Knowledge for Climate

State of the art review on climate change impacts on natural ecosystems and adaptation

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Disclaimer

This forecast is one of a series of studies carried out at the request of the Board of Directors of the *Knowledge for Climate Foundation* into the *State of Art* for several important adaptation themes in preparation of the actual commencement of the national research programme *Knowledge for Climate*. These forecasts are concerned with subjects of a scientific and technical nature as well as subjects in the field of social science. The goal was to find out which knowledge is available for the relevant adaptation theme and where the knowledge gaps lie. The *State-of-Art* overviews are intended not only to serve as advice for the Board of Directors and the Programme Board of the *Knowledge for Climate Foundation* with regard to the intrinsic demarcation of the research programme, but also as background information on a number of significant adaptation themes for a wide target group. It is for this reason that the Knowledge for Climate Foundation has made the *State-of-Art* foresight studies freely accessible via their website www.knowledgeforclimate.org. Responsibility for the actual content of these studies is borne by the authors themselves who also organised the review of the forecasts by submitting a draft to a group of scientists, experts and stakeholders.

Contents

Summary

Climate change has become unavoidable and the Netherlands has started to adapt the water systems and coastal defense to reduce vulnerability to the effects of climate change. These strategies to make the Netherlands climate-proof will also have its impact on nature and ecosystem functioning, in addition to the direct impacts of climate change. This report provides a state-of-the-art review of national and international research with respect to climate change impacts and adaptation, relevant to natural ecosystems in the Netherlands. This review is intended to serve as a reference of current available knowledge and will assist in programming new research required for climate-proofing the Netherlands.

Natural ecosystems, including semi-natural ecosystems, which can be found in Dutch nature reserves, provide habitats for plant and animal species including legally protected species. In addition, natural ecosystems deliver ecosystem services, such as protection against flooding, and carbon sequestration. Climatic changes (temperature increase, changing patterns of precipitation, and sea level rise) will likely affect ecosystem functioning. This will have consequences for the possibilities to achieve policy goals related to biodiversity, for ecosystem services, and for the management of nature reserves.

The effects of separate climatic changes on ecosystem processes and species composition have been relatively well studied in an international context. Global warming will shift species' ranges poleward, may cause mismatches in foodwebs, will likely increase plant productivity and will increase evapotranspiration leading to increased drought stress in summer. Elevated atmospheric CO2, however, will reduce plant transpiration rates and ameliorate drought stress.

Less evidence exists for the effects of changing precipitation patterns, with the exception of the effects of flooding. Possible increased occurrence of severe summer drought may reduce plant productivity, trigger shifts in species composition and increase the risks of wild fires, insect outbreaks and invasions by exotic species. Increased flooding is expected because of increased winter precipitation and extreme rain events in summer. Moreover, deliberate flooding will be accommodated in designated water retention or water storage areas as adaptation to prevent flooding of vulnerable areas. Research in this context has shown that flooding strongly increases nutrient availability, likely resulting in reductions of species richness.

Still far from clear is the integrated picture of how ecosystems will change due to climate change and adaptation. We do not know what the net effect of climatic changes combined with high CO2 concentrations is on site conditions such as soil moisture and nutrient availability which determine the competitive relations between plant species. This also affects animal species whose habitats are dependent on the vegetation composition.

In order to reduce the vulnerability of natural ecosystems to the impacts of climate change, adaptation strategies have been proposed. A primary adaptation strategy to climate change is to reduce and manage the other stresses on species and ecosystems, such as habitat fragmentation and eutrophication. In the Netherlands, focus is on reducing habitat fragmentation by increasing connectivity of the Dutch National Ecological Network and European Natura 2000 areas to facilitate northward movement of species. More room for natural landscape-forming processes, such as erosion and sedimentation processes along rivers, in estuaries and dune landscapes is another option. These "Natural climate buffers" are assumed to combine flood protection with more spontaneous and diverse nature. Thirdly, nature policy needs to be made climate-proof by introducing dynamic targets instead of conservation of static target species and habitat types in nature policy objectives.

Current research in the Netherlands is mostly related to adaptation of the "National Ecological Network", and to multifunctional adaptation ("Room for the River", "Natural Climate Buffers"), which often combines nature development with flood protection. In addition to research on adaptation, there is research on the development of indicators (species) for monitoring climate change effects, searching for species traits that determine vulnerability to climate change, dispersal of species, and development of models to predict the changes in vegetation and ecosystems of the Netherlands due to climate change.

Key uncertainties relate to the integrated long-term effects of climatic changes on whole ecosystems including abiotic site conditions and stochastic events like wild fires and pest outbreaks. Such knowledge is required to formulate adaptation strategies for the management of Dutch nature reserves. Therefore research priorities include:

- What is the net effect of expected climatic changes including atmospheric CO_2 on site conditions relevant to ecosystem functioning?
- What are the impacts of extreme weather events?
- Which types of species and ecosystems are most sensitive to the impacts of climate change?
- Where do adaptation measures for other sectors (water security) conflict with biodiversity targets?

Samenvatting

Klimaatverandering is onvermijdbaar geworden en Nederland is dan ook begonnen met het aanpassen van de watersystemen en de kustverdediging om de kwetsbaarheid ten aanzien van klimaatverandering te verminderen. Deze adaptatiestrategieën om Nederland klimaatbestendig te maken zullen gevolgen hebben voor de aanwezige natuur, bovenop de directe gevolgen van klimaatverandering. Dit rapport geeft een overzicht van het voor Nederlandse natuur relevante nationale en internationale onderzoek naar de gevolgen van klimaatverandering en adaptatie. Dit overzicht van beschikbare wetenschappelijke kennis draagt bij aan het programmeren van nieuw onderzoek door de stichting Kennis voor Klimaat.

Ecosystemen in Nederlandse natuurgebieden voorzien in habitats voor plant en diersoorten, inclusief de wettelijk beschermde soorten. Daarnaast leveren ecosystemen zogenaamde ecosysteemdiensten zoals bescherming tegen overstroming en het vastleggen van koolstof. Veranderingen in het klimaat (toename temperaturen, veranderingen in neerslagpatronen en zeespiegelstijging) zullen effect hebben op het functioneren van ecosystemen. Dit heeft gevolgen voor de mogelijkheden om beleidsdoelstellingen ten aanzien van biodiversiteit te halen, voor ecosysteemdiensten en voor het beheer van natuurgebieden.

De afzonderlijke effecten van een warmer klimaat en toenemende concentraties CO2 in de lucht zijn al uitgebreid aan bod gekomen in het internationale onderzoek. Aangetoond is dat toenemende temperaturen als gevolg hebben dat arealen van soorten naar het noorden opschuiven, dat in voedselketens mismatches kunnen ontstaan, dat de productiviteit van de vegetatie toeneemt en dat de evapotranspiratie toeneemt waarmee ’s zomers droogtestress kan ontstaan. Daar staat tegenover dat tegelijkertijd toenemende CO2-concentraties zorgen voor een afname van transpiratie en daarmee een verminderde kans op droogtestress.

Veel minder aandacht is er geweest voor de gevolgen van veranderende neerslagpatronen, met uitzondering van de gevolgen van overstroming. De mogelijke toename van droge zomers kan leiden tot verminderde productiviteit van ecosystemen, veranderingen in soortensamenstelling, en vergrote kans op natuurbranden, insectenplagen en invasies van exoten. Een toename van overstromingen wordt verwacht vanwege toenemende neerslag ’s winters en extremere buien ’s zomers. Daarnaast zal overstroming plaatsvinden in speciaal daarvoor ingerichte waterbergingsgebieden als adaptatiemaatregel om overstroming van meer kwetsbare gebieden te voorkomen. Onderzoek in dit kader laat zien dat overstroming kan leiden tot sterke eutrofiering met negatieve consequenties voor de biodiversiteit.

Het is nog verre van duidelijk wat de overall effecten van klimaatverandering op de Nederlandse natuur zijn. Zo weten we niet wat het gecombineerde effect is van klimaatsveranderingen en toenemende CO2 concentraties op standplaatsfactoren als bodemvocht en nutriëntenbeschikbaarheid die de concurrentieverhoudingen tussen plantensoorten bepalen. Dit heeft ook gevolgen voor diersoorten die aan habitats met een bepaalde vegetatiesamenstelling gebonden zijn.

Om de gevolgen van klimaatverandering voor natuur te beperken, worden er adaptatiestrategieën voorgesteld. Een generieke adaptatiestrategie is om andere stressfactoren, zoals versnippering en eutrofiering, te verminderen om zodoende de veerkracht van ecosystemen om klimaatverandering te kunnen doorstaan te vergroten. In Nederland bestaat de voornaamste adaptatiestrategie uit het tegengaan van versnippering door de samenhang in de Ecologische Hoofdstructuur en het Natura 2000 netwerk te vergroten om daarmee het verschuiven van soortsarealen te faciliteren. Meer ruimte voor natuurlijke processen, zoals erosie en sedimentatie in het rivieren-, estuarium- en duinlandschap, is een andere strategie. Deze “Natuurlijke klimaatbuffers” combineren bescherming tegen overstroming met spontane en soortenrijke natuur in ecosystemen met natuurlijke gradiënten. Belangrijk is ook om het natuurbeleid klimaatbestendig te maken door dynamische natuurdoelen te definiëren in plaats van de huidige statische natuurdoeltypen en –soorten.

Het huidige onderzoek in Nederland is voornamelijk gekoppeld aan adaptatie van de Ecologische hoofdstructuur en aan zogenaamde multifunctionele adaptatie (Ruimte voor de rivier, Natuurlijke klimaatbuffers), waarin bescherming tegen overstromingen gecombineerd wordt met natuurontwikkeling. Naast het onderzoek met een directe adaptatiecontext, is er momenteel

onderzoek naar het ontwikkelen van indicatorsoorten om klimaatveranderings-effecten te kunnen monitoren, naar soorteigenschappen die kwetsbaarheid ten aanzien van klimaatverandering bepalen, naar verspreidingssnelheden van soorten, en naar het ontwikkelen van modellen om de veranderingen in vegetatie en ecosystemen van Nederland als gevolg van klimaatverandering te voorspellen.

Kennisleemtes zijn er met name op ecosysteemniveau ten aanzien van lange termijn effecten van klimaatverandering op abiotische standplaatsfactoren en risico's zoals natuurbranden en insectenplagen die de soortensamenstelling en het functioneren van ecosystemen beïnvloeden. Zulke kennis is noodzakelijk om adaptatiestrategieën voor het beheer van Nederlandse natuurgebieden te kunnen ontwikkelen. Dit heeft geleid tot de volgende onderzoeksprioriteiten:

- Wat is het gecombineerde effect van klimaatsveranderingen en toenemende CO_2 concentraties op standplaatsfactoren die relevant zijn voor het functioneren van ecosystemen?
- Wat zijn de gevolgen van extremen in het klimaat?
- Wat voor soorten en ecosystemen zijn het meest kwetsbaar ten aanzien van de gevolgen van klimaatverandering?
- Waar ontstaan conflicten tussen adaptatiemaatregelen ten behoeve van andere sectoren (watersystemen) en natuurdoelen?

1. Introduction

1.1. Knowledge for Climate

The Earth has warmed by 0.7 degrees over the last 100 years. Most of this is due to the influence of human activities such as the use of fossil fuels. Measures to limit greenhouse gas emissions are initiated at an international level, though atmospheric carbon dioxide (CO_2) concentrations are currently increasing even more rapidly [Canadell et al., 2007a]. In addition, the time lag effect of the climate system means that, even if emission restrictions are successful, significant climate change is unavoidable. It is therefore particularly important that the Netherlands is able to adjust rapidly to the effects of climate change, being a densely populated country in a delta area vulnerable to the effects of climate change.

Recently the Delta Committee presented advice on protecting the coast and the entire low lying part of the Netherlands against the consequences of climate change [Deltacommissie, 2008]. The twelve recommendations are primarily aimed at protection against flooding and the security of our fresh water supplies, but will certainly interact with agriculture, nature, recreation, landscape, infrastructure and energy. Not only climate change itself, but also strategies to make the Netherlands climate proof will have impacts on nature and other functions.

Wageningen University and Research Centre and the University of Utrecht have jointly founded the Knowledge for Climate Foundation, which has the aim of bringing scientifically founded and practically obtained knowledge concerning climate and adaptation into the public arena. Knowledge for Climate will develop an ambitious research programme that aims “To develop the scientific and applied knowledge required for climate-proofing the Netherlands and to create a sustainable knowledge infrastructure for managing climate change.”

1.2. Objectives

Before programming new research, Knowledge for Climate needs an overview of existing scientific and applied research relevant to adaptation to climate change. The objective of this study is to produce a State of the Art review of national and international research with respect to climate change impacts, and adaptation, relevant to natural ecosystems in the Netherlands. This review addresses three topics: 1) impacts of climate change on natural ecosystems, including 2) impacts of adaptation measures to climate change (mainly aimed at flood protection) on natural ecosystems, and 3) adaptation strategies aimed at reducing vulnerability of natural ecosystems to climate change. This report includes a summary of current research in the Netherlands, and identification of key uncertainties in current knowledge. This review is intended to serve as a reference of current available knowledge for a broad public and will assist in programming new research.
Several reports and other publications already exist on one or two of the three above mentioned topics. This report brings together direct and indirect climate change impacts, through adaptation strategies for climate-proofing water security, on natural ecosystems and the consequences for adapting natural ecosystems to these climate change impacts. The emphasis is on ecosystems and a bit less on direct impacts on plant or animal species as in other Dutch reports. Ecosystems provide services such as water retention and carbon sequestration. Moreover many plant and animal species depend on specific habitats found in ecosystems. Apart from direct climate change impacts on species, changes in the functioning of ecosystems may additionally affect species and ecosystem services. This report also includes the effects of elevated CO2, ignored in many other Dutch reports.
The term natural ecosystems is used as opposed to agro-ecosystems, which will be treated in a separate state-of-the-art report. The term natural ecosystems in this report includes semi-natural ecosystems, in which management takes place to maintain the vegetation structure. Marine ecosystems were not considered in this study.

1.3. Methods

This report is mainly based on literature review. An important source of information was the latest, fourth, assessment report of working group II of the Intergovernmental Panel on Climate Change (IPCC). This report provides a synthesis of research on global and regional impacts of climate change, adaptation and vulnerability [IPCC 2007, Fischlin et al., 2007]. The book “Global Change and Terrestrial Ecosystems” [Canadell et al., 2007b] provided insights from meta-analysis of field experiments in which temperature and/or atmospheric CO_2 had been manipulated, an important

approach in getting insight in ecosystem responses to climatic changes. In addition, review articles, articles on studies carried out in the Netherlands and Dutch reports were used.
On December, 15, 2008 an expert meeting was organized, during which a draft version of this report was presented and discussed. The following experts commented on an earlier version of this report:

- Prof. Dr. R. Aerts — Vrije Universiteit, Amsterdam
- Dr. L.P.M. Lamers — Radboud Universiteit Nijmegen
- Prof. Dr. Ir. W.H. van der Putten — NIOO-KNAW, Wageningen Universiteit
- Dr. W.L.M. Tamis — Universiteit Leiden
- Prof. Dr. J.T.A. Verhoeven — Universiteit Utrecht
- Dr. C.C. Vos — Alterra, Wageningen
- Prof. Dr. M.J. Wassen — Universiteit Utrecht
- Prof. Dr. J.P.M. Witte — KWR Watercycle Research Institute, Vrije Universiteit

1.4. Outline of report

Climatic changes (temperature increase, changing patterns of precipitation, and sea level rise) likely affect ecosystem functioning with consequences for the possibilities to achieve policy goals related to biodiversity, for ecosystem services, and for the management of nature reserves (Fig. 1). Ecosystem services are the benefits provided by ecosystems to humans, which contribute to making human life both possible and worth living [Diaz et al., 2006]. Examples of ecosystem services are: regulation of water quantity and quality, provision of habitat, resistance to invasive organisms, regulation of climatic conditions, and protection against natural hazards. Most of these services depend on ecosystem processes such as productivity, nutrient cycling and evapotranspiration [Diaz et al., 2006].
Ecosystem functioning, as described by species composition, disturbances such as invasive species, plant productivity and abiotic conditions related to nutrient availability, soil moisture or water regime and salinity, is central in this report. This report does not give an overview of all factors that influence ecosystem functioning, it is restricted to the impacts of increasing temperatures, changes in precipitation patterns, sea level rise and elevated atmospheric CO_2 on ecosystem functioning and only mentions other factors like atmospheric nitrogen (N) deposition, when they are interacting with the effects of climatic changes.

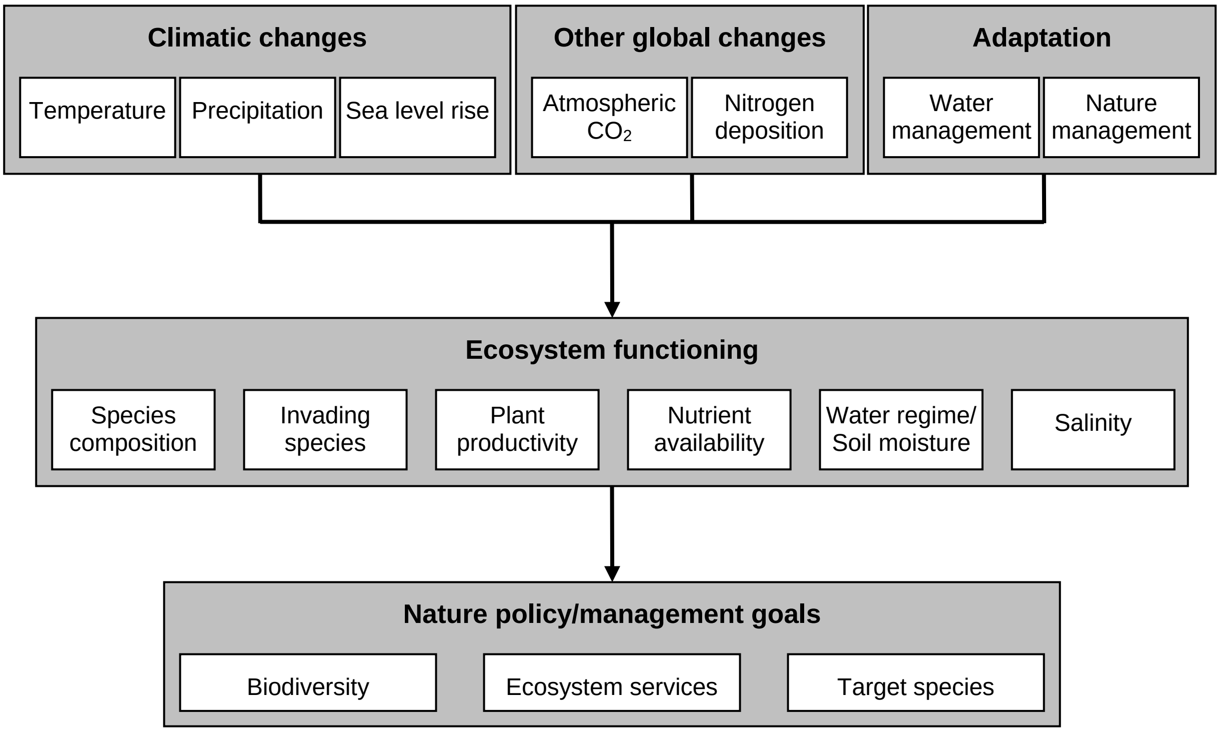

Figure 1. Diagram of climatic changes impacting on ecosystem functioning with consequences for biodiversity, ecosystem services and target species. Other global changes are also included as they are strongly related to climatic changes or interact with climatic changes. Concurrently with climatic and other global changes, management of water systems and nature reserves is changing as an adaptation to the anticipated impacts of climatic changes, with intended and unintended impacts on ecosystem functioning. Note that the impacts of nitrogen deposition, and adaptation strategies are only described when they interact with the impacts of climatic changes.

The general impacts of increasing temperatures, changing precipitation patterns, sea level rise and increasing atmospheric CO_2 concentrations, relevant to ecosystems in the Netherlands, based on international literature, are described in chapter 2. Chapter 3 gives an overview of adaptation strategies that have been proposed to reduce the vulnerability of natural ecosystems in the Netherlands to the impacts of climate change. Current research on impacts and adaptation is summarized in chapter 4, followed by identification of key uncertainties in current knowledge and research priorities.

2. Impacts

2.1. Climate change in the Netherlands

Before reviewing the impacts of climate change on natural ecosystems, climate change in the Netherlands for the past century and as anticipated for the current century needs to be briefly described in order to put the results from research on climate change impacts into perspective. Since 1900, the Netherlands has seen a temperature rise of 1.2 °C, which is more than the global temperature increase of 0.8 °C [KNMI, 2006]. Climate warming was most pronounced in the past two decades, as illustrated by the fact that the top ten of warmest years were all after 1988. The years 2006 and 2007 were the warmest years since the start of systematic temperature measurements in 1706 [KNMI, 2008]. Annual precipitation increased by 18%, with largest increases in autumn and winter, and smallest increase in summer. No trend in extreme precipitation was noticed. Average sea level rise was 2 mm per year. Soil subsidence was 0-4 mm per year.
For the 21st century, KNMI developed 4 climate change scenarios for the Netherlands. These 4 scenarios have been derived from assumptions on global climate warming (+ 1 °C or + 2 °C in 2050 relative to 1990) combined with assumptions on changes in regional air circulation patterns (change or no change) (Table 1). The four scenarios agree on: continued warming, more precipitation in winter, extreme rain events become more extreme, and sea level rise. Differences between the scenarios, which should be seen as equally likely to occur, can be found in: degree of temperature rise: 0.9-2.8 °C in 2050, precipitation increase or decrease in summer, degree of sea level rise: 15-35 cm in 2050, and 35-85 cm in 2100, all relative to 1990. Based on very recent scientific insights, the Delta Committee puts the upper limit of regional sea level rise at 130 cm in 2100. This includes the effect of land subsidence.

Table 1. Climate change in the Netherlands in 2050 relative to 1990 according to four KNMI'06 climate change scenarios [KNMI, 2006].

		G	**G+**	**W**	**W+**
Global temperature increase in 2050		**+ 1 °C**	**+ 1 °C**	**+ 2 °C**	**+ 2 °C**
Change of air circulation pattern		**no**	**yes**	**no**	**yes**
Winter	**average temperature**	+ 0.9 °C	+ 1.1 °C	+ 1.8 °C	+ 2.3 °C
	average precipitation	+ 4 %	+ 7 %	+ 7 %	+ 14 %
	extreme precipitation	+ 4 %	+ 6 %	+ 8 %	+ 12 %
Summer	**average temperature**	+ 0.9 °C	+ 1.4 °C	+ 1.7 °C	+ 2.8 °C
	average precipitation	+ 3 %	− 10 %	+ 6 %	− 19 %
	extreme precipitation	+ 13 %	+ 5 %	+ 27 %	+ 10 %
	potential evaporation	+ 3 %	+ 8 %	+ 7 %	+ 15 %
Sea level	**absolute rise**	15-25 cm	15-25 cm	20-35 cm	20-35 cm

The projected temperature increase and changed precipitation patterns are expected to result in larger dynamics in river flows, i.e. decreased summer flow and increased winter flow. With rising sea water level and reduced river discharges in summer, it is expected that salt water will penetrate further inland via groundwater and rivers that are not closed off from the sea, with salinization of water resources as a consequence.

2.2. Impacts of increasing temperatures

2.2.1. Ecosystem processes

Temperature affects all biological processes. Therefore, temperature is a key regulator of many ecosystem processes, such as soil respiration, litter decomposition, nitrogen mineralization and nitrification, denitrification, methane emission, fine root dynamics, plant productivity and plant nutrient uptake. Ecosystem responses to climate warming have been studied in field experiments in which temperature is manipulated. Meta-analysis of ecosystem warming experiments revealed that experimental warming of 2.4 °C on average, significantly increased rates of soil respiration by 20%, net N mineralization by 46% and net primary productivity by 19% [Norby et al., 2007]. The response of plant productivity may be smaller in the Netherlands as, in this meta-analysis, arctic vegetation was more responsive than forest and grassland ecosystems. These results are consistent with the hypothesis that warming directly increases rates of microbial processes, thereby increasing the availability of nutrients, and increasing plant productivity, particularly in nutrient-limited ecosystems such as arctic tundra. The stimulation of plant productivity may also be a direct effect of warming on rates of photosynthesis or the result of a warming-induced extension of the growing season.

In the Netherlands, experimental warming by ca. 1 °C of a dry heathland increased aboveground plant productivity, but not in the unusually hot year 2003 when plant productivity was strongly reduced [Peñuelas et al., 2007]. The warming treatment also increased nutrient availability and increased herbivory damage of the heather. As a consequence, grasslands may replace heathlands, reducing biodiversity and decreasing recreational values [Wessel et al., 2004]. Intensification of management activities involving the regular removal of nutrients and vegetation by grazing, sod-cutting, clipping, and burning could be used to counteract these climatic effects.

Temperature also affects the physical process of evapotranspiration. Warmer air has a lower relative humidity, because the maximum water content (at saturation) is larger in warmer air. The lower relative humidity results in larger evaporative water losses with drier soil conditions as a consequence. The KNMI scenarios assume an 8-15% increase in summer potential evaporation in 2050 when air circulation patterns will change with more frequent dry eastern winds in summer [Van den Hurk, 2006]. However, the net effect of warming-induced increases in evaporative water losses and CO_2-induced water savings by plants on ecosystem evapotranspiration and soil moisture conditions will be smaller [Kruijt et al., 2008].

In lakes, rising temperature will generally have negative effects on water quality, because less oxygen can dissolve in warmer water and concentrations of nutrients and toxicants will be higher when summer evaporation increases [Fischlin et al., 2007].

2.2.2. Disturbance

Climate warming makes it possible for new invasive species to establish in the Netherlands. In the absence of specific natural enemies, these species may cause tree mortality on a large scale [Moraal, 2007]. Since its first observation in the south of the Netherlands in 1991, the geographical range of the Oak processionary caterpillar (Thaumetopoea processionea) has increased steadily over the years, moving in north-eastern direction. As the Oak processionary caterpillar is mainly found on the southern side of solitary oaks, it is likely that it prefers warm conditions and that climate warming has been the main cause of the spreading in recent decades. This insect pest species is an egg-overwintering insect, a group of insect species that as a whole has become increasingly successful over the years [Moraal et al., 2004]. The relatively warm and humid winters of the last decades may have reduced winter survival of adult, larval and pupal stages more than of the eggs, presumably because of increased infections by pathogenic fungi for which the eggs are less vulnerable. In an ecosystem warming experiment, an outbreak of the heather beetle (Lochmaea suturalis) in the warming treatment strongly affected the vegetation response [Van Breemen et al., 1998]. Climate warming may increase viral infections in seals [Oost et al., 2005].

For lakes in the Netherlands, it is expected that toxic blue-green algae blooms may occur more frequently with climate warming. In studies on Dutch lakes, it has been observed that some cyanobacteria were more abundant after mild winters than following periods of ice cover, and that outbreaks of botulism have occurred mostly in exceptionally warm summers [Mooij et al., 2005]. Freshwater lakes are considered to belong to the most vulnerable among different ecosystems to invasions by exotics [Sala et al., 2000]. In the Netherlands, the rate of invasions has been accelerated by the interconnection of river basins in Central Europe. Climate warming is expected to support biological invasions into Dutch freshwater systems because most of the invading species originate from warmer regions in South-East Europe [Mooij et al., 2005].

2.2.3. Species composition

From geological history we can learn that species extinctions have accompanied large climate perturbations of the past. Evidence from Pleistocene glaciations indicates that range shifts have been a major species response [Lovejoy & Hannah, 2005]. Global meta-analyses documented range shifts averaging 6.1 km per decade towards the poles [Parmesan & Yohe, 2003]. This is though very different for different groups of organisms (plants, microfauna, insects, birds and mammals). The Intergovernmental Panel on Climate Change (IPCC) collected almost 29,000 observational data series, from 75 studies, that show significant change in many biological systems (terrestrial, marine, and freshwater), of which 89% are consistent with the direction of change expected as a response to warming (IPCC, 2007). This and other findings led to the conclusion with high confidence that “Anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems”.

For the Netherlands, there are numerous examples of plant and animal species moving northward [MNP, 2005], phenological changes, i.e. changed timing of life cycle events, such as start of flowering, leaf-unfolding, butterfly appearance, bird migration, and egg-laying [Van Vliet, 2008], and resulting mismatches within foodwebs [Both & Visser, 2001]. Based on 180,000 plant phenological observations, Van Vliet (2008) concluded that the duration of the growing season increased with on average one month since the end of the 1980s. Not only the start of flowering, leaf unfolding and fruit ripening was on average ten to fifteen days earlier in recent years compared to the period before 1990, also phenological events in autumn delayed with on average two weeks. The consequences of this extended growing season for plant populations and communities are largely unknown. When phenological responses to climate change differ across trophic levels, mismatches within foodwebs occur. For the long-distance migrant bird species Ficedula hypoleuca (Bonte vliegenvanger) it has been shown that it missed the peak in food abundance when returning from Africa as it did not arrive earlier at its breeding grounds, while its prey hatched earlier due to climate warming [Both & Visser, 2001]. This resulted in population declines in areas where the food peaks early in the season [Both et al., 2006]. In the Wadden Sea, the mild winters of 1988-1990 strongly reduced the abundance of molluscs leading to dramatic starvation of birds such as Haematopus ostralegus (Scholekster) and Somateria mollissima (Eidereend) [Oost et al., 2005].

Examples of southern species which became more abundant or enriched the Dutch flora and fauna are: bird species Alcedo atthis (IJsvogel), Egretta garzetta (Kleine zilverreiger) and Cettia cetti (Cetti’s zanger) [SOVON, 2007], plant species Ophrys apifera (Bijenorchis), and insect species Crocothemis erythraea (Vuurlibel), Oecanthus pellucens (Boomkrekel) and Argiope bruennichi (Wespspin). Among the numerous expanding southern insect species are plague insect species like Thaumetopoea processionea (Eikenprocessierups), Cameraria ohridella (Paardenkastanjemineermot), and Haemmatoloma dorsatum (Roodzwarte dennencicade).

For plant species, climate warming was the second most important cause of recent changes in the Dutch flora. Thermophiles (warmth-preferring species) increased in occurrence, though cold-preferring species are not (yet) on the decline [Tamis et al., 2005]. Particularly in dry ecosystems, such as calcareous grasslands, arable field margins and dunes, warmth-loving plant species are expanding rapidly, while northern species are on the decline [Van der Staaij & Ozinga, 2008]. In contrast, in some types of forest, northern species such as Empetrum nigrum (Kraaihei) and Vaccinium vitis-idaea (Rode bosbes) are doing well [Bijlsma & Ten Hoedt, 2006]. This can be explained by aging of the forests and changes in management, resulting in more mature, denser forests with a cooler microclimate [Van der Staaij & Ozinga, 2008].

For animal species, a group of 20 cold preferring species did show declining population trends, while the group of 20 warmth preferring species showed positive population trends [Nijhof et al., 2007]. These groups included bird, butterfly and amphibian species. For 91 species showing a forward shift in phenology, no relation between population trends and earlier appearance or egg-laying could be detected [Nijhof et al., 2007]. Examples of northern species which are likely to disappear from our country are butterfly species Plebeius optilete (Veenbesblauwtje), and plant species Goodyera repens (Dennenorchis), Neottia cordata (Kleine keverorchis) and Linnaea borealis (Linnaeusklokje).

For the future, IPCC (2007) concluded that “Approximately 20 to 30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5 °C (medium confidence).”. These numbers are based on climate envelope studies. The “bioclimatic envelope” is based on species’ distribution data, thus describing the climatic conditions under which the species currently occurs. Future distributions of species' are projected on the assumption that the current envelopes reflect species' environmental preferences, which will be retained under climate change. This approach assumes instantaneous species-range change, so does not capture time lags associated with processes of dispersal, establishment, and local extinction. For Europe the numbers of species at risk of extinction are smaller than those in the worldwide assessment of the IPCC. Based on 1350 European plant species, it is predicted that 2-5% of the species experiences a range size loss of more than 80% in 2080, leading to endangerment or extinction from Europe [Thuiller et al., 2005]. In case there are no possibilities for species to move across landscapes, the numbers increase up to 2% of species becoming extinct and 22% becoming critically endangered. Any shift in range will lead to an increased risk of local extinction. For the Atlantic region in which the Netherlands is located on average 48% of the plant species will be lost at the local scale under the severest climate change scenario tested [Thuiller et al., 2005].

For the Netherlands, it must be noted that 75% of the plant species are in the centre or subcentre of their geographic range [Ozinga et al., 2007]. The number of southern species that might benefit from climate change is relatively large in comparison to the number of northern species that are at risk. Of the native species for which the Netherlands are not central in the geographical range, only 14% are northern species, the majority are southern species. There is thus a potential for increases in plant species richness at the national level, as more southern species may establish than the relatively few northern species that may disappear. However, the southern species may not all arrive in the Netherlands when climate changes proceeds faster than their dispersal or when the fragmented occurrence of their habitats inhibits dispersal. For butterflies it has been shown that only those species that were capable of dispersing over large distances or using widespread habitats were able to respond to climate change by expanding northwards [Warren et al., 2001]. Therefore, species natural adaptation responses to climate change can be strongly inhibited by habitat fragmentation [Hill et al., 1999; Opdam & Wascher, 2004].

Ecosystem types in the Netherlands with a relatively large percentage of cold preferring species are: raised bogs and moist heathlands, shallow pools on sandy soil, forests of poor soils and wet grasslands. These ecosystems will likely face significant changes in species composition with unknown consequences for ecosystem functioning and achieving nature policy goals. Ecosystem types with a relatively large percentage of warmth loving species are: arable fields, calcareous grasslands, dry grasslands and shrublands [Blom et al., 2007; Vos et al., 2007a].

Long-term effects on whole ecosystems remain largely unclear. It can be expected that species with high nutrient demands would benefit from the warming-induced stimulation of nitrogen mineralization, but this has not been tested. Interactions with other global change components could also be important. Results of a peat bog ecosystem model suggested that climate warming may still increase carbon accumulation under low nitrogen conditions, but will decrease carbon accumulation at high N deposition sites [Heijmans et al., 2008]. This was because warming at high nitrogen conditions caused a strong expansion of vascular plants at the cost of peat-forming peat mosses. Shifts in species abundances had consequences for the ecosystem service of carbon sequestration.

For lakes in the Netherlands it is expected that a temperature rise of 2-3 °C may cause a switch from waterplant-dominated clear lakes to algae-dominated 'green soup' lakes with negative impacts on biodiversity [Van de Bund & Van Donk, 2004]. This is expected because internal nutrient loading increases with temperature, exacerbating existing eutrophication problems [Moss et al., 2003]. Results of mesocosm experiments carried out in shallow lakes along a north-south gradient in Europe indicated that negative effects of eutrophication on ecosystem functioning will increase by warmer temperatures [Moss et al., 2004]. To counteract the effects of climate warming, lake restoration measures combating eutrophication, such as reduction of planktivorous fish mass, will need to be intensified. In addition, measures that enhance the resilience of lake ecosystems [Scheffer et al., 2001], such as more natural water level fluctuations and development of a vegetated shoreline, have been suggested to withstand the additional stress resulting from climate change [Mooij et al., 2005].

2.3. Impacts of changing patterns of precipitation

2.3.1. Increased frequency of flooding

The expected increase in winter precipitation will increase winter discharge of the rivers and streams, resulting in more frequent flooding or longer duration of inundation of flood plains and low lying areas. More frequent extreme rain events in summer additionally increase the frequency of flooding. Moreover, deliberate flooding will be accommodated in designated water retention or water storage areas as adaptation to prevent flooding of vulnerable areas (see also chapter 3). Research in this context has shown that flooding strongly increases nutrient availability, likely resulting in reductions of species richness. Inundation of areas with (a history of) agricultural land use may cause the release of large quantities of phosphorus, because of iron reduction under anoxic conditions [Loeb, 2008]. Increased frequency of flooding will likely lead to changes in vegetation composition as plant species differ in susceptibility to waterlogging and flooding. The duration of the flooding, as well as the seasonality and frequency of flooding, all impact on species distributions [Lamers et al., 2006]. Most plants will survive winter flooding, but many species are very sensitive to summer flooding [Van Eck et al., 2006]. Floodplain sites with high frequency of flooding have been shown to harbor a small set of common plant species in comparison to other river floodplain sites [Beumer et al., 2008]. Therefore, using existing wetlands for water storage poses a serious threat to their biodiversity [Lamers et al., 2006]

The creation of water retention and water storage areas is generally being combined with nature development strategies. However, high nutrient availability in combination with altered hydrological regimes will impose major constraints on the development of wetlands. Up till now, species-rich sedge marshes, floodplain forests or mesotrophic grasslands have hardly developed in these areas [Lamers et al., 2006]. Results from pilot projects on combining water storage with nature development [Stuijfzand et al., 2007] demonstrate that sediments including adsorbed nutrients and toxicants are mostly deposited close to the stream on the first possible occasion, leaving more downstream areas less impacted by the high water peak. Flooding will have more (negative) impacts on low productive ecosystems than on high productive ecosystems such as wetland forests. Another aspect is that inundation reduces the possibilities for management, i.e. mowing or grazing. The combination of nature development and water retention upstream of existing nature could be beneficial, because of improvement of the water quality after passage of the retention area and buffering against large water table fluctuations [Stuijfzand et al., 2008].

For two shallow lakes in the Botshol nature reserve it has been observed that the lakes switched from waterplant-dominated clear state to phytoplankton-dominated turbid state after wet winters. In wet winters with high groundwater levels runoff from land to lake water transports phosphorus and humic acids to the lake, increasing phytoplankton density and light attenuation in the water column, enhancing instability of the waterplant populations [Rip et al. 2007].

2.3.2. Summer drought

Decreased summer precipitation is assumed in 2 of the 4 KNMI scenarios. This would decrease summer discharge of rivers and lower summer groundwater levels, particularly in areas which depend on rain water for water supply. For raised bog vegetation, an outdoor mesocosm experiment showed that more frequent summer water table drawdown brought about shifts in Sphagnum species abundance and a shift from graminoid to ericoid vascular plant cover [Breeuwer et al., 2008].
Experimental summer drought during two months in a Dutch dry heathland ecosystem tended to reduce plant aboveground productivity [Peñuelas et al., 2007], which was opposite to the response to the warming treatment (Table 2). Although soil nutrient availability was decreased, which would give the heather a competitive advantage, herbivory damage of the heather was increased in the drought treatment. Therefore, it is uncertain whether drought will increase the abundance of heather [Wessel et al., 2004].

2.3.3. Extreme weather events

Future climate changes are expected to be accompanied not only by a shift in mean values, but also by increasing temporal variability. Extreme weather events such as drought and heavy rainfall are likely to become more frequent. In Europe, severe floods and summer heat waves are expected to occur more frequently. The ecological effects of extreme events have been identified as one of the main gaps of knowledge in community ecology.

Alterations in vegetation composition after severe drought, heavy rainfall events and heat waves have all been documented [Jentsch & Beierkuhnlein, 2008]. Future projections for Europe suggest significant reductions in species richness even under mean climate change conditions [Thuiller et al., 2005], and an increased frequency of extreme events is likely to exacerbate overall biodiversity losses [Thuiller et al., 2005]. It is assumed that increased frequency of extreme weather events enlarges fluctuations in the size of populations leading to local extinctions. Following two extreme winter floods in 1993-94 and 1994-95, an overall reduction in species richness, from c. 24 to 15 species m^{-2}, and an increase in biomass production have been observed in Rhine floodplain grasslands. These effects were only partly reversed after ten years [Beltman et al., 2007].

The 2003 heatwave affected ecosystems through heat and drought stress and wildfires [Fischlin et al., 2007]. Fire extent was exceptionally large in Europe in 2003. Also in the Netherlands there were wildfires in summer 2003 and July 2006 (A. Getz, personal communication). Other reported effects following extreme weather events are: a rapid switch of ecosystem into alternative ecological regime [Scheffer & Carpenter, 2003], and biotic communities becoming more susceptible to invasion following extreme events. For example bark-boring pest insect species are expected to become more abundant, because they benefit from reduced resistance of trees in dry summers such as in 2003 [Moraal, 2007]. For plant species it has been shown that both exotic species from other continents and southern species expanding their range gradually can establish successfully because of enemy release [Van Grunsven et al., 2007]. Enemy release means that the plant species disperse faster than their natural enemies (such as soil pathogens), so that the plants become released from top-down control.

2.4. Impacts of sea level rise

2.4.1. Coastal ecosystems: erosion

Effects of sea level rise on coastal ecosystems depend strongly on the rates of sea level rise. Beyond a critical limit of 3-6 mm/yr, tidal flats and beyond 8.5 mm/yr salt marshes may drown, causing loss of habitat for benthos consuming birds and seals [Oost et al., 2005]. According to the Delta Committee we should consider a sea level rise of 11 mm/yr as a possibility [Vellinga et al., 2008].
Research on the effects of soil subsidence due to gas extraction at Ameland gives us information on the effects of relative sea level rise. The observed soil subsidence of about 30 cm in 20 years, i.e. 15 mm/yr, did not affect tidal flats because of compensatory sand deposition [Eysink, 2005]. No indications of impacts on wader birds were found. Similarly, salt marshes have not been affected because of compensation by sedimentation. The dune valleys are clearly wetter and inundated for a longer time in winter which affects the vegetation composition. Dry dunes have not been affected at all. Coastal sand suppletion, the main adaptation strategy for flood protection of the North Sea coast, may contribute to adaptation of the Wadden Sea area to sea level rise by supporting the natural process of sedimentation.

2.4.2. Inland ecosystems: salinization

For the lower part of the Netherlands it is expected that salinization of ground and surface water will increase, mainly because of sea level rise and land subsidence. Low groundwater levels and river discharges in dry summers will further enhance inland intrusion of salt water. In addition, restoration of salinity gradients, as suggested for Haringvliet, deliberately causes salinization. Restoration of a salinity gradient in Krammer-Volkerak Zoommeer has been suggested by the Delta Committee in order to solve the water quality problem, which can offer new ecological opportunities. Another suggestion, raising lake IJsselmeer level up to 1.5 m in order to secure fresh water supplies, however, combats salinization in the Western Netherlands.

Many freshwater organisms can adapt to some extent to increased salt concentrations in their environment. However, the large variation in salt concentration typical of brackish environments poses a larger threat. Therefore, brackish environments are generally poor in number of species, but contain specialized species which do not occur in other places.

Literature study by Paulissen & Schouwenberg (2007) revealed that little is known about salt tolerance of fresh water organisms and communities. Most plant communities of the lower part of NL occur exclusively in freshwater areas, suggesting they are sensitive to salinization. Salt water indicating plant species mostly occur in tidal areas and closed-off sea arms.

It is noted that salinization will not only have negative effects. Salinization may result in new brackish areas which are currently rare because of artificial sharp borders between fresh and saltwater areas. Mesocosm experiments by Loeb (2008) suggest that restoration of the tidal regime with brackish water is likely to bring back the characteristic brackish water plants.

2.5. Impacts of elevated atmospheric CO_2

2.5.1. Ecosystem processes

Apart from being a greenhouse gas, which largely caused the anthropogenic part of 20th century climate change, CO_2 is the major substrate for plant photosynthesis with cascading effects on vegetation structure and composition and plant-herbivore relationships. Atmospheric CO_2 concentrations have risen from 280 ppm in pre-industrial times to 383 ppm in 2007, which exceeds any experienced during the past 20 million years [Global Carbon Project, 2008]. CO_2 concentrations in the atmosphere will continue to rise to 540 – 830 ppm in 2100, depending on emission scenarios. As living biomass (plants and animals) consist roughly for 50% of carbon, it is hard to imagine that a doubling of the atmospheric carbon availability would not have impacts on plants and ecosystems. For these reasons we cannot ignore CO_2 when discussing climate change impacts on natural ecosystems. We will briefly review the general effects of atmospheric CO_2 on natural ecosystems, although the steady CO_2 enrichment of the atmosphere is strictly seen not a climatic change.

It is well known that when plants are exposed to increasing atmospheric CO_2, they will increase photosynthetic CO_2 uptake, saturating at close to 1000 ppm. When plants are grown individually, species with C3 type of photosynthesis produce more biomass under elevated CO_2 than species with C4 type of photosynthesis [Poorter & Navas, 2003]. However, after thirty years of CO_2 research, it turned out that the rate of CO_2 uptake per unit leaf area is a rather unreliable predictor of plant growth and related ecosystem processes (Körner et al. 2007). Carbon uptake by photosynthesis can not be directly translated into plant production, because the investment of carbon in structural plant tissues requires mineral nutrients. A comparison of 6 field experiments in 8 natural grassland ecosystems, in which elevated CO_2 treatments have been compared to ambient CO_2 conditions, revealed an average 20% increase of grassland biomass [Körner et al., 2007]. Also in mature trees, experimental exposure to elevated CO_2 resulted in a 10-20% increase in net primary production (NPP) [Körner et al., 2007]. This is much less than the predicted 60% increase in NPP on average by 2100 by six dynamic global vegetation models, which are mostly based on plant physiological processes such as photosynthesis [Cramer et al., 2001].

It is assumed that part of this observed CO_2 fertilization effect is actually an indirect effect through improved water relations. When CO_2 concentrations are elevated, plants stomata need less time to be open to absorb a given amount of CO_2, resulting in smaller water losses through stomata. This increased water use efficiency, which mitigates drought stress for plants, is found in nearly 100 controlled experiments. At the ecosystem level a remarkably consistent 5-10% reduction of evapotranspiration is observed among several types of vegetation [Körner et al., 2007]. At the landscape level the reduction is probably less, because vegetation-atmosphere feedbacks cannot be included in plot-scale field experiments. Reduced plant water losses at the landscape level would mean a reduced loading of the atmosphere with water vapor, and the resulting lower relative humidity would then increase evaporative water losses. For the Netherlands, it is estimated that the direct effects of CO_2 reduce evapotranspiration up to 5% in 2050 and up to 15 % by 2100, particularly in summer and in natural vegetation [Kruijt et al., 2008]. These reductions are of comparable but opposite magnitude to predicted temperature-induced increases in evapotranspiration (Table 2). Using a hydrological model they demonstrated that this CO_2-effect would lead to a much reduced groundwater drop in summer than can be expected from climate change alone [Kruijt et al., 2008].

The response of natural ecosystems to elevated CO_2 seems strongly dependent on the availability of nutrients. Elevated CO_2 has indirect effects on soil nutrient availability. It has been assumed that elevated CO_2 changes plant litter quality (by increased C:N ratio) and leads to a slowing down of decomposition, but this is not generally supported by experimental results. Under elevated CO_2 the additional carbon taken up, which is not invested in structural plant growth, may be exported through roots. The increased availability of these excreted carbohydrates may stimulate microbial activity and nutrient mineralization. On the other hand, these microbes become competitors for nutrients thereby reducing soil nutrient availability for plants. There was no significant effect of elevated CO_2 on net N mineralization in a meta-analysis of CO_2 experiments [De Graaff et al., 2006].

2.5.2. Species composition

Given that changes in atmospheric CO_2 alter the relative availability of carbon, water, and nutrients, important resources for plant growth, which in turn alters competitive interactions among plants, changes in diversity or dominance patterns are likely to occur. Indeed, several field experiments in natural ecosystems showed that plant species respond differentially to elevated CO_2, in the long term resulting in shifts in vegetation composition [Potvin et al., 2007]. In the Netherlands, field experiments involving CO_2 enrichment have been conducted in peatland plant communities [Heijmans et al., 2001b; Milla et al., 2006; Toet et al., 2006]. The effects of the elevated CO_2 treatment were limited, particularly in the Sphagnum-Phragmites reedland, but in the raised bog vegetation summer evapotranspiration was significantly reduced [Heijmans et al., 2001a] and peat mosses grew faster in height giving them a competitive advantage over low-statured vascular plants [Heijmans et al., 2001b].

Far from clear is which species, in general, take competitive advantage from elevated CO_2. Although for many species it has been tested how they respond to high CO_2 concentrations in greenhouse experiments, this does not predict who will win in natural communities. For example, fast-growing species responded most strongly to elevated CO_2 when grown in isolation in a greenhouse, but this was not the case in mixed communities [Poorter & Navas, 2003]. A peat bog modeling study suggested that the species whose growth is least limited by nitrogen, in this case peatforming Sphagnum mosses, will benefit from elevated CO_2 at the cost of species that require more nitrogen [Heijmans et al., 2008]. This might be more generally applicable, but it remains to be seen whether this pattern is also visible in field experiments and observations.

Table 2. Summary of the effects of higher temperatures, changed patterns of precipitation, sea level rise, and increase in atmospheric CO2 on several components of ecosystem functioning.

	Temperature	**Precipitation**	**Sea level rise**	**Atmospheric CO_2**
Species composition	Species shifting Northward	Extreme events increase risk of extinctions		Potential shifts in species composition
Disturbance	Warming supports biological invasions	Summer drought increases wildfires, insect damage	Possibly drowning of tidal flats and salt marshes	
Plant productivity	Longer growing season increases plant productivity	Increased drought stress in summer reduces productivity		Enhanced net primary productivity
Nutrient availability	Increased nitrogen mineralization	Summer drought may reduce nitrogen mineralization		
Water regime/ soil moisture	Increased evapotranspiration	Increased flooding, more dynamic (ground)water levels		Reduced evapotranspiration
Salinity		Low river discharges in summer contribute to salinization	Increased salinity of estuaries and low-lying freshwater systems	

3. Adaptation

3.1. Adaptation in the Netherlands

Throughout its history, Dutch society has always taken adaptation measures dealing with many water-related challenges. From the early Middle Ages dikes have been built. Flood abatement measures and reclamation projects took place on increasingly larger scales. This culminated in large-scale works such as the closure of the Zuiderzee and the Delta Project in the twentieth century. Flood protection remains a top priority, but nowadays interactions with agriculture, nature, recreation, landscape, infrastructure and energy are taken into consideration when developing adaptation strategies [Kabat et al., 2005]. The Delta Committee even stresses the opportunities for Dutch society in their recent advice on how to increase safety against flooding, while still remaining an attractive place to live, to reside and work, for recreation and investment.

The main change in the Dutch adaptation policy for flood protection is that instead of heightening the dykes along rivers, occasional flooding will be accommodated and carefully managed in specific designated areas [Kabat et al., 2005]. In the river area, many works are on-going, in order to make more “Room for the River” inbetween the dykes. This involves creation of side channels, lowering the flood plains and removing barriers to water flow. These adaptation measures increase hydrodynamics, which may conflict with biodiversity conservation goals when low-dynamic parts of the floodplains will disappear. Many protected and endangered riverine animal species require ecotopes along the entire hydrodynamic gradient [De Nooij et al., 2006]. Pilot projects on water storage and water retention in designated areas in order to reduce peak water flows have started (see also 2.3.1.).
For coastal protection the emphasis is on beach nourishments by sand suppletion. This may enhance the capacity of coastal ecosystems to adapt naturally to sea level rise (see also 2.4.1.). In the peat areas of the Netherlands, climate warming is assumed to accelerate peat oxidation, leading to further land subsidence and more complex water management [Kwakernaak & Dauvellier, 2007]. This oxidation of peat also contributes significantly to the Dutch emission of greenhouse gases. Adaptation measures involve increasing water levels or inundation in combination with nature development. The impacts on existing nature have not been addressed. Inundation may for example conflict with current meadow bird conservation in grassland ecosystems. 96 adaptation options have been described in the “Routeplanner” project [Van Drunen, 2007]. These include adaptation strategies to combat the negative effects of climate change on water systems, nature and agriculture, energy, transport, housing and infrastructure, public health, and recreation.

3.2. Adaptation to climate change for natural ecosystems

As described in chapter 2, climatic changes will impact on abiotic site conditions, plant productivity and species composition, with consequences for the habitats of plants and animals. In order to reduce the vulnerability of natural ecosystems to the impacts of climate change, adaptation strategies have been proposed (Table 3). While an integrated picture of how ecosystems in the Netherlands will change due to climate change is still lacking, a general adaptation strategy to climate change is to reduce and manage the other stresses on species and ecosystems, such as habitat fragmentation and eutrophication. In the Netherlands, focus is on reducing habitat fragmentation.

Range shifts of species in response to climate change have been reported for a wide range of taxa and regions and further shifts are projected. Whether species can colonize new areas to expand their range northward depends both on species and landscape characteristics. A primary adaptation strategy is therefore to increase spatial cohesion of ecological networks, such as the Dutch National Ecological Network (NEN, Ecologische hoofdstructuur (EHS) in Dutch) and the EU Natura 2000 network. By combining bioclimate envelope models, which project future species distributions, with dispersal models, Vos et al. (2008) developed a method to identify areas where the spatial cohesion of ecosystem networks is not sufficient to accommodate species’ responses to climate change. The best locations for ecological corridors where improving connectivity is most urgent can then be pinpointed.

Table 3. Seven adaptation strategies to counteract the impacts of climate change on natural ecosystems (based on Vos et al., 2007b).

	Adaptation strategy	How ?
I	Increase spatial cohesion of the NEN and Natura 2000 ecological networks	Robust ecological corridors and other measures to increase connectivity
II	Increase ecological resilience of ecosystems	Increase the area of nature reserves and increase heterogeneity within nature reserves
III	Improve abiotic conditions within nature reserves	Management and increase the water holding capacity of nature reserves
IV	Embedding of NEN and Natura 2000 areas within multifunctional climate buffers	
V	Nature as integral part of multifunctional spatial adaptation	Nature development in water retention or water storage areas
VI	Increase learning capacity of society, dealing with uncertainty	Monitoring adaptation projects
VII	New vision on nature in spatial planning	Introduce dynamics in nature policy instead of conservation of static target species and nature types

Recently “natural climate buffers” have been proposed by a consortium of nature conservation organizations. Natural climate buffers involve restoration of natural landscape-forming processes for adaptation of the water system to climate change and creating opportunities for other functions such as nature, recreation and housing. Examples are: meandering rivers, increase water holding capacity in sand region, and increase water level in fen peat area (Table 4). Restoration of natural landscape-forming processes likely creates more spontaneous and diverse nature.

Most nature reserves in the Netherlands are rather intensively managed by national organizations like Staatsbosbeheer en Natuurmonumenten. So there is already quite some experience in adaptation to changing environmental conditions. The management is often aimed at nature conservation or at restoring prescribed nature target types. Consensus is growing that conserving current species composition and using static target species and nature target types is not very climate-proof. Nature management will need to shift from conserving nature to accommodating natural processes. In addition, creation of an international network of nature reserves including ecological corridors is in the light of climate change more urgent than it has been before, in order to facilitate northward movement of plant and animal species.

Table 4. Five natural climate buffers sorted by landscape type, their objectives, intended measures and benefits to natural ecosystems (based on Andriesse et al., 2007).

	Objective	Measures	Nature benefits
River landscape	To increase room for the river for flood protection and restoration of natural erosion and sedimentation processes	Increase floodplain area (relocate winterdykes) Remove shore defense	More complete river landscape including low-dynamic ecosystems
Estuary landscape	To restore a natural estuary which can grow along with sea level rise contributing to flood protection	Increase area of natural estuary (ontpolderen) Re-open closed-off sea arms	More complete estuary landscape in SW delta by restoration of salinity gradients
Dune landscape	To restore a dynamic dune system for coastal defense and dynamic dune ecosystems	Increase dune area at land side Sand suppletion	More complete dune landscape including young dunes
Fen peat landscape	To combat soil subsidence, salinization and increasing complexity of water management	Inundation of lowest places leading to peat formation Increase ground water levels	New wetlands Less stress on existing nature reserves
Sand landscape	To reduce water extremes by increasing water retention and restoration of natural groundwater flows	Remove draining elements Restoration of meandering streams	Restoration of natural groundwater flows, improves quality of wetland ecosystems

4. Current research, uncertainties and research priorities

4.1. Current research

Analyses of current research on climate change and adaptation in relation to nature have been carried out by Veraart et al. (2006) and Vos et al. (2007b). Much of ongoing research in the Netherlands is related to adaptation of NEN, and to multifunctional adaptation, which often combines nature development with river flood protection as in “Room for the River” and “Natural Climate Buffers”. The research on multifunctional adaptation includes research on all three phases described by Vos et al. (2007b), i.e. more fundamental research on the effects and biogeochemical processes of flooding, research on spatial translation into adaptation strategies, and monitoring of pilot projects to evaluate implemented adaptation measures.

In addition to research on adaptation, there is research on the development of indicators (species) for monitoring climate change effects, searching for species traits that determine vulnerability to climate change, and development of models to predict the changes in vegetation and ecosystems of the Netherlands due to climate change. Most of this research is embedded in programmes of “Climate changes Spatial Planning” (Klimaat voor Ruimte) and the Dutch Ministry of Agriculture, Nature and Food Quality. Additional research, mainly at universities and the research institute NIOO, takes place on phenological shifts, invasive species both in aquatic and terrestrial ecosystems, and impacts on aquatic ecosystems. Field studies to investigate the effects of climate change on whole ecosystems or to provide the models with supporting data are currently lacking.

4.2. Key uncertainties and research priorities

The effects of separate climatic changes on ecosystem processes and species composition have been relatively well studied in an international context. Still far from clear are the long-term effects of climatic changes on whole ecosystems including abiotic site conditions and stochastic events like wild fires, pest outbreaks and invasions of exotic species. Such knowledge is required to formulate adaptation strategies for the management of Dutch nature reserves. We do not know what the net effect of climatic changes combined with high CO_2 concentrations is on site conditions such as soil moisture and nutrient availability which determine the competitive relations between plant species. This also affects animal species whose habitats are dependent on the vegetation composition. Therefore research priorities include:

- What is the combined effect of expected climatic changes, including increasing atmospheric CO_2, on the site conditions relevant to ecosystem functioning (e.g. soil moisture, soil temperature, nutrient availability)?
- What is the impact of climate change on disturbances such as wild fires, pest outbreaks, and invasions by exotic species and what is the role of extreme weather events? Are they catalysts of gradual changes or will they result in ecological surprises?
- Which types of species (apart from northern species) and ecosystems will be most vulnerable to the impacts of climate change, as determined by exposure and sensitivity to climatic changes?
- Are there interactions of climate change effects with the effects of other environmental disturbances (e.g. N deposition or eutrophication of aquatic ecosystems)?
- Where do adaptation measures aimed at flood protection or reducing peat oxidation conflict with existing nature and what level of biodiversity and ecosystem services can be expected in areas where adaptation is combined with nature development?
- What references and targets should be used in nature management and policy to replace the current static target species and habitat types in order to climate proof nature policy

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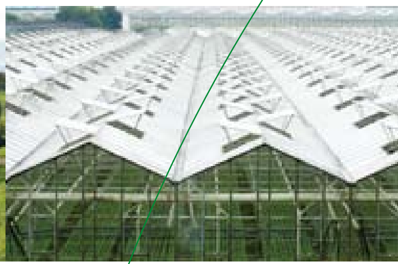
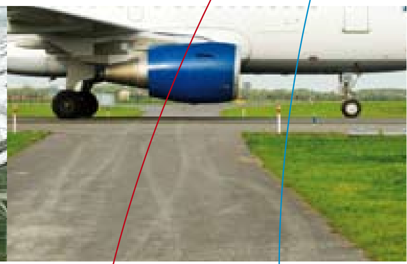

To develop the scientific and applied knowledge required for climate-proofing the Netherlands and to create a sustainable knowledge infrastructure for managing climate change

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