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Monitoring the Responses of Freshwater Ecosystems to Climate Change

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Introduction

Since 1970, freshwater biodiversity has decreased more drastically than marine or terrestrial biodiversity (Loh & Wackernagel 2004). This is the result of a complex mix of stressors and impacts (Stanner & Bordeau 1995; Malmquist & Rundle 2002). The major drivers can be summarized as multiple use (such as fisheries, navigation and water abstraction), nutrient enrichment, organic and toxic pollution, acidification and habitat degradation. Climate change is adding further stresses (temperature increase, hydrological changes) and interacts in complex ways with existing ones (Travis 2003; Wrona *et al*. 2006; Durance & Ormerod 2007; Huber *et al*. 2008).

As with other stressors, climate change will result in complex cause–effect chains, the link between them provided by many interacting environmental parameters, which are directly or indirectly influenced by temperature and precipitation. The response of the biota is, therefore, less predictable than the response of chemical or hydrological variables. On the other hand, biotic parameters such as species richness, community composition or functional diversity integrate the complex effects of many stressors on freshwater ecosystems, including those directly or indirectly associated with climate change. This is the reason for using biotic communities (such as phytoplankton, invertebrates or fish) for monitoring the ecological integrity of European surface waters, as stipulated by the EU Water Framework Directive (Heiskanen *et al*. 2004). The recently established Europe-wide monitoring programmes, however, are mainly targeted at detecting the effects of those stressors that have been dominant in the past, such as eutrophication, organic pollution, acidification or hydromorphological degradation. Climate change is not specifically targeted by the Water Framework Directive, though there is likely to be greater pressure on European aquatic ecosystems in future because of it.

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The direct and indirect effects of climate change on the biota of lakes, rivers and wetlands will depend on ecoregion, ecosystem type and other stressors affecting the water body. Owing to the natural variability of surface waters and the effects of many other stressors, no simple dose–response relationships among climate change and biotic effects can be expected; the linkages between climate change and biodiversity patterns cannot be understood without the overall, complex picture.

The purpose of this chapter is to suggest indicators for the effects of climate change on lake, river and wetland ecosystems that reflect the direction of their pathways, relative importance, and magnitude of change. The term 'indicator' is used here in a broad sense, i.e. a simple detectable sign of a complex process that can be used as an early warning of ecosystem change. Indicators may be chemical, hydrological, morphological, biological or functional parameters, which reflect key processes influenced by climate change and are relatively simple to monitor. There is a focus on parameters that are already used for monitoring programmes under the Water Framework Directive, but other indicators (e.g. hydrological parameters) are considered as well.

The selection of indicators is based on a literature review (up to 2007), in which we first categorize and describe potential direct and indirect climate change effects on lakes, rivers and wetlands. From this description a selection of parameters judged to most clearly reflect the effects of climate change on freshwater ecosystems is made. In two case studies, the susceptibility of selected taxonomic groups to climate change effects is analysed.

Climate change impacts on the biota of lakes

Monitoring and assessing the effects of stress on lakes

Monitoring of lake ecosystems in Europe has changed significantly in recent years. While formerly the use of physicochemical and selected biological variables (such as chlorophyll) was most widespread, the EU Water Framework Directive places emphasis on biological indicators. A variety of organism groups (phytoplankton, macrophytes, benthic invertebrates and fish) have now to be monitored, supplemented by hydromorphological and physicochemical measurements.

Most biological assessment systems, developed for the purpose of the Water Framework Directive, aim to reflect the deviation of the observed assemblage from an undisturbed reference state, thus providing an integrated appraisal of a water body's ecological quality. The current assessment systems are therefore reflecting the impact of a variety of stressors. The impact of climate change has rarely been considered in assessment systems and, as noted above, is not specifically addressed by the Water Framework Directive. However, almost all indices used to monitor the ecological status of European lakes will be affected by climate change.

Climate change impacts will be among the most important stressors on freshwaters in future, and will initiate chains of processes that are complex and difficult to classify. Simple indicators are required to judge how advanced these processes already are, and which of them could be integrated into presently applied assessment systems. Given the different types of impact in cold, temperate and warm ecoregions, different sets of indicators may be required. The theoretical background for indicator selection is described below and in earlier chapters, while a potential set of indicators for lakes in cold, temperate and warm ecoregions, respectively, is given in Table 5.1. Most indicators could be easily incorporated into routine monitoring programmes, e.g. by adding indices reflecting the impact of temperature increase on phytoplankton already monitored for the purpose of the Water Framework Directive. In many cases, simple physicochemical measurements are most appropriate, as they are easy to make, are often included in routine monitoring programmes and are located at the starting points of cause–effect chains, thus giving context to subsequent changes.

Hydrology and physicochemistry

The timing of ice cover is directly dependent on winter and spring temperatures, and therefore is one of the early indicators for climate change in lakes in cold and temperate regions as are the nature and duration of summer stratification. They have been discussed in Chapters 3 and 4. Likewise, there are many consequent chemical features of these that have already been discussed and provide strong initial indicators.

Primary production

Climate-sensitive physicochemical and hydrologic conditions can be major determinants for primary production in lakes. Phytoplankton community composition may be altered by changes in winter and spring temperatures, depending on lake type and location (Anneville *et al*. 2002; Christoffersen *et al*. 2006; Elliott *et al*. 2006). The phytoplankton assemblages of shallow cold-water ecosystems seem to be especially sensitive to temperature changes (Schindler *et al*. 1990; Findlay *et al*. 2001).

A shift towards dominance of cyanophytes in warmer water, with possible implications for water quality, is widely predicted and may lead to a progressive loss of phytoplankton biodiversity (Chapter 6). Models suggest that cyanobacterial dominance will be greatest if high water temperatures are combined with high nutrient loads. At low nutrient levels, the effect of water temperature change is reduced considerably (Anneville *et al*. 2004; Elliott *et al*. 2005, 2006).

Generally, increased phytoplankton productivity and biomass are correlated with higher spring water temperatures as well as changes in hydrochemistry such as increased nutrient availability (Schindler *et al*. 1996; Straile & Geller 1998; Findlay *et al*. 2001). Earlier stratification and deeper thermoclines may have an opposite effect, however. Furthermore, improved light conditions affect phytoplankton biomass. The better light conditions during warmer winters with shorter ice cover and less snow promote phytoplankton growth in winter, even doubling chlorophyll *a* levels (Pettersson *et al*. 2003).

Table 5.1 Direct and indirect impacts of climate change on lakes. c, t, w: variable relevant in cold (c), temperature (t) or warm (w) ecoregions

Category		*Response*	*Indicator*	*Justification of indicator*	*c*	*t*	*w*
Hydrology	Ice cover	Higher air, and thus higher water temperature, leads to a shorter ice cover period. The relationship between air temperature and timing of lake ice break-up shows an arc cosine function. This nonlinearity results in marked differences in the response of ice break-up timing to changes in air temperature between colder and warmer regions.	Ice-cover duration, timing of ice break-up, ice thickness	Ice cover duration is simple to monitor, e.g. by remote sensing.	x	(x)	
	Stratification	Higher temperatures result in earlier onset and prolongation of summer stratification. As a result, changing mixing processes occur and systems may change from dimictic to warm monomictic. A lack of full turnover in winter might lead to a permanent thermocline in deeper regions.	Duration of summer stratification as reflected by water temperature	Water temperature reflects the status of lake stratification.	x	x	(x)
	Water level	Increased temperature and decreased precipitation in conjunction with intensive water use will decrease water volumes. This will lead to water level imbalances and, in many cases, to the complete loss of water bodies.	Lake surface	Easy to monitor by remote sensing.	(x)	(x)	x

Table 5.1 (*Cont'd*)

Category		*Response*	*Indicator*	*Justification of indicator*	*c*	*t*	*w*
Physicochemistry	Oxygen depletion	High temperatures will stimulate phytoplankton growth, which will lead to oxygen depletion of profundal habitats.	Oxygen concentration of the bottom water in summer	The parameter is easy to record and often incorporated into routine water chemistry monitoring.	(x)	(x)	x
	Sulphate concentration	With less precipitation in El Nino years and resulting droughts, stored reduced S in anoxic zones (wetlands) is oxidized during drought, with subsequently high sulphate export rates. Elevated sulphate concentrations in lakes will be the result.	Sulphate concentration	Directly reflecting the responding parameter; often incorporated into routine water quality monitoring	x	(x)	
	DOC	Rising temperatures in combination with declining acid deposition cause increasing DOC concentrations.	DOC	Incorporated into routine water quality monitoring	x	(x)	
	Acidification effects on phytoplankton	Acidification pulses occur due to drought (El Nino). Acidification pulses will cause changes in phytoplankton richness and biomass.	pH; biotic acid indices	pH is easy to record and often incorporated in water chemistry monitoring. As pH varies seasonally and daily, biotic indices are often more stable.	x		

	Salinity	Warmer winters cause extreme rainstorms and heavy sea-salt deposition, which might affect water chemistry.	Acidifying substances	These parameters are easy to record and often incorporated into routine water chemistry monitoring.	x		x
	Total Organic Carbon (TOC) runoff patterns	Warmer winters produce higher levels of runoff TOC release with subsequently increasing TOC water concentrations.	TOC levels and/or absorbance (water colour)	Water TOC concentrations reflect changes in runoff and input of allochthonous material.	x		
Primary production	Water temperature effects on phytoplankton	Increasing water temperatures lead to shifts from a dominance of diatoms and cryptophytes to cyanobacteria. This effect is especially pronounced at temperatures > 20°C, since cyanobacteria (especially large, filamentous) and green algae are favoured at higher temperatures.	Phytoplankton biomass and composition, cyanobacterial algal blooms	The shift in community composition gives information about the response of biota to changed lake characteristics as water temperatures. Phytoplankton community composition is routinely monitored for the Water Framework Directive.	x	x	(x)
	Water temperature effects on macrophytes	Inter-annual variation in water temperature results in deeper macrophyte colonization, greater wet weight biomass, and an increase in whole lake biomass.	Water temperature	The parameter is easy to record and often incorporated into routine monitoring programmes.		x	

Table 5.1 (*Cont'd*)

Category		*Response*	*Indicator*	*Justification of indicator*	*c*	*t*	*w*
	Water temperature effects on zooplankton	Higher water temperature leads to shifts in zooplankton community composition. Higher, earlier population growth rates of *Daphnia* and earlier summer decline occur due to higher spring temperatures. As a result, higher *Daphnia* biomass leads to earlier phytoplankton suppression and a shift from a dominance of large-bodied to smaller species.	Zooplankton biomass and composition, size classes	The response of zooplankton (although not monitored for the Water Framework Directive) might be a good indicator for changes in food web dynamics due to temperature increase.	(x)	x	(x)
Secondary production	Water temperature effects on cold water fish	Higher water temperatures (especially in the epilimnion) lead to the progressive reduction of thermal habitats for, e.g. *Salvelinus namaycush*. As a result, cold-water species will disappear from littoral areas in spring and summer. Furthermore, higher water temperatures will reduce reproduction success of cold-water species and increase parasitic and predator pressure on the egg and young life stages.	Summer water temperature or air temperature	Water temperature is easy to measure, but even air temperature reflects warming up of mixed layer temperature.	x	x	

	Spread of alien species	Higher temperatures often favour alien fish, macrophyte or macroinvertebrate species.	Share of alien species in the community	This parameter can often be inferred from routine monitoring for the Water Framework Directive.	(x)	x	x
Food webs	Water temperature effects on food webs	Increased water temperature generates principal shifts in food webs. As cyprinid planktivorous fish species are supported, large zooplankton species are suppressed and grazing intensity is reduced.	Proportion of planktivorous and piscivorous fish species; proportion of large and small zooplankton species	Food web structure is well reflected by these two parameters. The share of large zooplankton species determines the effects on phytoplankton, the share of planktivorous species determines the effects on zooplankton.	x	x	x

Category: ecosystem component being affected by direct or indirect climate change effects. Response: describes how the variables change under the stressor considered. Indicator: a judgemental selection of the variables that most clearly reflect climate change.

With increasing spring water temperature and light availability, spring phytoplankton species may grow earlier (Chen & Folt 1996; Müller-Navarra *et al*. 1997; Elliott *et al*. 2006; Adrian *et al*. 2006). The spring peak may also be more heavily grazed (Chen & Folt 1996; Müller-Navarra *et al*. 1997; Straile 2000). In summer, nutrient limitation may occur earlier. For example, the summer cyanobacteria peak may decline earlier because of nutrient limitation from increased spring growth at higher water temperatures (Bleckner *et al*. 2002; Elliott *et al*. 2005). Larger growths can be expected in autumn and winter, benefitting from higher temperatures and delayed light-limitation before ice forms (Bleckner *et al*. 2002).

Increased temperatures may result in greater macrophyte biomass or changes in macrophyte community composition (Rooney & Kalff 2000; McKee *et al*. 2002; Feuchtmayr *et al*. 2007).

Secondary production

Trends in average temperature sometimes correlate significantly with changes in zooplankton community composition, even over comparatively short periods of 10–15 years (Burgmer *et al*. 2007). Water temperature increase may be associated with a shift of zooplankton assemblages from larger to smaller bodied forms, a shift in food availability to inedible Cyanobacteria and possibly a heightened sensitivity to algal toxins (Moore *et al*. 1996). Individual taxa have very different threshold or maximum temperatures for growth that are species specific rather than functional group specific. A shift from the dominance of large-bodied *Daphnia galeata* to smaller *D. cucullata* has been observed with higher spring temperatures (Adrian & Deneke 1996). Slow-growing summer zooplankton with more complex life cycles responded specifically to seasonal warming, depending on its timing (Adrian *et al*. 2006). Changes in the vertical temperature gradient of a lake may affect zooplankton vertical migration. In warmer months, zooplankton occurred closer to the surface (Helland *et al*. 2007). There are, however, powerful effects of predation on zooplankton communities that may mask any direct climate effects.

Community composition and species richness in lake fish communities is strongly related to air temperature. In a study in third-order catchments, the presence or absence of 33 out of 61 fish species was related to temperature, as well as to geographic factors (Minns & Moore 1995). For many species, the relationships with temperature have long been investigated: for instance, *Coregonus albula*, an autumn spawning fish species, is vulnerable to spring temperature increases because of a timing mismatch of hatching and the spring development of zooplankton, in combination with higher rates of predation by warm-water predatory fish species (Nyberg *et al*. 2001). Another threat for this species is a general reduction in occurrence of the cold, oxygen-rich hypolimnetic conditions that it requires in summer (George *et al*. 2006). Generally, higher water temperatures increase growth and production for warm water fish and inhibit growth and production for fish at or above their thermal optimum (DeStasio *et al*. 1996; Petchey *et al*. 1999; Mackenzie-Grieve & Post 2006).

Changes in precipitation and temperature may have opposing effects on fish populations. In Norway, higher winter precipitation, leading to more accumulated snow in April, can be detrimental to the recruitment of brown trout (*Salmo trutta*), whereas warmer summers increase recruitment to levels that may lead to overpopulation and to the establishment of brown trout populations at higher elevations (Borgstrom & Museth 2005). Exceeding water temperature thresholds may limit the survival of fish in lakes. More fish may die from oxygen deficiency or physiological stress in warmer water (DeStasio *et al*. 1996). On the other hand, in shallow, eutrophic lakes, winter fish-kills caused by low dissolved oxygen under ice will be reduced or eliminated (Fang & Stefan 2000). Increased hypolimnetic temperatures may lead to a loss of juvenile fish requiring cool water as a summer refuge; thus, climate change can eliminate fish populations at the margins of their range (Gunn 2002). The effect of climate change at different latitudes has been modelled based on temperature and the minimum oxygen requirements of cold-, cool- and warm-water fish (Stefan *et al*. 1996). Zoogeographical boundaries could move significantly north (Carpenter *et al*. 1992; Petchey *et al*. 1999), a problem for several Salmonidae (DeStasio *et al*. 1996; Jansen & Hesslein 2004), whereas Percidae and Cyprinidae may benefit from an increased thermal habitat in the case of moderate warming (Jansen & Hesslein 2004). Hydrologic changes, together with changes in temperature, will probably favour invasive species over rare and threatened native species (Rogers & McCarty 2000).

As lake fish communities are well correlated with temperature patterns through the variety of pathways described above, water (or air) temperature is an indicator for changes in fish communities, supported by composition measures, such as the proportion of alien species in the fish community.

Food webs

The principal alteration in lake food webs caused by global warming may be a reduction in zooplankton grazing intensity, leading to eutrophication effects (see Chapter 6 for detailed discussion). This is caused by a variety of factors: the density of planktivorous cyprinid fish species is enhanced (Jansen & Hesslein 2004) and the density of piscivorous species reduced, which may lead to a strong top-down control of large zooplankton species (Jeppesen *et al*. 2005). Warmer spring temperatures may disrupt food web linkages between phytoplankton and zooplankton because of different sensitivities to warming. The timing of thermal stratification and spring diatom growth may advance significantly with increasing spring temperatures. Thus, a long-term decline in *Daphnia* populations, frequently a keystone herbivore, may be associated with an expanding temporal mismatch with the spring diatom bloom (Winder & Schindler 2004). A timing mismatch between phytoplankton maxima and the peak abundance of *Daphnia* may lead to the absence of a clear water phase (De Senerpont Domis *et al*. 2007) that is a feature of many lakes in late spring. Even modest warming (less than 2°C) during a short but critical seasonal period may induce changes in whole lake food webs and thus alter entire ecosystems (Strecker *et al*. 2004; Hampton *et al*. 2006; Wagner & Benndorf 2007).

Climate change impacts on the biota of rivers

Monitoring and assessing the effects of stress on rivers

As with lakes, monitoring of European rivers has changed with the introduction of the Water Framework Directive. Formerly, the use of physicochemical variables and selected hydromorphological and biological indices using primarily macroinvertebrates (such as Average Score per Taxon (ASPT) or Saprobic Indices) was most widespread, while now several organism groups (phytoplankton for large rivers, benthic algae, macrophytes, benthic invertebrates and fish) are being monitored, supplemented by hydromorphological and physicochemical variables.

The biological assessment systems for the Water Framework Directive reflect the deviation of the observed assemblage from an undisturbed reference state; in the case of rivers, the deviation is mainly caused by organic pollution, hydromorphological degradation, eutrophication and acidification. While organic pollution was formerly the most widespread stressor, hydromorphological degradation is now a main concern, particularly in Central Europe. Acidification is mainly restricted to northwest Europe, some Alpine regions and a number of other upland areas, although eutrophication universally affects the lowland reaches of rivers in Europe.

Table 5.2 gives a selection of potential indicators for climate change impacts for small rivers in cold, temperate and warm ecoregions of Europe. As for lakes, many of the biotic indicators could be easily incorporated into routine monitoring programmes, e.g. by adding indices reflecting the impact of temperature change on benthic invertebrates, which are already monitored for the purposes of the Water Framework Directive. However, physicochemical variables are most appropriate as early warning indicators.

Hydrology

Changes in hydrology have been discussed in Chapters 3 and 4.

Primary production

Changed runoff and water temperature are expected to cause changes in riparian vegetation (Hauer *et al*. 1997; Primack 2000) and may enhance macrophyte and algal growth. Lower water levels and increased nutrient availability will lead to a greater proportion of terrestrial plant species in floodplains (Hudon 2004). In Fennoscandia, macrophyte species richness decreases with latitude and altitude, mainly due to decreased July temperature. Thus, macrophyte biodiversity is expected to respond strongly to climate change (Heino 2002).

Secondary production

Water temperature, flow regime, channel morphology and sedimentation, which are all subject to impacts from climate change, are decisive factors for river invertebrates and fish. Key variables are summer and maximum temperatures.

Table 5.2 Direct and indirect impacts of climate change on rivers. c, t, w: variable relevant in cold (c), temperate (t) or warm (w) ecoregions

Category		*Response*	*Indicator*	*Justification of indicator*	*c*	*t*	*w*
Hydrology	Decrease in ice cover duration	Higher temperatures will reduce ice cover duration.	Ice cover duration	Ice cover is a key factor for the productivity of boreal aquatic ecosystems and easy to monitor.	x	(x)	
	Increase in drought frequency and duration	Decreased summer precipitation and increasing air temperature in some parts of Central, Eastern and Southern Europe change the character of several small streams from permanent to temporary.	Drought periods	As gauging stations are not installed in most small headwater streams, drought periods can be easily recorded by visiting the respective streams.		x	x
	Change of permanent to intermittent regime	Due to less precipitation and increased demand for freshwater, higher temperatures, and higher transpirations, many small rivers will become intermittent with long dry phases in summer.	Drought periods	As gauging stations are not installed in most small headwater streams, drought periods can be easily recorded by visiting the respective streams.		(x)	x
Morphology	Increased fine sediment entry	Extreme precipitation events increase surface runoff and lead to large amounts of fine sediments entering the streams; sediments accumulate and clog the bottom interstitial.	Number and discharge or flood events in unusual seasons (recorded by gauging stations)	Extreme precipitation events will wash out fine sediments from adjacent cropland and other land-use types. They are well reflected by the discharge of a river.	(x)	x	(x)

Table 5.2 (*Cont'd*)

Category		*Response*	*Indicator*	*Justification of indicator*	*c*	*t*	*w*
Physicochemistry	Increase of eutrophicating substances	N flux in the runoff and decomposition of soil organic matter increases with temperature, which increases nutrient concentrations. Eutrophication is further promoted by high water retention time through low discharge, while denitrification counteracts this effect.	Nitrate, total N, phosphate	Nutrients are routinely monitored in most European countries.	x	x	x
	Reduced water quality	Increasing water temperatures enhance production and decomposition intensity, thus leading to oxygen depletion, particularly at night.	Saprobic indices	Saprobic indices reflect the organic load in streams and eventually the oxygen content. Species with a high oxygen demand (typical for low saprobic indices) will disappear while species with a low oxygen demand (typical for high saprobic indices) will benefit.	(x)	x	x

	'Potamalization' – effects on nutrients	Higher water temperatures lead to a more rapid mineralization of organic matter (leaves, wood) and thus to eutrophication effects. As a result, small streams ('rhithral') will change character and resemble larger rivers ('potamal').	Water temperature (maximum monthly values)	The response of communities is mainly determined by extremes; secondary effects (e.g. oxygen depletion at night times) are most extreme in summer.	(x)	x	(x)
	Acidification	Increased precipitation increases acid runoff from borealic coniferous forests leading to cascading acidification effects on aquatic biota.	pH, invertebrate-based acid-indices	pH-values decrease with increasing acid deposition. Since these events are of short duration, community based indices are often better at reflecting acidification.	x		
Primary production	Increased macrophyte/algae growth	Higher water temperatures and lower discharge enhance macrophyte and algae growth. Furthermore, higher temperatures increase mineralization processes and deliver more nutrients for macrophyte and algae growth.	Water temperature (mean monthly values), macrophyte coverage	Mean monthly temperatures indicate overall temperature increase. Macrophyte coverage is simple to record and well correlated with biomass.	x	x	x
Secondary production and food webs	Increase of respiration rate	The metabolic rates of bacteria and fungi and the metabolic rates of detritivorous species will rise with increasing temperatures. The proportion between primary production and respiration will decrease.	Percentage of collectors in the invertebrate community	Collectors gather organic material. If this food source increases, the percentage of collectors rises to about 40%.	x	x	(x)

Table 5.2 (*Cont'd*)

Category		*Response*	*Indicator*	*Justification of indicator*	*c*	*t*	*w*
	Reduced availability of leaves	Processing rates of leaves and wood increase with temperature. Floods in winter cause more than 50% of leaf inputs to be exported, leaving little detrital material available for invertebrate consumption.	Share of the feeding type 'shredder' in the invertebrate community	Benthic invertebrates are routinely monitored in most European countries. If the availability of leaves decreases, the share of shredders will decrease, too; in small headwater streams, shredders should typically account for 30%–40% of the invertebrate community.	x	x	(x)
	Replacement of cold water species (fish, macroinvertebrates)	Many fish and invertebrate species in cold regions are highly adapted to cold water temperatures (cold stenotherms) and vanish with higher temperatures.	Water temperature (maximum monthly values)	Physiologic barriers are mainly determined by extremes. For cold water species, these are too warm temperatures in crucial phases of their life cycle.	x	x	(x)
	Increase or decrease of species number	Low temperatures are a migration and physiological barrier for many aquatic species. With temperature increase, several species can invade rivers in cold ecoregions. In contrast, in temperate and warm regions, increasing water temperatures lead to the extinction of cold stenothermic taxa.	Number of species (e.g. fish, selected invertebrate groups)	The increase of species numbers is best evaluated by a simple richness index, e.g. the number of species that can be easily inferred from routine monitoring results.	x	x	x

Increase of r-strategists	Invertebrate r-strategists benefit from unpredictable flood events, e.g. in summer, which remove most invertebrates and thus favour species rapidly colonizing the competition-free space.	Number and discharge of flood events in unusual seasons (recorded by gauging stations)	Unusual hydrological events, e.g. floods in summer, cause catastrophic drifts of invertebrate species and favour r-strategists.	(x)	x	x
Changes in life strategies	If small rivers become intermittent, species with a bivoltine or semivoltine life cycle cannot survive and the community will change to univoltine species with an early emergence period.	Drought periods	As gauging stations are not installed in most small headwater streams, drought periods can be easily recorded by visiting the respective streams.		(x)	x
'Potamalization' – effects on invertebrates	Higher water temperature leads to the disappearance of species adapted to cold water temperature and the associated high oxygen content, e.g. several stonefly (Plecoptera) species. They are replaced by species typical for warmer water previously colonizing more downstream reaches. Thus, invertebrate species typical for small streams ('rhithral') will be replaced by species from larger rivers ('potamal').	Share of invertebrate taxa preferring the metarhithral (trout zone)	Benthic invertebrates are routinely monitored in most European countries. The response of the invertebrate community to temperature increase is reflected by their longitudinal zonation preference. The share of 'metarhithral taxa' in an unimpacted small stream differs between ecoregions, but should typically be around 50%.	(x)	x	(x)

Table 5.2 (*Cont'd*)

Category		*Response*	*Indicator*	*Justification of indicator*	*c*	*t*	*w*
	Replacement of salmonid by cyprinid fish species	Higher water temperatures will reduce reproductive success of salmonid species and increase parasitic and predator pressure on the egg and young larval stages. Warm water cyprinid species will invade in cold water regions.	Water temperature (maximum and minimum monthly values); fish species composition	The eggs of salmonid species need high oxygen concentrations, which will be reduced by higher water temperatures. Parasites and fungi benefit from high temperatures.	x	x	(x)
	Standing stock of cold water fish	Brook trout populations could either benefit from increased growth rates in spring and fall or suffer from shrinking habitat and reduced growth rates in summer, depending on the magnitude of temperature change and on food availability.	Abundance and biomass of brook trout	Brook trout is a keystone species in most Northern European countries.	x	x	(x)
	Spread of alien species	Higher temperatures often favour alien species that increasingly colonize small streams. These could be alien fish, macrophyte or macroinvertebrate species.	Water temperature (maximum and minimum monthly values); share of alien species in the community	The survival and reproduction of several alien species in temperate ecoregions is controlled by minimum temperatures. The second parameter can often be inferred from routine monitoring for the Water Framework Directive.	(x)	x	x

Category: ecosystem component being affected by direct or indirect climate change effects. Response: describes how the variables change under the stressor considered. Indicator: a judgemental selection of the variables that most clearly reflect climate change.

Invertebrates

In studies that compared invertebrate communities throughout Europe, community composition was shown to change with maximum stream temperature, mean July temperature, and with decreasing latitude and altitude (Lake *et al.* 2000; Heino 2002; Xenopoulos & Lodge 2006). Temperature affects invertebrate community composition by influencing species-specific developmental rates and overall assemblage phenology and by excluding taxa unable to tolerate certain temperature ranges (Hawkins *et al.* 1997; Haidekker & Hering 2008). Higher summer water temperature and low flow result in the progressive replacement of upstream, cold-water invertebrate taxa by downstream, thermophilic invertebrate taxa (Daufresne *et al.* 2004). Benthic invertebrate abundance and diversity (particularly of Ephemeroptera, Plecoptera and Trichoptera) is predicted to decrease as a result of changes in water temperature, flow regime, increased sedimentation and changes in channel morphology, and thus changes in habitat availability (Lake *et al.* 2000). Flow regime is another key factor for invertebrate assemblage structure. From a set of hydrological variables, those associated with flow had the highest correlation with macroinvertebrate community metrics for sites in England and Wales (Monk *et al.* 2006). Leaf litter quality and quantity, major food sources in small streams, respond also to climate change with coarse particulate organic matter availability, decreasing with flood frequency. Buzby & Perry (2000) showed that more than 50% of leaf inputs were exported, leaving only sparse leaf litter available to invertebrates. Many of these changes are reflected in the invertebrate community, e.g. by the composition of feeding types and life history traits (Table 5.2).

The vulnerability of freshwater organisms to the direct and indirect effects of climate change can be estimated by the ecological preferences of species. Species may be classified as follows:

- Species with limited distribution ('endemic species') are characterized by a restricted ecological niche and limited dispersal capacity, and are thus more affected by climate change than widely distributed species (Malcolm *et al.* 2006; Brown *et al.* 2007).
- Species inhabiting large rivers characterized by relatively high water temperatures are generally physiologically adaptive and may react to globally rising temperatures by colonizing upstream river reaches; species inhabiting springs cannot move further upstream and are thus more threatened (Fossa *et al.* 2004).
- Species adapted to low water temperatures ('cold-stenothermic species') are threatened by climate change more than eurythermic species (compare Schindler 2001).

Insect species potentially endangered by climate change are unevenly distributed in Europe, but there are also differences between individual insect orders. Three insect orders provide a case study of the above classification. A database on the distribution and ecological preferences of European freshwater mayflies (Ephemeroptera), stoneflies (Plecoptera) and caddisflies (Trichoptera) (www.freshwaterecology.info)

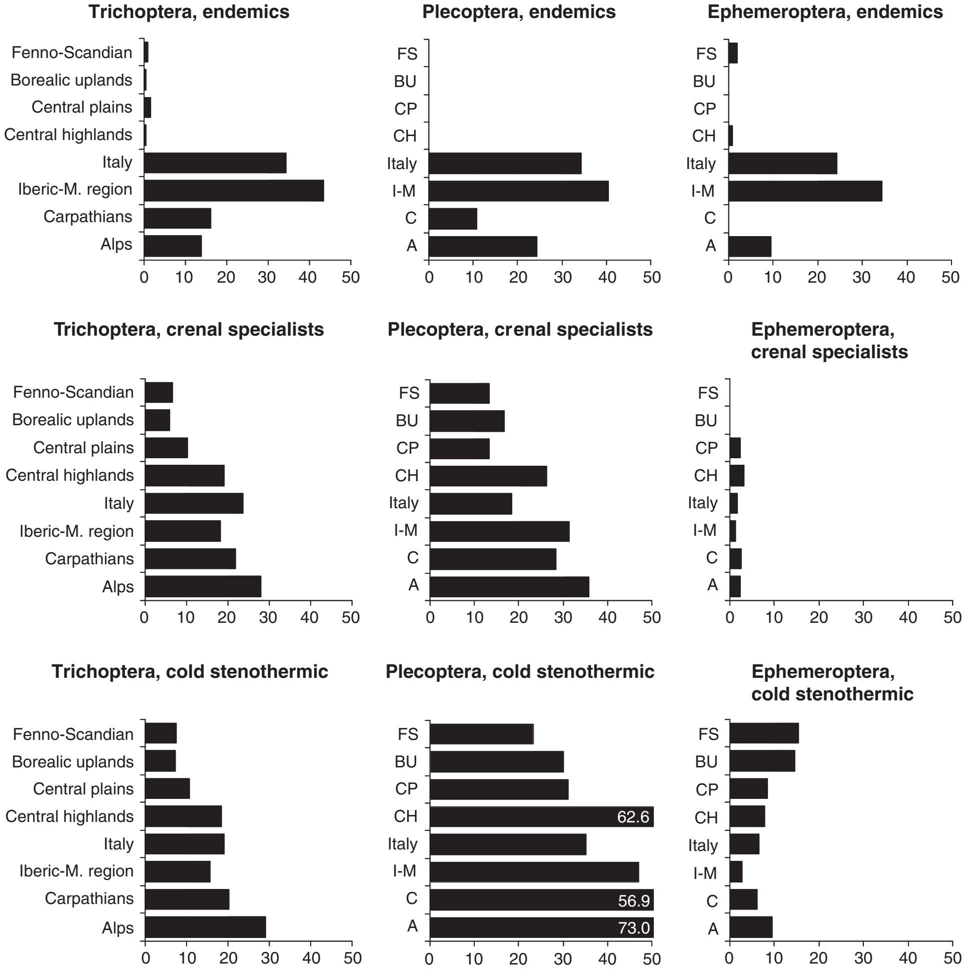

Figure 5.1 Share of species of three aquatic insect groups, caddisflies (Trichoptera), stoneflies (Plecoptera) and mayflies (Ephemeroptera), potentially endangered by climate change in selected European ecoregions according to Illies (1978) (two Northern European ecoregions, two Central European ecoregions, two Mediterranean ecoregions and two high mountain areas). Data based on 1134 Trichoptera taxa, 563 Plecoptera taxa and 344 Ephemeroptera taxa.

was used to calculate the fraction of species in each of the above groups. The data are based on an intensive literature survey and cover all European taxa of the selected organism groups (see Graf *et al.* (2008) for Trichoptera, Graf *et al.* (2009) for Plecoptera and Buffagni *et al.* (2009) for Ephemeroptera).

For all three orders, a high proportion of species in the Mediterranean ecoregions and in high mountain areas are highly vulnerable to climate change (Fig. 5.1). Most Central and Northern European species, however, are widely distributed and likely to be less affected by climate change.

Patterns of endemism are similar for the three insect orders. Up to 45% of species occurring in the Iberic-Macaronesian region are endemic and high fractions of endemic species are also found in Italy, the Balkan ecoregions and the high mountain ecoregions, such as the Alps and the Carpathians. Species restricted to springs (crenal zone) are common among the Trichoptera and Plecoptera, but rare among Ephemeroptera. Most crenal specialists are found in the Mediterranean and in the high mountain areas, while only very few of such species occur in Northern Europe. Cold-stenothermic species of Trichoptera and Plecoptera mainly occur in high mountain areas, while relatively few such species are distributed in Scandinavia. This is different from Ephemeroptera, which have generally a low number of cold stenothermic species, predominantly occurring in Northern Europe.

In general, a south-north gradient in species richness of aquatic insects can be observed. Similar patterns are found for endemic species and (to a lesser degree) for crenal specialists and cold-stenothermic species. These patterns are mainly a result of fluctuations in continental ice cover during the Pleistocene, which, in turn, caused several range extensions and regressions of species (Malicky 2000; Pauls *et al*. 2006). While glaciers covered most of Northern Europe, species retreated to Southern Europe or to ice-free parts of high mountain areas. This isolation of populations resulted in many new species and increased diversity in these areas. Most aquatic insect species occurring in Northern Europe live in Central or Southern Europe too. Mainly, generalists and species with a high dispersal capacity recolonized Northern Europe after the last ice age, while specialist species and those with limited dispersal capacities extended their range only slightly. In consequence, most of the species occurring in Northern Europe are likely to be capable of resisting climate change impacts, since they are generalists or able to rapidly colonize other areas.

Fish

Temperature and hydrological factors are major environmental determinants for fish communities, thus alterations induced by climate change are expected to modify fish assemblage structure (Poff & Allan 1995; Heino 2002). Changing river discharge causes a reduction in community richness and life cycle changes (Schindler 2001; Xenopoulos *et al*. 2005). Water temperature increase may be a threat to cold stenothermic fish species because habitats for cold stenotherms decline, isolating them in increasingly confined headwaters (Eaton & Scheller 1996; Hauer *et al*. 1997; Schindler 2001). As a result, fish assemblages are expected to shift to fewer cold-water taxa and more warm-water taxa, as well as fewer northern taxa and more southern taxa (Daufresne *et al*. 2004). As for invertebrates, fish responses to water-temperature increase are highly species-specific and depend on individual thresholds. For example, the size of Atlantic salmon (*Salmo salar*) is negatively correlated with spring air and water temperatures and with discharge and precipitation (Swansburg *et al*. 2002). Increases in winter temperature and ice break-up may affect winter survival significantly, particularly in northern populations. Because energetic deficiencies are assumed to be an important cause of winter mortality, strong negative effects on the energy budget can be expected (Finstad *et al*. 2004).

In the river Rhone (France), analysis of long-term fish data revealed that the variability of fish abundance was correlated with discharge and temperature during the reproduction period (April–June). Low flows and high temperatures coincided with high fish abundance. In line with temperature increase, southern, thermophilic fish species, e.g. chub (*Leuciscus cephalus*), and barbel (*Barbus* sp.) progressively replaced northern, cold-water fish species, e.g. dace (*Leuciscus leuciscus*) (Daufresne *et al*. 2004). With increasing water temperature the incidence of proliferative kidney disease increased in Switzerland, and populations declined by up to 66% for brown trout (Hari *et al*. 2006). High temperatures may induce an upward migration of fish at their thermal limits: e.g. brown trout (Heggenes & Dokk 2001; Hari *et al*. 2006), charr (*Salvelinus* sp.), and salmon (Carpenter *et al*. 1992) or an alteration in their migration behaviour, increasing the use of thermal refugia in cooler tributaries (chinook salmon, Cole *et al*. 1991). The timing of migration and spawning is also closely linked to thermal state (Salinger & Anderson 2006). Water temperature increase and earlier snowmelt causes an earlier return of adult salmon and alewives, and also affects the timing of migration and spawning of brown trout (Huntington *et al*. 2003). Several metrics related to the composition of fish communities and key species are suited as indicators of these changes (Table 5.2).

In a study of climate change and fish biodiversity, a list of river fish species occurring in 152 European river basins was collected from an intensive literature survey. In all, the fish database contained 306 fish species. To describe fish autecology, 21 fish species traits were considered. Species traits were diverse but most of them concerned reproduction (e.g. fecundity), feeding (e.g. trophic group) or morphology (e.g. body length). Each trait was coded in several categories ('modalities') totalling 72 trait modalities. The 306 fish species present in the database were assessed for these attributes based on the Fish-based Assessment Method for the Ecological status of European rivers (FAME) database (Schmutz *et al*. 2007) or the existing unpublished and published literature and were completed by expert judgement. The trait composition of fish assemblages was thus available for each of the 152 basins. First, 9 ecoregions (Illies 1978) describing a latitudinal gradient were selected. Only the river basins contained within a single ecoregion were retained. Fish trait composition was then compared among the different ecoregions (Fig. 5.2). A north-south gradient was observed for fish body length and traits related to reproduction, but not for traits describing habitat and feeding. In the southern ecoregions, fish assemblages are characterized by small fish, early maturation, small eggs with a short incubation period and the absence of a strategy for egg protection. Those traits are biologically concordant and counter to strong investment in reproduction, which is one of the main features of the more northern cold-water species.

Fish trait composition thus appeared to vary strongly along the latitudinal gradient. To understand more precisely this latitudinal structure, the fish trait composition was related to environmental variables that are good descriptors of the latitudinal gradient. These environmental data were extracted from 0.5°× 0.5°grid data (CIESIN 2005)

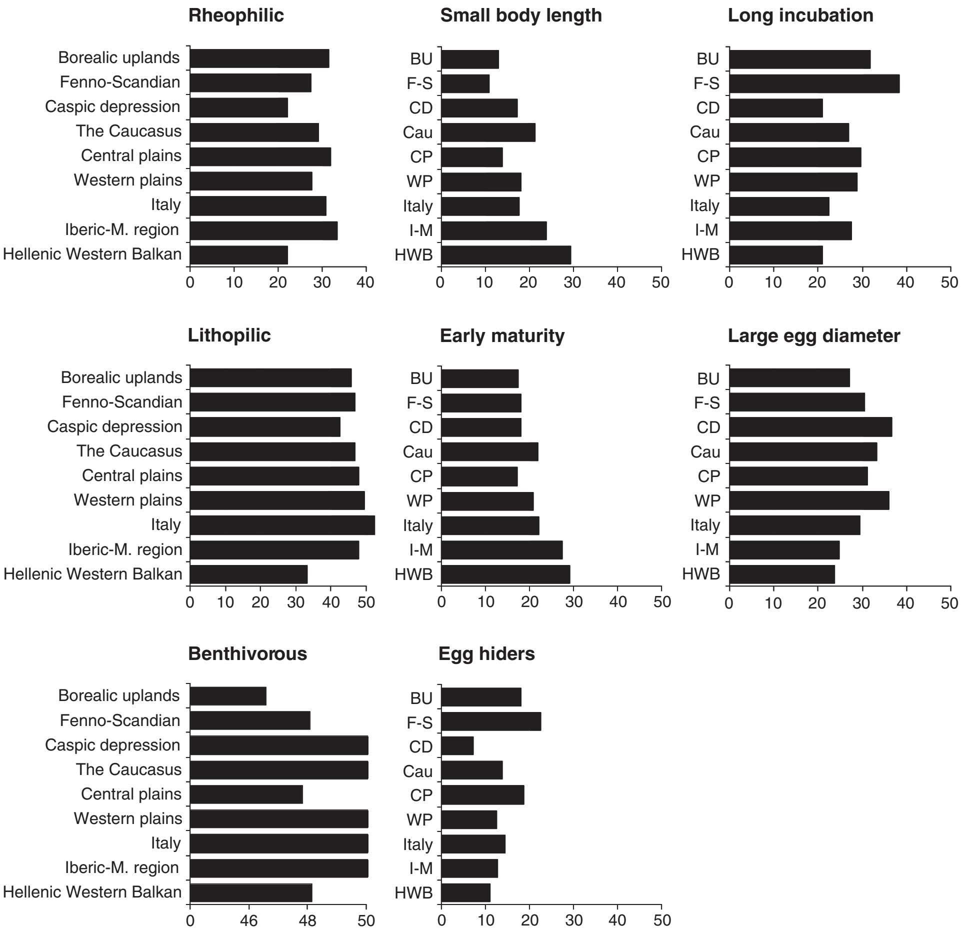

Figure 5.2 Share of fish species in selected European ecoregions according to Illies (1978). Data based on 306 fish species.

and the Atlas of Biosphere (SAGE 2002) and were thus available at the river basin scale. Climate data (temperature and precipitation) were related to fish trait modalities using Generalized Additive Models (GAMs). Among the 62 most common trait modalities, 44 and 48 responded significantly ($p < 0.05$) to mean annual temperature and precipitation, respectively (Fig. 5.3). For instance, with an increasing temperature, there is an increase in the proportion of benthivorous species but a decrease in the proportion of species laying large eggs and having long incubation periods. With an increase in precipitation, more rheophilic species are observed and these species mature early, few of them exhibiting parental care. Only 5 of the 62 modalities tested were not influenced by at least one of the two climatic variables. These relationships explain the differences in fish trait composition observed between ecoregions and suggest that Northern and Southern European fish species will not be affected equally by future climate change.

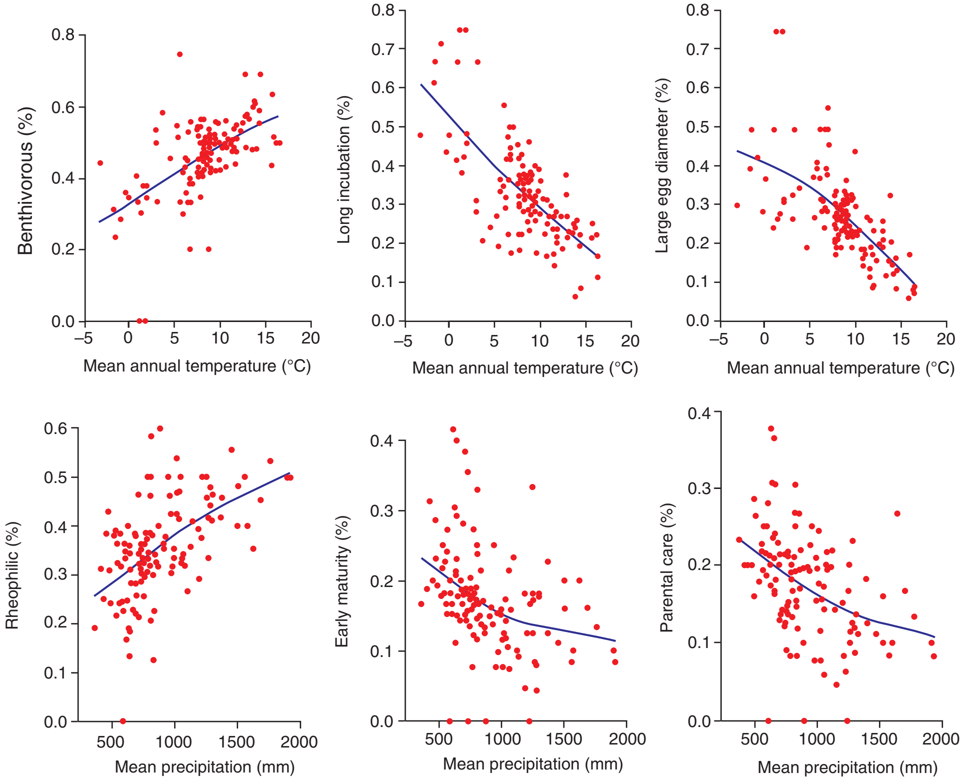

Figure 5.3 Relationships between fish trait composition (percentage of trait modality) and two climatic variables (mean annual temperature and mean precipitation) for 152 European river basins. The line was fitted using a generalized additive model (GAM).

Climate change impacts on the biota of wetlands

Monitoring and assessing the effects of stress on wetlands

Wetlands are not directly included in the Water Framework Directive, but any logical interpretation of the pristine nature of floodplain rivers must include them as key components. There is a limited number of more regional assessment systems, while Europe-wide approaches are less common. Several variables may reflect the effects of climate change on wetland ecosystems, particularly on processes and functioning. Table 5.3 lists suitable indicators for climate change impacts on wetlands.

Hydrology

Wetland hydrological regimes face impacts from both land use and climate. A rise in ambient temperature will result in increased water abstraction, and, with more

Table 5.3 Direct and indirect impacts of climate change on wetlands

Category		*Response*	*Indicator*	*Justification of indicator*
Hydrology	Ice cover duration	Increased air temperatures lead to a later thaw.	Date of ice break-up	Indicates direct temperature effects. Influences length of season.
	Retention of flood water	Increased temperature may lead to increased rates of evaporation.	Water table height	Retention of flood water will be enhanced if the water table is lowered but reduced if the water table is higher.
	Recharge of groundwaters	Ability to recharge aquifers is affected by desiccation.	Water table height	If the water table is high, the rate of recharge of groundwater (if any) will be increased.
	Retention of sediment	Scouring of sediments by extreme weather events.	Frequency and severity of storms	Storms and associated flash floods and spates may wash away sediments and detritus, reducing their retention.
Physicochemistry	Acquisition of carbon I	Warm and wet conditions together increase carbon acquisition.	temperature and precipitation	Indicates gross C dynamics.
	Acquisition of carbon II	Early snow melt followed by wet and warm conditions lead to high carbon acquisition through photosynthesis.	Date of snow melt, temperature and precipitation	A combination of early spring plus wet and warm weather promotes vegetation growth. Photosynthesis sequesters carbon, while rates of respiration remain comparatively stable year to year. Thus, carbon is accumulated in these conditions.

Table 5.3 (*Cont'd*)

Category		*Response*	*Indicator*	*Justification of indicator*
	Export of organic carbon	Organic carbon is provided for downstream ecosystems in runoff water.	Water table height	Organic carbon can be released as dissolved organic carbon (DOC) in runoff water.
	Release of CH_4	Lowered water table reduces CH_4 emission.	Water table height	Water table height and greenhouse gas emission are directly correlated.
	Retention of carbon	Retention of carbonaceous material will be enhanced if warmer temperatures increase primary production while water availability is sufficient, but will be reduced if runoff events increase in frequency.	Rate of primary production	Retention of carbon in vegetation and detritus will be enhanced by increased production.
	Mineralization	Lowered water table stimulates enzyme activity leading to increased mineralization.	Rates of enzyme activity	Indicates carbon loss from peat.
	Export of nutrients	Increased production leads to greater provision of organic detritus, which is then available for export downstream.	Production of litter	Export of nutrients will increase if detritus production is high.
	Retention of nutrients	Longer season and warmer temperatures can lead to increased primary production.	Rate of primary production	Retention of nutrients is potentially greater where production is high.

Primary production	Tree survival	Increase in flooding can lead to progressive replacement of forest with bogs.	Water table height	Water table height and tree survival are directly correlated.
	Vegetation assemblages	Elevated water table leads to increase in bryophytes and reduction of shrubs in the bog, but increase in graminoids and forbs in the fen. Lowered water table leads to increased proportion of dicotyledonous plant species.	Water table height vegetation assemblages	Water table height and vegetation assemblages are directly correlated.
	Vegetation type	Lowered water table leads to succession to forest-type vegetation from the graminoids and mosses occurring in pristine conditions.	Water table height, occurrence of higher plant species	Water table height and vegetation assemblages are directly correlated.
Secondary production	Insect species	Milder winters and hot summers are important factors in the survival of temperature-sensitive species. This will probably alter the tolerable ranges of some species, including pest species, and may lead to increased invasions into new areas by exotic species.	Taxonomic composition and abundance of insect species, especially butterflies and aquatic insects	Indicates impacts on habitat integrity.

Table 5.3 (*Cont'd*)

Category		*Response*	*Indicator*	*Justification of indicator*
	Bird migration	Spring migrations start earlier with warming. This is more pronounced early in the season and with terrestrial and wetland birds than with waterfowl.	Beginning of spring migration period	
Food webs	Ecosystem support	Ecosystems potentially will suffer if detritus and species are lost due to severe flooding and runoff events, and if drought levels exceed the tolerance limits of species.	Frequency and severity of storms	Reduction of biomass and species due to wash out.
	Support of food webs	Drought and flooding both contribute to mineralization and release of nutrients from organic matter. This can increase the build up of plant-available nutrients in the sediments, which are readily washed into water courses and wetlands in runoff.	Frequency and severity of storms	Increase in eutrophication may result from large runoff events.

Category: ecosystem component being affected by direct or indirect climate change effects. Response: describes how the variables change under the stressor considered. Indicator: a judgemental selection of the variables that most clearly reflect climate change. As less data than for lakes and rivers is available we do not distinguish between wetlands in different climatic regions.

frequent droughts predicted, irrigation demands will increase. Changes in land use may require the construction of dams, with barrier effects for hydrological conditions. This has implications for the size and spatial distribution of wetlands (Brinson & Malvarez 2002; Pyke 2004; Perotti *et al*. 2005). Additionally, nutrient enrichment and pollution are possible consequences of land-use changes from intensified crop growth, prolonged growing seasons and increasing urbanization and industrialization (van Breemen *et al*. 1998; Hudon 2004). Changes in precipitation, evaporation and temperature determine the groundwater level, which influences the wetland cover cycle, the transition between permanent and temporary wetlands and hydrochemical variables (e.g. Johnson *et al*. 2004; Lischeid *et al*. 2007). Water table height reflects the influences of climate change in many wetland types.

Physicochemistry

Mineralization and release of nutrients are determined by hydrology and temperature. Moisture and temperature influence microbial enzyme activity and decomposition rates. Drier, warmer conditions could stimulate nutrient mineralization and enhanced release from sediments to runoff water (Freeman *et al*. 1996; Fenner *et al*. 2005). Mineralization of C, N, and P may differ significantly among wetland types. In bog peats, nitrogen mineralization and CO_2 production may decrease with increasing ambient temperatures and lower water tables, whereas in fen peats, nitrogen mineralization may decrease and methane production may increase with higher water tables (Keller *et al*. 2004), but the generality of these findings is questionable. Stored reduced sulphur in anoxic zones of wetlands oxidizes during drought periods. Owing to the subsequent efflux into streams and lakes, sulphate concentrations and acidity can increase after droughts (Dillon *et al*. 1997; Aherne *et al*. 2004). Carbon acquisition may increase under warmer and wetter conditions, whereas in warmer and drier years, wetlands experience significant carbon losses (Carroll & Crill 1997; Griffis & Rouse 2001). Climate change is predicted to cause a doubling of net total C loss rates in wetlands (Clair *et al*. 2001). Maximum soil temperatures are correlated with maximum CH_4 emission values, whereas reduced water table levels suppress CH_4 emissions. Thus, long-term climatic changes with less precipitation and decreased water tables may reduce the incidence of CH_4 release from wetlands (Moore *et al*. 1998; Gedney & Cox 2003; Werner *et al*. 2003). Nonetheless, lowered groundwater changes due to climate change may lead to increased nitrous oxide fluxes in natural peatland soils (Regina *et al*. 1999). Under extreme drought, emissions may increase exponentially with a linear decrease in the water table (Dowrick *et al*. 1999).

Primary production

A key driver of changes in the community composition of wetland vegetation is the altered hydrological regime. Drought results in a proportional loss of native species, an influx of invasives, and a community change towards dicotyledonous species in northern wetlands (Hogenbirk & Wein 1991). In bogs, increased temperature, together with an experimentally lowered water table, caused a 50% increase in the cover of shrubs, and a 50% decrease in the cover of graminoids (Weltzin *et al.* 2003). More frequent droughts cause wetland vegetation to become both woodier and drier. Pond-meadow wetlands may acquire more species, particularly nonwetland species (Hudon 2004; Mulhouse *et al.* 2005).

Soil temperature rise causes shifts in the productivity of plant communities, e.g. an increase in shrub productivity and decreased forb (herbaceous flowering plant) productivity. A higher water table caused bryophyte productivity to increase in bog samples, while shrub productivity was lower (Weltzin *et al.* 2000). Altered riparian vegetation (herb vegetation and trees), and an altered biomass and productivity, affects detritivores and results in lower decomposition rates (Carpenter *et al.* 1992). Decomposition in river marginal wetlands is highly dependent on precipitation, whereas climate change or river flow management could disrupt floodplain nutrient dynamics, i.e. the periodic processes of organic matter retention, breakdown, mineralization and release (Andersen & Nelson 2006). Species' sensitivity to climate change is dependent on plant traits and niche properties (Thuiller *et al.* 2005). Besides water table height, which reflects many of these changes to some degree, the occurrences of certain species and vegetation assemblages may be used as indicators for climate change in plant communities (Table 5.3).

Secondary production

Lower water tables, increased temperatures and more frequent droughts lead to a loss of habitat for obligate wetland species. Invertebrates are affected directly by changing water table or temperature, but also indirectly by shifts in nutrient availability. Invasive, exotic plant species and changed nutritional quality of litter affect detritivores (Carpenter *et al.* 1992; Andersen & Nelson 2006). Other taxa affected by increased drought, weaker spring flows and reduced inundation are fish, amphibians, waterfowl and muskrat (Schindler 2001; Diamond *et al.* 2002).

Climate change advances the spring arrival of migrating birds, in both short- and long-distance migrants (Zalakevicius & Zalakeviciute 2001). It also changes the winter distribution of shorebirds (Gillings *et al.* 2006). Furthermore, global climate change alters the ranges and population state of different breeding bird species and populations. The impact of global warming on terrestrial and wetland birds is more evident than upon waterfowl (Zalakevicius & Zalakeviciute 2001). Variability of precipitation in wetlands affects population and community dynamics of wetland birds owing to egg and nestling predation, which was negatively correlated with water levels in wetlands (Fletcher & Koford 2004). Suitable indicators might include the beginning of the bird's spring migration period and metrics related to taxonomic composition of indicator taxa groups (Table. 5.3).

Conclusions

Climate change will lead to complex cause–effect chains between temperature/precipitation and ecosystem response. As climate change will be a main stressor for aquatic ecosystems in Europe and beyond, the effects need to be specifically targeted in monitoring programmes, e.g. those implemented for the EU Water Framework Directive. Possible indicators are to some degree specific for ecoregions and freshwater ecosystem types and can be selected from a wide range of chemical, functional and biological parameters. Dose–response relationships between drivers and indicators need to be defined in future.

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