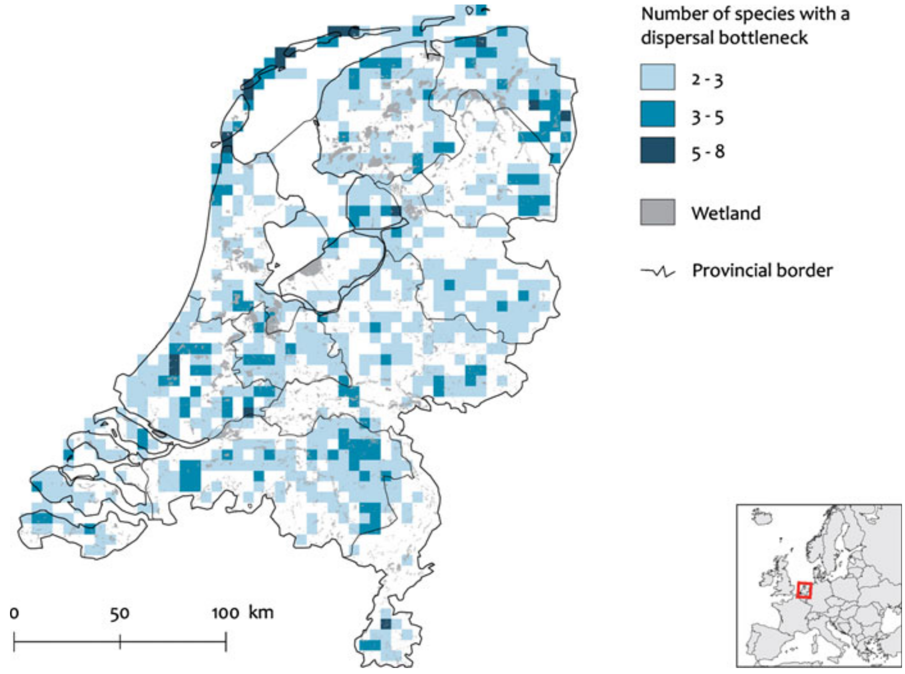

Fig. 1 The distribution of dispersal bottlenecks in the wetland habitat network for a sample of 42 target wetland species. The number of species that encounter a bottleneck is summarised in 5 × 5 km grid cells. A dispersal bottleneck occurs where the distance between suitable habitats exceeds the dispersal distance of the species

the number of species that encounter a bottleneck per grid cell.

Identifying areas with increased extinction risks

Large areas, holding large populations, are important for the protection of species in ecological networks. These relatively stable populations, called key populations, increase the survival probability of the metapopulation as a whole (Verboom et al. 2001; Opdam et al. 2003). We analysed the potential loss of these key populations, where the carrying capacity of areas would be too small to compensate for additional population fluctuations. Verboom et al. (2001) have defined a key population as a relatively large local population in a network, which is persistent under the conditions of one immigrant per generation. The area required for one key population, a 'key area', differs between species as it depends on the individual area requirements of target species. Spatial standards for the sustainable protection of target species have been formulated based on a minimum required number of key areas within the NEN for each target species (Verboom et al. 2001; Reijnen et al. 2007). These spatial standards are based on metapopulation models and incorporate a certain level of environmental fluctuations (Verboom et al. 2001). However, should environmental fluctuations increase because of climate change, population fluctuations will also increase (Soulé 1987) and larger habitat patches, holding larger populations, will be needed to maintain the same level of sustainability of the habitat network (Verboom et al. 2010). As it is unknown to what extent population fluctuations will increase in the future, we performed a sensitivity analysis assuming that double area requirements for key populations would be required to compensate for the increased extinction risk. We analysed the pattern of all suitable wetland habitats of the NEN using the LARCH model. For all fauna target species, it was calculated where habitat areas would be sufficient to hold a key population, using double spatial standards, based on species-specific carrying capacity standards per wetland habitat type (Verboom and Pouwels 2004). Figure 2 shows the percentage of target species for each wetland area of the NEN that finds a key population, assuming double area requirements. Figure 3 shows a decline in the sustainable protection of wetland target species from 72 to 55% when the area requirements for a key population are doubled. These results would imply a considerable loss in the effectiveness of the NEN for biodiversity protection should indeed larger population fluctuations occur because of climate change. On the other hand, the

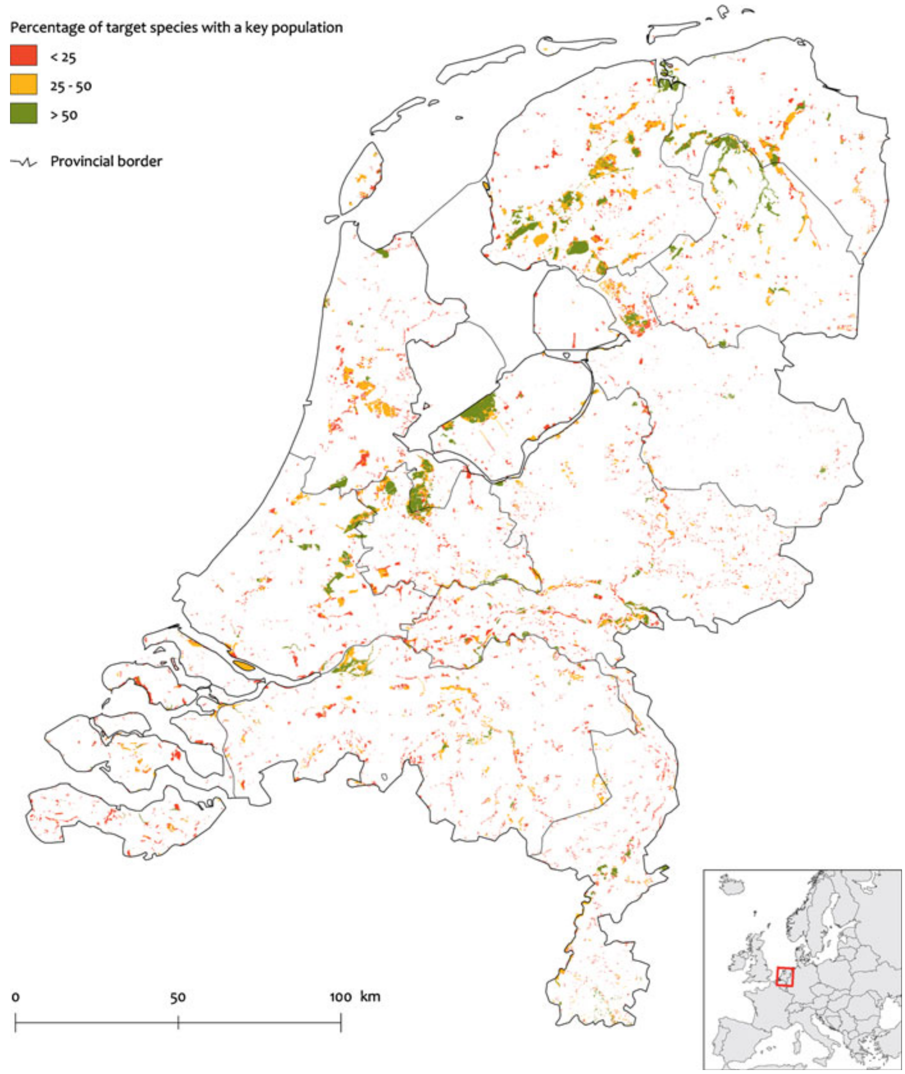

Fig. 2 Percentage of target species for each wetland area of the NEN that finds a key population, assuming double area requirements are needed to compensate for additional population fluctuations caused by climate change

analysis also indicates which areas remain strongholds within the wetland network, holding key populations for almost all target species, even when individual area requirements are doubled (Fig. 2).

Planning the climate adaptation zone

Adaptation measures are spatially concentrated in the climate adaptation zone to increase the adaptive capacity of the NEN. The planning process to determine the optimal location for the adaptation zone consisted of two phases. In the first phase we held several interactive sessions with ecological experts and produced a rough sketch of the best location for the climate adaptation zone, based on the first three criteria below. In the second phase we delineated the zone boundaries in more detail using GIS, based on the criteria under 4. The result of the planning process is presented in Fig. 4.

1. First of all, the position of the climate adaptation zone is determined by the large already existing wetlands, the 'strongholds'. These are the wetlands that will hold key areas for almost all target species even with doubled individual area requirements (see also dark green areas in Fig. 2).
2. The second criterion is to incorporate those regions of the NEN that already consist of wetland networks with relatively high spatial cohesion into the climate adaptation zone, to

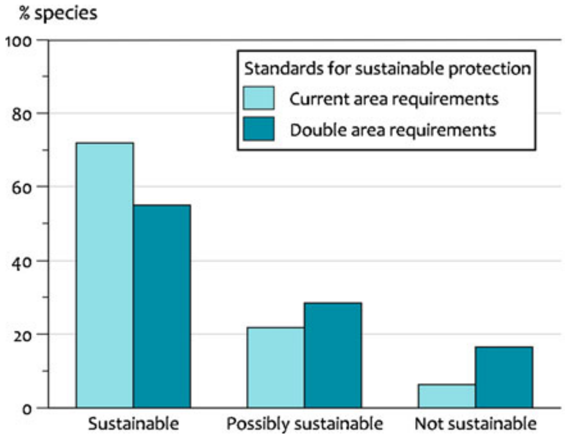

Fig. 3 When the area requirements for a key population are doubled to compensate for additional population fluctuations caused by climate change, the sustainable protection of wetland target species in the NEN declines from 72 to 55 %

minimise the amount of dispersal bottlenecks that need to be solved. We used Fig. 2 to identify NEN regions with a high density of wetlands and combined this information with Fig. 1, where regions can be identified with no or a low number of spatial bottlenecks.

3. The third criterion for the position of the climate adaptation zone is determined by potentials for international connectivity (Fig. 5). The Rhine and Scheldt rivers form natural zones for international wetland connectivity (Jungwirth et al. 2002). Many nature development projects are planned and have already been developed along the banks of the River Rhine. Flood protection plans also provide opportunities to develop natural wetlands, such as the Rhine High Water Action Plan (International Commission for the Protection of the Rhine Action Plan on Floods 2005). The existing connectivity is less favourable in the north and possibilities for wetland restoration should be further explored.
4. The more detailed delineation of the zone boundaries was carried out in GIS using maps of habitat suitability and maps of other land-use types, such as urbanised areas. We incorporated only regions with the most suitable conditions for wetland habitat into the adaptation zone. These represent those parts of the Netherlands with the highest potentials for enlarging existing wetlands and creating new wetlands. Figure 6 shows the aggregated potentials for several wetland types such as mesotrophic grasslands, floodplain grasslands and floodplain shrub lands. The potentials for wetland habitats are derived from current site conditions based on information on soil type, hydrology (groundwater level and seepage) and

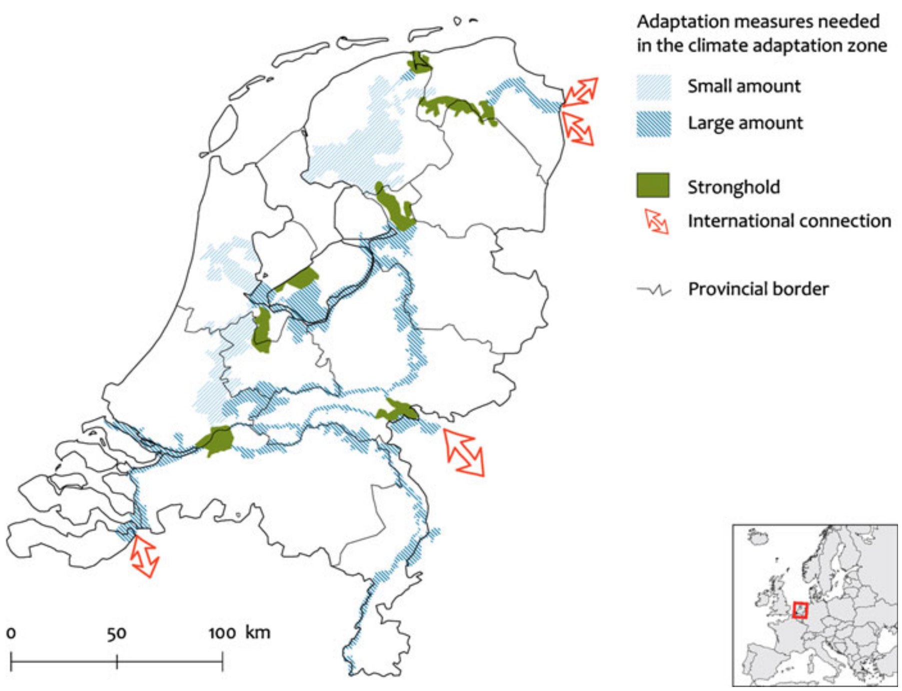

Fig. 4 The proposed climate adaptation zone for wetland ecosystems. The climate adaptation zone is a focus zone for adaptation measures. The optimal location for the climate adaptation zone is determined by the large existing wetlands (strongholds), a high spatial cohesion of the wetland network, a low number of dispersal bottlenecks, high suitable conditions for wetland restoration and potential international connectivity

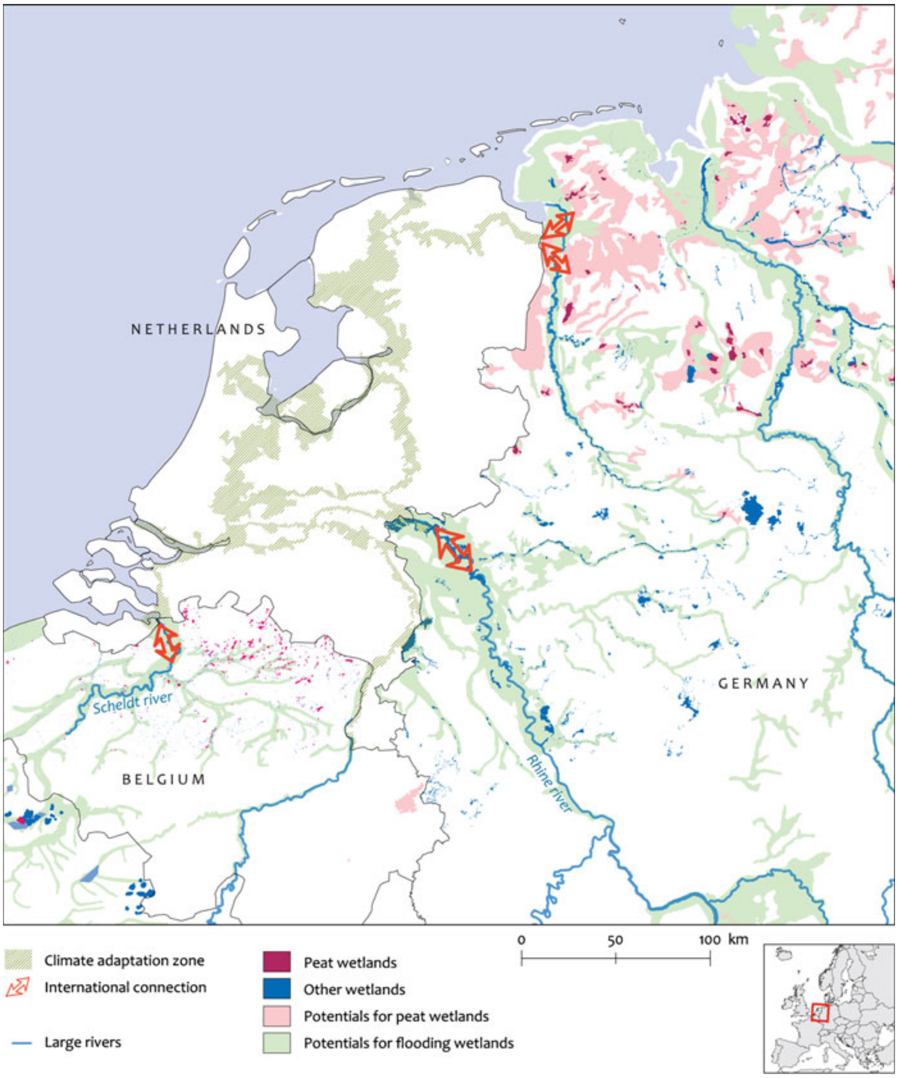

Fig. 5 The potentials for international connectivity of the wetland climate adaptation zone

management (Runhaar et al. 2005). We excluded areas that might have suitable conditions but are highly urbanised from the climate adaptation zone as much as possible, as in these areas pressure on land use is high, and conflicts for space might be expected.

The following adaptation measures need to be taken in the climate adaptation zone:

1. Enlarge existing wetlands and create new wetlands within the climate adaptation zone. The dark blue trajectories (Fig. 4) indicate priority zones where most additional habitat is needed as the current wetlands are too small and scattered (see Fig. 2).
2. Solve bottlenecks for dispersing wetland species (see Fig. 1) and avoid the creation of future bottlenecks within the climate adaptation zone. A measure to increase connectivity is to increase network density by adding new habitat patches and stepping stones between existing patches. For species that are sensitive to barriers in the landscape, additional measures to increase the permeability are needed by increasing the density of natural or semi-natural elements in agricultural landscapes (Ricketts 2001) and taking mitigating measures regarding infrastructure (Van der Grift 2005).
3. Improve the abiotic conditions within wetland areas, preferably by better accommodating

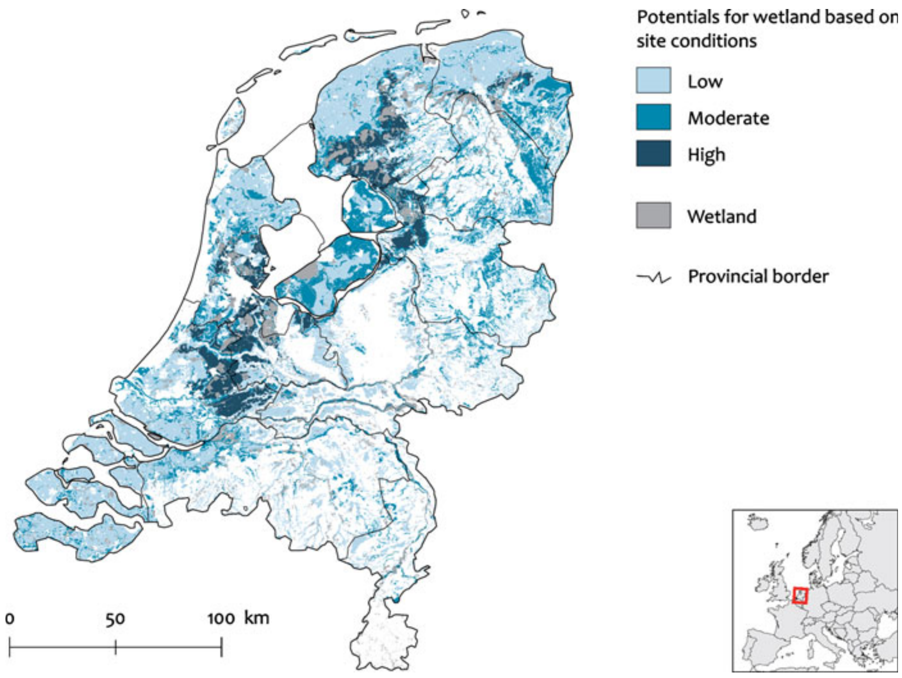

Fig. 6 The distribution of potentials for wetland habitats based on current site conditions. The potentials are aggregated for several wetland types such as: mesotrophic grasslands, floodplain grasslands and floodplain shrub lands

natural processes and diminishing the negative impacts of the surrounding land use. Figure 6 gives the present most suitable conditions. The water balance will change because of climate change but it is still highly unpredictable to what extent and how this will affect the functioning of wetland ecosystems. Depending on the climate change scenario, there will be an increase in drought stress in summer, more dynamic water and groundwater levels, an increased frequency of flooding and different degrees of sea-level rise (KNMI 2006).

Discussion

We present a new method for the implementation of adaptation measures in conservation planning for ecological networks, to enhance the adaptive capacity of ecosystems to cope with climate change, using wetlands as an example. We identified potential bottlenecks where the effectiveness of the Dutch National Ecological Network (NEN) for biodiversity protection might be weakened and defined several adaptation measures that will help to increase the adaptive capacity of the NEN to cope with climate change. An essential part of our adaptation strategy is to concentrate adaptation measures in a 'climate adaptation zone', as a cost-effective strategy. Concentrating adaptation measures in a climate adaptation zone will increase the adaptive capacity of the wetland ecosystem to cope with disturbances at the site as well as facilitate range expansions for species whose suitable climate zone is predicted to shift northwards. Habitat networks need to be linked over large distances within the climate adaptation zone, enabling species to disperse from present to future suitable climate zones. As an adaptation measure to cope with the predicted weather extremes we proposed the enlargement of areas and the stimulation of habitat heterogeneity, to avoid regional extinctions. Enlarging the carrying capacity will shorten population recovery after disturbances. Increasing heterogeneity, preferably by encouraging natural landscape forming processes such as sedimentation, meandering of rivers and freshwater-salt water gradients, spreads the risk by avoiding large synchronised extinctions after extreme weather events.

Concentrating adaptation measures in the climate adaptation zone is a cost-effective planning strategy, rendering the largest benefit per area unit. A first advantage is that measures are taken at those locations where abiotic potentials for nature restoration are optimal. A second advantage is that measures to enhance the spatial cohesion of the network are most effective when situated in the vicinity of existing areas (Johst et al. 2002), thus creating the highest connectivity with the lowest area demands. A third important benefit of a climate adaptation zone is that it provides a spatial planning protection zone where the potential impact of activities on the spatial cohesion and abiotic conditions of the wetland ecosystems is considered and can either be avoided or mitigated. Thus, the climate adaptation zone could function as a zone where no irreversible actions are taken that would block future adaptation of the wetland ecosystem networks, such as large scale urbanisation. Within the zone it remains possible to adjust measures in future, when the effects of the changing climate on the wetland ecosystem become more apparent. This approach safeguards future adaptive capacity.

Several aspects of the presented approach need further underpinning. An important knowledge gap is the impacts of weather extremes on population dynamics in ecological networks. As a consequence, the effectiveness of proposed adaptation measures to compensate for these effects is also still uncertain. It is also uncertain whether species will be able to keep track with the rate of their shifting suitable climate zones. The required expansion rate will obviously depend on the rate of climate change, where slowing down global warming will buy species time to adjust. In addition, species-specific traits such as dispersal capacity and population growth rate will also influence colonising capacity. For the proposed adaptation measures it is relevant to further quantify how additional spatial cohesion within the climate adaptation zone might enhance species expansion rates. Recent modelling studies do suggest a positive effect of large habitat patches and high connectivity on expansion rate (Travis 2003; Brook et al. 2008; Schippers et al., submitted); these findings however need to be confirmed by empirical data. Long-term monitoring studies of the effectiveness of landscape adaptation measures, such as the here proposed climate adaptation zone, are needed to test its effectiveness and to adjust adaptation measures when necessary.

The climate adaptation zone strategy is supported by a recent review by Heller and Zavaleta (2009) on biodiversity management in the face of climate change, where increased connectivity was the most often recommended adaptation measure. Recommendations either focused on measures that facilitate dispersal, such as designing corridors and removing barriers for dispersal, or on measures that increase both the connectivity and carrying capacity of ecological networks by increasing the number of reserves, increasing reserve size and habitat restoration (e.g. Shafer 1999; Opdam and Washer 2004; Da Fonseca et al. 2005; Hannah and Hansen 2005; Scott and Lemieux 2007). Brooker et al. (2007) particularly recommend an adaptation strategy where Natura 2000 areas function as core areas within a permeable landscape through which species are able to move freely.

As a next step towards implementation the adaptation measures need to be translated into regional adaptation plans. Note that the climate adaptation zone primarily functions as a search area for adaptation measures. Within this zone there are still many alternatives possible for designing the actual measures at a more detailed level, incorporating spatial demands from other land-use functions. The location of the climate adaptation zone was however chosen based on supra-regional considerations and will only be effective when networks are linked over large distances. Thus the climate adaptation zone is a means to communicate these stakes that go beyond the regional scope into the decision-making processes at lower scale levels, thus stimulating supra-regional cooperation. In addition, the feasibility of the implementation of these adaptation measures for sustainable biodiversity protection will be enhanced by an integrated planning approach, finding common objectives between for instance water management, agriculture and biodiversity adaptation measures. An integrated adaptation strategy is also supported by the recent EU policy on climate change (Commission of the European Communities 2009), in which emphasis is put on mainstreaming adaptation measures into EU policies in, for example, agriculture, forestry, biodiversity, ecosystems, water management and coastal areas. There are several opportunities for forging links between nature policy, river and coastal management and water storage policy (Secretariat of the Convention on Biological Diversity 2009). Adaptation measures in particular that combine wetland restoration goals with water safety or water management goals have a high feasibility for creating wetlands (Hey and Philippi 1995; Acreman et al. 2007).

We identified best opportunities for the international connection of the climate adaptation zone to neighbouring countries. As suitable climate zones for some species are predicted to move several hundreds of kilometres in the 21st century (Huntley et al. 2007), our strategy will be most effective if European climate adaptation zones are created (Vos et al. 2008). Preparing the Natura 2000 conservation network across Europe for the impacts of climate change, it becomes of vital importance to prioritise regions in which improvements in connectivity are most urgent or in which the potential gain is highest.

We see no limitations to applying the presented method to other ecosystem types inside or outside Europe. An exception might be regions where habitat fragmentation is not a limiting factor in biodiversity responses to climate change. However, an approach is still required in these regions to protect certain zones from the future intensification of land use to sustain future spatial quality.

Conclusions

Adaptation to climate change is about making decisions for possible future outcomes that involve a considerable amount of uncertainty. Anticipatory adaptation strategies are extremely difficult to implement as they depend on the uncertain consequences of climate change and involve long-term consequences, and because they have a low immediate profile for stakeholders (Wilson and Piper 2008). Adaptation of the natural system cannot therefore be regarded in isolation of the social–economic system, and these need to be integrated to be successful. The adaptation of land-use patterns intended to both diminish the impacts of climate change and to improve opportunities for natural and social–economic systems to respond is essential for the future adaptive capacity of the landscape. A conservation strategy needs to be flexible and adjustable in the future when new impacts and new knowledge might ask for further adjustments. Strengthening ecological networks in climate adaptation zones is a good adaptive strategy, as ecological networks are flexible, are able to cope with processes on different spatial scales, and have proven to be effectively implemented in planning processes (Jongman and Pungetti 2004; Opdam et al. 2006).

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