CHAPTER 7.3

Climate change and freshwater fisheries

Chris Harrod
Instituto de Ciencias Naturales Alexander Von Humboldt, Universidad de Antofagasta, Antofagasta, Chile

Abstract: Climate change is among the most serious environmental challenge facing humanity and the ecosystems that provide the goods and services on which it relies. Climate change has had a major historical influence on global biodiversity and will continue to impact the structure and function of natural ecosystems, including the provision of natural services such as fisheries. Freshwater fishery professionals (*e.g.* fishery managers, fish biologists, fishery scientists and fishers) need to be informed regarding the likely impacts of climate change. Written for such an audience, this chapter reviews the drivers of climatic change and the means by which its impacts are predicted. It details observed and future predicted effects of climate change on freshwater ecosystems across Arctic, temperate and tropical climatic zones and highlights those areas where data are currently limiting our understanding of how and if climate change is affecting freshwater fisheries. Observed and predicted consequences of climatic change on the ecology of freshwater fishes are examined at different levels of biological organization, including individual, population, community and ecosystem levels, and future scenarios are discussed. The chapter examines the likely impacts of such changes on the exploitation and management of freshwater fishes across recreational, artisanal and commercial fishery sectors, including observations on the vulnerability of fishers themselves to climate change.

Keywords: rivers, lakes, future climates, water temperature, precipitation, river flow, emission scenarios, Arctic, temperate, subtropical, tropical, fisheries yield, fishers

Introduction

Climate change is among the most serious environmental challenge facing humanity and the ecosystems on which it relies (Vitousek, 1994; Parry *et al.*, 2007). There is a strong scientific consensus (Cook *et al.*, 2013) that climate change is not only real but that it has (Trenberth *et al.*, 2007; Blunden & Arndt, 2013) and will continue to have a major global impact (Walther *et al.*, 2005; Rosenzweig *et al.*, 2008), including species extinctions and extirpations (Xenopoulos *et al.*, 2005), changes in the seasonality of important ecological events (Ahas & Aasa, 2006; Thackeray *et al.*, 2010), effects on the provision of natural goods and services (O'Reilly *et al.*, 2003; Millennium Ecosystem Assessment, 2005; Fischlin *et al.*, 2007) and even conflict between groups of humans (Hsiang *et al.*, 2013). These impacts will extend to freshwater ecosystems, *e.g.* warming (Adrian *et al.*, 2009; Schneider & Hook, 2010), and organisms across all levels of biological organization (McCullough *et al.*, 2009; Woodward *et al.*, 2010), with resulting effects on the freshwater fisheries that provide food, employment and recreation worldwide (Holmlund & Hammer, 1999; Welcomme, 2001). The effects of climate change have probably been acting for several decades and, like other overlooked sources of ecosystem degradation (Hermoso & Clavero, 2013), have probably affected our understanding of 'baseline' conditions in freshwater ecosystems (Nõges *et al.*, 2007; Logez & Pont, 2013) and of fundamental life history traits in freshwater fishes (Crozier & Hutchings, 2014).

Global mean surface temperatures have increased by *c.* 0.75°C (probable range: 0.56–0.92°C) over the past century, with the rate of change increasing from the 1970s (Trenberth *et al.*, 2007). Warming has also been recorded from freshwater ecosystems worldwide (Webb, 1996; Nicholson, 2001; Vollmer *et al.*, 2005; Rosenzweig *et al.*, 2007*a*; Bates *et al.*, 2008; Lough & Hobday, 2011). Warming will continue even if emissions are controlled, due to inertia in the climate system. Estimates of the rate and scale of change differ between models, but by 2100, global air temperatures may be 6.4°C above current temperatures (Christensen *et al.*, 2007; Meehl *et al.*, 2007), resulting in climatic conditions unprecedented in recent geological time (Solomon *et al.*, 2007; Williams *et al.*, 2007). The scale of change is such that air temperatures once

Freshwater Fisheries Ecology, First Edition. Edited by John F. Craig.

considered as extreme (*e.g.* heatwaves) will rapidly (by mid-century) become normal (Mora *et al.*, 2013). Furthermore, unprecedented climatic conditions will occur first in the tropics and among low-income countries where freshwater fisheries provide an important source of income and protein (Welcomme *et al.*, 2010).

There is some evidence that the rate of change in global surface temperatures has slowed recently; however, other indicators of climatic change continue to show that global temperatures continue to rise in the atmosphere as well as terrestrial and aquatic systems (Blunden & Arndt, 2013). Furthermore, there is growing evidence that the number and intensity of some extreme climatic events such as droughts, floods and heavy precipitation have recently increased (Trenberth *et al.*, 2007). Biological systems have responded to this climatic change: over the 20–140 years prior to their study, Parmersan and Yohe (2003) reported that *c.* 60% of the 1598 terrestrial, freshwater or marine species they examined displayed measurable changes in their phenologies and distributions, a period when the world warmed on average only by a relatively small amount (0.75°C).

Freshwater ecosystems are considered as sensitive indicators of climate change (Adrian *et al.*, 2009; Jeppesen *et al.*, 2010*a*), and freshwater taxa may be most at risk of extinction due to climate change (Millennium Ecosystem Assessment, 2005). Clearly, fish biologists, fishery managers and fishery scientists (fishery professionals) need to consider climate change in their activities, policies and future management (Daw *et al.*, 2009; Link *et al.*, 2011; Peterson *et al.*, 2013). Aquatic resource management has long been based on the principle that the future behaviour of a particular ecosystem can be predicted from its past characteristics (Kundzewicz *et al.*, 2008). As climate change impacts fresh waters, freshwater fishes and fishers alike (Sharp, 1987), we face unknowable risks and probably surprises, with unprecedented climatic conditions (Williams *et al.*, 2007) and new species interactions, *e.g.* as species invade (Britton *et al.*, 2010) or are intentionally introduced (Povlsen, 1993). As the climate and fish communities change, novel interspecific interactions will result that have no current analogue (Williams & Jackson, 2007), and the assumption regarding past behaviour will probably become less valid, requiring new thinking by fishery professionals, fishers and the wider community (Tompkins & Adger, 2004; Russell *et al.*, 2012; Peterson *et al.*, 2013).

The consequences of climate change are manifold and complex (Parry *et al.*, 2007), but have been largely perceived by the public as changes in average global air temperatures (Trenberth *et al.*, 2007). During the period of recent warming, terrestrial regions have warmed faster than the oceans, with subsequent associated increases in water temperatures in lakes, rivers and wetlands worldwide (Kundzewicz *et al.*, 2007) reflecting the often strong relationship between air and water temperature in freshwater ecosystems (Caissie, 2006; Arai, 1981) that are already subject to a series of non-climate stressors such as eutrophication, over-abstraction of water, habitat degradation and invasive species (Carpenter *et al.*, 2011).

Apart from changes in air and water temperatures (Trenberth *et al.*, 2007), climate change has modified the global hydrological cycle (Trenberth *et al.*, 2007; Kundzewicz *et al.*, 2008), resulting in changes in the timing, type and intensity of precipitation. During the 20th century, precipitation over land has generally increased between latitudes 30°N and 85°N, while over the past 30–40 years, it has decreased in latitudes between 10°S and 30°N (Bates *et al.*, 2008), with a 50% reduction in precipitation in central Chile recorded in the second half of the 20th century (Magrin *et al.*, 2007). This in turn has impacted run-off, river discharge and groundwater recharge, leading to subsequent changes in the availability of water. This will become increasingly intensified in the future, and at a global level, precipitation and evaporation will increase (Solomon *et al.*, 2007). The impacts of climate change, however, will not be homogeneous across the earth's surface (Arnell, 1999; Baettig *et al.*, 2007; Kundzewicz *et al.*, 2008). Current predictions (Kundzewicz *et al.*, 2007; Trenberth *et al.*, 2007) indicate that by the end of the current century, climate change will be particularly marked in the most northern of latitudes and the tropics (Baettig *et al.*, 2007). Precipitation (and associated river run-off and water availability) will markedly increase in northern latitudes but decrease in the arid regions already suffering water stress, such as the dry tropics and temperate regions (van Vliet *et al.*, 2013). As air temperatures increase, so will evaporation rates, resulting in water availability being further reduced (Junk, 2002). Furthermore, continued human modifications of catchment hydrology (reservoirs, extraction and changes in land use) will enhance the already considerable natural variability in river flow (Kundzewicz *et al.*, 2007).

Climate has naturally varied greatly over geological time (Crowley, 1983) with fundamental biological effects (Grimm *et al.*, 2013). A core assumption of biogeographical theory is that as a feature of the natural world, climate has and continues to influence the distribution and suitability of habitats (Carpenter *et al.*, 1992; Kutzbach *et al.*, 1998), which in turn have driven the distribution and dispersal of species (Pearson & Dawson, 2003) and influenced speciation patterns (Sturmbauer *et al.*, 2001; April *et al.*, 2013; Macqueen & Johnston, 2014). Further climate change will have a strong controlling effect on freshwater ecosystems, communities, species and individual organisms in the future (Levitus *et al.*, 2000; Parmesan & Yohe, 2003; Root *et al.*, 2003), as well as for those societies and individuals whose activities rely on those ecosystems and species (Holmlund & Hammer, 1999; Meyer *et al.*, 1999; Millennium Ecosystem Assessment, 2005). This chapter examines the impacts of climate change on freshwater fishes and their fisheries, including commercial, artisanal and recreational fisheries.

Fishes, as individuals, populations or communities, experience climate through seasonal and daily variation in water temperature, winds, currents and precipitation (Ottersen *et al.*, 2001). In environments where such abiotic conditions display strong and predictable seasonality, the timing of key components of the life cycle of resident taxa is often associated with certain conditions (Shuter & Post, 1990; Bryant, 2009), *e.g.* temperature in temperate regions or precipitation or water levels in tropical regions (Lewis, 2000; Latrubesse *et al*., 2005). Climate change has and will continue to modify abiotic conditions encountered by fishes and, as such, has significant implications for freshwater fisheries (Ficke *et al*., 2007; Graham & Harrod, 2009).

The influence of climate acts on fishes through a wide range of processes, both directly through metabolic and reproductive processes and indirectly through phenology, prey, predators and competitors (Graham & Harrod, 2009). The importance of climatic variation as a driver of freshwater fish population dynamics and exploitation has long been recognized (Shuter *et al*., 1980; Schlesinger & Regier, 1982; Casselman, 2002). Although less marked than the effects reported from terrestrial habitats, climate change has already impacted globally important freshwater fisheries, *e.g.* in the African Great Lakes (O'Reilly *et al*., 2003; Vollmer *et al*., 2005; Tierney *et al*., 2010), and will continue to affect freshwater fisheries worldwide, albeit in different ways and intensities, reflecting geographical location and the intensity of multiple other non-climate stressors. These non-climate stressors are also driven by human activities (Pereira *et al*., 2010) and include invasive species, changes in land use, pollution, hydrological regulation, over-extraction of water and over-exploitation of resources including overfishing (Malmqvist *et al*., 2002; Allan *et al*., 2005; Millennium Ecosystem Assessment, 2005; Nilsson *et al*., 2005; Carpenter *et al*., 2011). Due to interactions between climate change and these non-climate stressors, there is concern that climate change will act as an amplifier of these impacts (Whitehead *et al*., 2009; Warren *et al*., 2011).

Climate change and its impacts on freshwater fishes and fisheries have been discussed by fish biologists for almost four decades (Meisner *et al*., 1987; DeAngelis & Cushman, 1990; Magnuson *et al*., 1990; Meisner, 1990; Shuter & Post, 1990; Tonn, 1990; Maitland, 1991; McDowall, 1992; Meisner & Shuter, 1992; Shuter & Meisner, 1992; Hlohowskyj *et al*., 1996). Its importance is officially recognized: statutory agencies across the world include climate change as a principal area of concern, while international and national funding agencies increasingly support research into climate change. The importance of climate change impacts on fisheries has been recognized by the Food and Agriculture Organization (FAO) of the United Nations (Sharp, 2003; Cochrane *et al*., 2009), while the Intergovernmental Panel on Climate Change (IPCC) includes reference to freshwater fisheries in their assessment reports (Kundzewicz *et al*., 2007; Parry *et al*., 2007), and the interested reader is directed there (and subsequent IPCC reports) for more information.

Freshwater fisheries

Freshwater fisheries are found on all continents but Antarctica, and fishes are exploited in waters ranging from the largest rivers (Welcomme, 1985; Junk *et al*., 2007) and lakes (Evans, 2007) through to the streams, small ponds and wetlands that make large contributions to global fish production relative to their size (Welcomme *et al*., 2010). Freshwater fisheries differ from the marine fisheries that dominate fisheries science in terms of scale (FAO Fisheries and Aquaculture Department, 2012), function (*e.g.* trophic level) (Pauly *et al*., 2002) and the natural and anthropogenic drivers that drive them (Welcomme *et al*., 2010), although the total number of people involved in freshwater fisheries may be larger, *e.g.* in the developing world (Welcomme *et al*., 2010). Freshwater fisheries provide a range of important ecosystem goods and services to human populations (Holmlund & Hammer, 1999; Welcomme, 2001) including provision of food, employment and recreation through commercial, artisanal, subsistence and recreational fisheries (Allison *et al*., 2009; Welcomme, 2011; Nelson *et al*., 2013), and each sector differs in their vulnerability and ability to adapt to climate change. Furthermore, the focus of fisheries typically varies according to the relative level of development of a particular region (Welcomme *et al*., 2010).

Generally, fisheries in developing countries are seen as a means to provide food, while fisheries in developed or transitional countries are largely focused on recreation and conservation, although non-recreational fisheries continue to operate in these regions (Welcomme *et al*., 2010). Freshwater fisheries across the globe make significant economic and social contributions (Daw *et al*., 2009) but are less dominated by large-scale intensive commercial fisheries compared to marine fisheries, with a greater contribution of local- or family-level operations (Welcomme *et al*., 2010). Fishing activities often play only a part in the livelihood strategy of many freshwater fishers (Allison *et al*., 2001; Wrona *et al*., 2005; Badjeck *et al*., 2010), many of whom are involved in other activities such as farming (Neiland *et al*., 2000*a*; Welcomme *et al*., 2010).

The FAO of the United Nations estimated that in 2011 the total global capture production of fish from inland waters in 2011 was 11.5×10^6 t (*cf.* 78.9×10^6 t from marine habitats), an increase of >30% since the early 2000s (FAO Fisheries and Aquaculture Department, 2012), with catches increasing annually (Welcomme *et al*., 2010; Welcomme, 2011). These figures are probably underestimates and highlight the pressures placed on freshwater fisheries by an ever-growing world population. In large parts of the world, freshwater fisheries dominate the supply of animal protein to human populations, *e.g.* Africa (Allison *et al*., 2001) where large fisheries exist (2010 estimate = 2 567 427 t), largely in the African Great Lakes as well as productive river fisheries in Nigeria and Egypt and wetland and lake and reservoir fisheries in the Sahel (Neiland, 1992). The FAO (2012) noted that the recent growth in inland catch was associated with Asian countries including India, China and Myanmar and that 70% of global production is from Asia.

Climate change and freshwater fisheries

There is a large (and rapidly growing) literature examining how climate change will affect fresh waters, fish and fisheries. The level of output recently led Moss (2012) to refer to the situation as a cottage industry producing ever-increasing numbers of scientific articles. The implications of climate change for fisheries has been examined particularly thoroughly in marine systems, and this is reflected in a strong bias to marine fisheries in the climate change literature (Hennessy *et al.*, 2007). There is a large and growing literature, however, on the probable impacts of climate change on freshwater ecosystems (George, 2010; Kernan *et al.*, 2010; Goldman *et al.*, 2013) and fishes, with numerous reviews (Magnuson & Destasio, 1997; Magnuson *et al.*, 1997; Ficke *et al.*, 2007; Comte *et al.*, 2013) focusing on a range of different geographical locations (McDowall, 1992; Hlohowskyj *et al.*, 1996; Meyer *et al.*, 1999; Schindler, 2001; Mooij *et al.*, 2005; Graham & Harrod, 2009; Thieme *et al.*, 2010; Bell *et al.*, 2011; Koehn *et al.*, 2011; Pratchett *et al.*, 2011; Goldman *et al.*, 2013), habitat types (Carpenter *et al.*, 1992; Xenopoulos *et al.*, 2005; Caissie, 2006; Jeppesen *et al.*, 2010*a*; Schneider & Hook, 2010; Dell *et al.*, 2013; Dokulil, 2013), biomes (Filipe *et al.*, 2012; Reist *et al.*, 2006*a, b*) or particular life history strategies, *e.g.* diadromous taxa (Bryant, 2009; Lassalle & Rochard, 2009). As generally seen in the literature (Kundzewicz *et al.*, 2007), there is an extreme bias towards studies from temperate North America and Europe (Comte *et al.*, 2013; Vincent *et al.*, 2013). There are very few reliable data from the southern hemisphere (Welcomme *et al.*, 2010; Comte *et al.*, 2013) or the productive and speciose tropics (Hlohowskyj *et al.*, 1996).

Climate change

What is climate?

It is important to clarify what is meant by climate, as there is a common misunderstanding regarding climate and weather. Weather is typically considered to represent the day-to-day state of the atmosphere, as described using normal metrological indicators, *e.g.* air temperature and precipitation. Climate goes beyond this and reflects the long-term (*e.g.* 30 years) average weather that can be expected for a particular geographical location. As such, climate change can be considered as shifts in these long-term averages.

Natural climatic variation: time and space

The impacts of climate change on freshwater fisheries will differ depending on geographical location reflecting how climate varies globally. The principal global climatic gradient reflects latitudinal differences in the level of solar radiation striking the earth (Schultz, 2002; Solomon *et al.*, 2007). This affects the relative warmth and precipitation falling on a particular location, with equatorial regions receiving maximum concentrations of solar radiation (Schultz, 2002; Solomon *et al.*, 2007). The climate at a particular location, however, is further influenced by a number of additional factors. Oceanic–atmospheric circulation affects air temperature and precipitation and can lead to regions encountering an atypical climate for a given latitude, *e.g.* the British Isles are located at a relatively northern latitude (49°–61°N), but the North Atlantic Drift prevents the climatic extremes more typical of these latitudes (Barrow & Hulme, 1997; Hulme & Barrow, 1997). In temperate regions, the dominant annual climate cycle that drives changes in freshwater ecosystems is air temperature, while in the tropics, air temperatures remain relatively constant (and high), as does day length, but the principal cycle affecting freshwater ecosystems is precipitation (Meisner & Shuter, 1992), with variation in wind also being important, *e.g.* for lakes (Lowe-McConnell, 1987). Local geomorphological patterns can further disrupt the predictable latitudinal patterns in average temperature, precipitation and wind strength (Schultz, 2002). For example, cold highland areas found in the tropics are climatically similar to highland environments in temperate regions. Due to the controlling relationship between climatic variables and the environmental tolerances of different taxa, the global distribution of terrestrial biomes reflects geographical differences in climate (Kutzbach *et al.*, 1998; Schultz, 2002).

The sensitivity of ecosystems to climatic change is highlighted by a growing body of work revealing ecological responses at a range of levels of biological organization to large-scale natural climatic cycles [*e.g.* El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Arctic Oscillation (AO)] (Trenberth *et al.*, 2007) with large-scale effects reported from marine fishes and fisheries (Ottersen *et al.*, 2004; Stenseth *et al.*, 2003; Lehodey *et al.*, 2006; Defeo *et al.*, 2013). These cycles also influence diadromous fishes (Elliott *et al.*, 2000; Friedland *et al.*, 2003; Jonsson & Jonsson, 2004). Freshwater ecosystems, *e.g.* rivers (Amarasekera *et al.*, 1997; Enfield *et al.*, 2001), lakes (Blenckner *et al.*, 2007) and taxa (Straile *et al.*, 2003; Blenckner *et al.*, 2007), are also sensitive to natural climatic cycles such as ENSO or NAO, particularly at lower trophic levels (Straile *et al.*, 2003; George *et al.*, 2004). Although some evidence for similar responses in freshwater fishes exists (Ahas & Aasa, 2006; Blanco *et al.*, 2007; Nunn *et al.*, 2007; Rypel, 2009), it is much less marked than that seen in marine fishes (Stenseth *et al.*, 2004).

Future climates: what to expect

Throughout the history of the earth, climate has changed, with associated impacts, including the loss and gain of different habitats (Kutzbach *et al.*, 1998). For instance, in previous geological epochs, large freshwater palaeolakes covered large areas of what are now deserts in North Africa and South America (Sylvestre *et al.*, 1999; Battarbee, 2010). Natural climatic variation results from a range of natural drivers including volcanic eruptions, changes in solar output and natural changes in the orbital characteristics of the earth (Hulme & Barrow, 1997). There is now convincing evidence, however, for a growing anthropogenic influence on global climate. The global industrial economy supported by carbon-based fuels has led to marked alteration of the properties of the earth's atmosphere, with increased concentrations of several key atmospheric gases, *e.g.* carbon dioxide (CO_2), methane (CH_4) and water vapour (H_2O), following human activities, *e.g.* industrial and agricultural activities, deforestation and the burning of fossil fuels (Solomon *et al.*, 2007). These so-called greenhouse gases are naturally present in the atmosphere and are essential for much life on earth, as without them atmospheric temperatures would be *c.* 30°C colder than they are today (Ruddiman, 2001). The greenhouse gases allow short-wave radiation from the sun to pass through the atmosphere and heat the earth and also to retain some of the radiation that is subsequently emitted from the warmed surface of the earth (Kiehl & Trenberth, 1997). Anthropogenic emissions are such, however, that they have increased greenhouse gas concentrations to levels greater than at any time in the preceding 650 000 years (Siegenthaler *et al.*, 2005), *e.g.* at the time of writing, global atmospheric CO_2 concentrations sit close to 400 ppm (Blunden & Arndt, 2013). This has resulted in an enhanced greenhouse effect, with a subsequent warming and a non-linear increase in global air and ocean temperatures, as well as widespread melting of snow and ice (Karl & Trenberth, 2003; Solomon *et al.*, 2007). Average global air temperatures have increased by *c.* 0.75°C in the past 100 years (Trenberth *et al.*, 2007), with northern latitudes showing relatively greater warming than other regions.

Emissions of greenhouse gases continue to rise, and there is a large ongoing effort to characterize climate change, its drivers, probable future scale and impacts on humans and the ecosystems on which they rely. Although workers from a range of backgrounds are actively publishing their work on climate change (Blunden & Arndt, 2013), global efforts are centralized through the IPCC (http://www.ipcc.ch), an organization first established by the United Nations Environment Programme and the World Meteorological Organisation in 1988. Its remit is to provide information on the current state of knowledge regarding climate change and its potential environmental and socio-economic impacts, typically provided through periodic assessment reports. The First Assessment Report (FAR) was published in 1990 (IPCC, 1990), and the most recent, the Fourth Assessment Report (AR4), was published in 2007. AR4 included reports from different working groups examining the physical science basis (Solomon *et al.*, 2007), the impact, adaptation and vulnerability (Parry *et al.*, 2007), and mitigation of climate change (Metz *et al.*, 2007) and a synthesis report (IPCC, 2007). A fifth report (AR5) is to be published in 2013–2014. These reports provide a useful means by which the interested non-expert can gain a rapid understanding of the current issues regarding climate change: for example, AR4 includes chapters detailing observed changes and responses to climate change (Rosenzweig *et al.*, 2007b), descriptions of the physical basis of climate change in fresh waters (Trenberth *et al.*, 2007) as well as the implications of climate change on fresh waters (Kundzewicz *et al.*, 2007). Furthermore, Parry *et al.* (2007) includes chapters focussing on different regions of the earth where freshwater habitats and fisheries are considered.

In order to understand the probable impacts of climate change on fisheries (and other components of the human and natural worlds), an understanding of future climatic conditions is required (Solomon *et al.*, 2007; Skeffington *et al.*, 2010). This is usually done through the use of mathematical models that range in complexity (Meehl *et al.*, 2007): the interested reader is directed to Hobday and Lough (2011) and Wilsey *et al.* (2013) for excellent reviews of climate modelling written from a fisheries perspective. Climate modelling is typically done through the use of coarse-resolution numerical models referred to as global circulation models (GCMs). These mechanistic models of the climate system are based on physical processes in the atmosphere, ocean, land surface and the cryosphere and represent a powerful means of predicting future climate under different scenarios at a coarse (*c.* 270 × 270 km) geographical resolution. Results can be downscaled to a more usable resolution to allow modelling and predictions at a finer resolution, through a number of downscaling methods, *e.g.* by dynamic downscaling, which nests regional climate models (RCMs) within GCMs, or through statistical downscaling where empirical relationships between local- and wider-scale conditions are used to predict future climatic conditions. Downscaling allows predictions to be made at a scale useful for those interested in regional-, catchment- or local-level management (Skeffington *et al.*, 2010; Hobday & Lough, 2011). By combining RCMs with ecosystem models such as those developed for lakes, it is possible to predict the future response of lakes to climate change, in terms of thermal response, lake hydrodynamics, nutrient dynamics and phytoplankton biomass and community structure (Blenckner *et al.*, 2010; Jones *et al.*, 2010).

Typically, climate models are run under a range of different scenarios (Nakicenovic & Swart, 2000; Moss *et al.*, 2010) that reflect alternative potential futures (*e.g.* different concentrations of greenhouse gases) including both qualitative and quantitative components. Such scenarios allow climate scientists to provide predictions of future conditions, *e.g.* warming, under different levels of emissions and economic growth, with the IPCC using four main scenarios for AR4 (Solomon *et al.*, 2007). Models become increasingly refined and scenarios evolve over time, and new radiative forcing-based scenarios will be used in AR5 that will also reflect the probable effects of mitigation and adaptation: they will also provide increased resolution for the period reflecting the next few decades (Moss *et al.*, 2010).

Climate models vary greatly in their complexity, scope and capacity to represent features of the natural world, *e.g.* small lakes (MacKay *et al.*, 2009), and have become increasingly complex as processes known to influence climate are added and as the demands of end users increase (Randall *et al.*, 2007). Climate models are inherently uncertain and include a cascade of uncertainties that vary from the particular emission scenario used through to responses by biogeochemical cycles and errors driven by downscaling from global to regional models or even catchment levels (Skeffington *et al.*, 2010). Although these increase uncertainty in the probable range of possible impacts, such models are useful means to understand future changes, especially when the results of multiple models are combined to provide multi-model ensemble projections (Hamilton, 2010). Recent assessments indicate that the predictions for global temperature from the first IPCC assessment report (IPCC, 1990) have largely been observed (Frame & Stone, 2012).

Predicted changes in climate

AR4 includes detailed estimates of future climate change including predicted shifts in surface air temperature (Table 7.3.1) and precipitation (Table 7.3.2), and the interested reader is directed to the relevant sections for either global (Meehl *et al.*, 2007) or regional summaries (Christensen *et al.*, 2007; Parry *et al.*, 2007). Although predictions vary according to scenario, average global air temperatures are likely to increase (relative to the period 1980–1999) between 1.1 and 6.4°C by the end of the 21st century, and warming is predicted to be greatest over northern latitudes, and the cryosphere is predicted to contract (Lemke *et al.*, 2007). Many models show relatively similar predictions in terms of the direction of temperature change but are less clear in terms of precipitation and the subsequent availability of water (Meehl *et al.*, 2007). Precipitation patterns, however, are predicted to change, with increased risk of heavy precipitation and other extreme events in the future. Precipitation is thought to generally increase in northern latitudes, but to decrease over most subtropical areas (Table 7.3.2; Meehl *et al.*, 2007; Christensen *et al.*, 2007).

In terms of those involved in freshwater fisheries, the usefulness of climate change model outputs varies between models and regions, largely reflecting the regional quality of climate science. In some areas, general information is available in the form of figures or maps indicating past or probable future changes in the climatic variable of choice (http://www.ipcc-data.org/ddc_visualisation.html) or long-term average data (Hijmans *et al.*, 2005). More detailed information may be missing or present in a form that is not accessible for non-specialists: in these cases, the interested individual may think of contacting experts working in the field. Increasingly, past climate data (http://www.ipcc-data.org/; http://www.esrl.noaa.gov/psd/data/gridded/) and detailed climate model outputs are freely available, *e.g.* in the United Kingdom (http://ukclimateprojections.defra.gov.uk) and Australia (http://www.csiro.au/ozclim/home.do). These allow detailed indicative climatic variables to be downloaded for a given location and emission scenario, typically as probabilistic estimates of change (*e.g.* per cent change in precipitation or changes in air temperature). The probability of more complex climatic scenarios with relevance to freshwater fisheries can be predicted through the use of so-called weather generators (Jones *et al.*, 2009, Wilks, 2010), for example, the probability of certain weather events occurring that may lead to stress or even mortality for certain sensitive fishes, *e.g.* periods of high temperature and low rain during future summers (Brooker *et al.*, 1977).

Table 7.3.1 Variation in predicted air temperatures for the period 2080 to 2099 relative to the period 1980 to 1999 based on a set of 21 global models in the multi-model data set for the IPCC A1B scenario (Christensen *et al.*, 2007). Estimates are presented as median (interquartile range) annual, December to February (DJF, northern winter and austral summer) and June to August (JJA, northern summer and austral winter) changes in air temperature

Region	Annual	DJF	JJA
Arctic, boreal and highland			
Alaska	4.5°C (3.7–5.2°C)	6.3°C (5.6–7.5°C)	2.4°C (1.8–3.8°C)
Eastern Canada, Greenland and Iceland	4.3°C (3.5–5.0°C)	5.9°C (5.2–7.2°C)	2.8°C (2.1–3.7°C)
Northern Asia	4.3°C (3.4–5.3°C)	6.0°C (4.8–6.6°C)	3.0°C (2.7–4.9°C)
Tibetan Plateau	3.8°C (3.2–4.5°C)	4.1°C (3.7–4.9°C)	4.0°C (3.2–4.7°C)
Temperate			
Northern Europe	3.2°C (2.7–4.6°C)	4.3°C (3.6–5.5°C)	2.7°C (1.9–3.3°C)
Southern Europe and Mediterranean	3.5°C (3.0–4.0°C)	2.6°C (2.5–3.3°C)	4.1°C (3.7–5.0°C)
Central Asia	3.7°C (3.2–4.4°C)	3.2°C (2.6–3.9°C)	4.1°C (3.7–4.9°C)
Western North America	3.4°C (2.9–4.1)	3.6°C (3.1–4.4)	3.8°C (3.2–4.7)
Central North America	3.5°C (3.0–4.4°C)	3.5°C (2.9–4.2°C)	4.1°C (3.1–5.1°C)
Eastern North America	3.6°C (2.8–4.3°C)	3.8°C (3.1–4.6°C)	3.3°C (2.6–4.3°C)
Southern South America	2.5°C (2.3–3.1°C)	2.7°C (2.5–3.3°C)	2.4°C (2.1–2.8°C
Southern Australia	2.6°C (2.4–2.8°C)	2.7°C (2.4–3.2°C)	2.3°C (2.0–2.5°C)
Tropical and subtropical			
West Africa	3.3°C (2.7–3.6°C)	3.0°C (2.7–3.5°C)	3.2°C (2.7–3.7°C)
East Africa	3.2°C (2.5–3.4°C)	3.1°C (2.6–3.4°C)	3.4°C (2.7–3.6°C)
Southern Africa	3.4°C (2.9–3.7°C)	3.1°C (2.7–3.4°C)	3.4°C (3.0–3.6°C)
Sahara	3.6°C (3.2–4.0°C)	3.2°C (2.9–3.5°C)	4.1°C (3.6–4.4°C)
East Asia	3.3°C (2.8–4.1°C)	3.6°C (3.1–4.4°C)	3.0°C (2.5–3.9°C)
South Asia	3.3°C (2.7–3.6°C)	3.6°C (3.2–3.9°C)	2.7°C (2.2–3.2°C)
Southeast Asia	2.5°C (2.2–3.0°C)	2.5°C (2.1–2.9°C)	2.4°C (2.2–2.9°C)
Central America	3.2°C (2.6–3.6°C)	2.6°C (2.2–3.5°C)	3.4°C (2.7–3.6°C)
Amazonia	3.3°C (2.6–3.7°C)	3.0°C (2.4–3.7°C)	3.5°C (2.7–3.9°C)
Caribbean	2.0°C (1.8–2.4°C)	2.1°C (1.8–2.4°C)	2.0°C (1.8–2.4°C)

Data from Christensen *et al.* (2007).

Table 7.3.2 Projected shifts in average precipitation for the period 2080 to 2099 relative to the period 1980 to 1999 based on a set of 21 global models in the multi-model data set for the IPCC A1B scenario (Christensen *et al*., 2007). Estimates are presented as median (interquartile range) annual, December to February (DJF, northern winter and austral summer) and June to August (JJA, northern summer and austral winter) percentage changes in precipitation

Region	Annual	DJF	JJA
Arctic, boreal and highland			
Alaska	21% (13–24%)	28% (20–34%)	14% (8–20%)
Eastern Canada, Greenland and Iceland	15% (12–20%)	5.9% (5.2–7.2%)	11% (8–12%)
Northern Asia	15% (12–19%)	26% (20–37%)	9% (6–12%)
Tibetan Plateau	10% (2–13%)	19% (12–26%)	4% (0–10%)
Temperate			
Northern Europe	9% (6–11%)	15% (13–22%)	2% (–5–7%)
Southern Europe and Mediterranean	–12% (–16–9%)	–6% (–10–1%)	–24% (–35–14%)
Central Asia	–3% (–6–2%)	4% (0–9%)	–13% (–28–4%)
Western North America	5% (0–9%)	7% (2–11%)	–1% (–10–2%)
Central North America	3% (–3–7%)	5% (0–8%)	–3% (–15–4%)
Eastern North America	7% (5–10%)	11% (9–19%)	1% (–3–6%)
Southern South America	3% (–1–5%)	1% (–2–7%)	0% (–7–3%)
Southern Australia	–4% (–13–3%)	–11% (–20–4%)	–2% (–12–2%)
Tropical and subtropical			
West Africa	2% (–2–7%)	6% (–2–13%)	2% (–2–7%)
East Africa	7% (2–11%)	13% (6–16%)	4% (–2–7%)
Southern Africa	–4% (–9–2%)	0% (–3–5%)	–23% (–2–7%)
Sahara	–6% (–24–3%)	–18% (–31–12%)	–4% (–28–16%)
East Asia	9% (4–14%)	10% (6–17%)	9% (5–11%)
South Asia	11% (4–15%)	–5% (–9–1%)	11% (4–16%)
Southeast Asia	7% (3–8%)	6% (3–10%)	7% (3–9%)
Central America	9% (–16–5%)	–14% (–18–9%)	–9% (–25–4%)
Amazonia	–3% (–10–2%)	4% (0–11%)	–3% (–10–2%)
Caribbean	–12% (–19–3%)	–6% (–11–0%)	–20% (–35–6%)

Data from Christensen *et al.* (2007).

From climate models to future fisheries: how to estimate the impact of climate change on fisheries

In a relatively early study, Shuter and Meisner (1992) asked how the potential impact of climate change on wild freshwater fishes could be assessed. They identified two broad questions: (1) How will aquatic habitats change in response to atmospheric climate change? (2) How will fishes respond to habitat change at both the individual and population levels? Today, fish biologists and fishery managers face the same questions. They must identify vulnerability to climate change and predict how stocks, communities and fisheries will respond to climate change, *i.e.* will they persist or undergo significant change (either negative or positive)? This is an onerous task, faced by ecologists and resource managers worldwide (Moritz & Agudo, 2013; Wilsey *et al.*, 2013). There are three principal means by which fishes (and other taxa) can respond over the long-term to environmental shifts driven by climate change (Holt, 1990; Jackson & Overpeck; 2000; Reusch & Wood, 2007): if they possess the necessary phenotypic plasticity to cope with new conditions, they can remain, they can adapt genetically (evolve) or they can move to more suitable habitats (migrate). Conversely, if they cannot, they will become locally extirpated or even globally extinct (Holt, 1990). Many fishes show considerable phenotypic plasticity (Robinson & Parsons, 2002; Crozier & Hutchings, 2014) and can show rapid evolution to new environments (Hendry, 2001; Witte *et al.*, 2008; Elmer *et al.*, 2010), but their relative capacity to withstand the major abiotic and biotic shifts predicted for the near future will clearly differ between lineages, and there will be winners and losers (Graham & Harrod, 2009; Somero, 2010) with obvious impacts on freshwater fisheries. Interestingly, those fishes currently exposed to elevated temperatures, *e.g.* in the tropics, may be the most threatened by future increases in water temperature, as their thermal optima and limits are close to current maximum ambient temperatures, leaving little scope to adapt to higher temperatures (Somero, 2010; Tomanek, 2010).

Climate influences ecological processes in a number of direct, indirect and complex ways (Friedland *et al.*, 2000; Ottersen *et al.*, 2001; Straile *et al.*, 2003) and acts across different levels of biological organization (Mykles *et al.*, 2010; Woodward *et al.*, 2010). A number of complementary and potentially synergistic processes may be acting on a fish population or aquatic ecosystem, *e.g.* invasive species, eutrophication and climate change (Winfield *et al.*, 2008; Britton *et al.*, 2010; Cucherousset & Olden, 2011; Moss *et al.*, 2011). Furthermore, climate-induced changes may act on several aspects of the ecology of fishes (Shuter & Meisner, 1992) and their interactions with biotic and abiotic environments [Schiedek *et al.* (2007) provide a review of interactions between climate change and contaminants].

Predicting the outcomes of environmental change on freshwater ecosystems, fishes and fisheries in order to best direct sustainable fisheries (Allison *et al*., 2001; Daw *et al*., 2009) and conservation action (Rahel *et al*., 2008) is a challenging task but is probably best served by taking a quantitative (Brown *et al*., 2011), integrative (Russell *et al*., 2012) and multidisciplinary approach (Mykles *et al*., 2010).

How to do it?

Climate model outputs provide biologists with fundamental data (*e.g.* temperature and river flow) by which the impact of climate change on species (Fig. 7.3.1) and communities (Wilsey *et al*., 2013), as well as the services and goods they provide to human populations, can be estimated. A raft of potential approaches are available to understand how aquatic systems, fishes and fisheries will respond to climate change (Shuter & Meisner, 1992; Hlohowskyj *et al*., 1996; Kernan *et al*., 2010). These include palaeoecological reconstructions (Chatters *et al*., 1995), analyses of long-term monitoring data (Winfield *et al*., 2010; Isaak *et al*., 2012*a*; Comte *et al*., 2013) or macroecological patterns (Conover, 1992; Griffiths & Harrod, 2007; Lappalainen *et al*., 2008). Manipulative experiments either in the laboratory (Brett, 1956; Fry, 1971; Wismer & Christie, 1987) or in the field, *e.g.* using mesocosms (Beitinger *et al*., 2000; Moss *et al*., 2003; Moss, 2010*a*), have also shown their worth. Fishery professionals and colleagues in associated fields have long used predictive models to estimate key data important in managing freshwater ecosystems such as water temperature (Caissie, 2006), ice cover (Magnuson *et al*., 1997), lake mixing (Meyer *et al*., 1999), water quality (Stefan *et al*., 2001) and river discharge (Isaak *et al*., 2012b). Other models are routinely used (Regier *et al*., 1990) to predict responses of individual fishes or populations and communities, *e.g.* growth (Ricker, 1979; Larsson *et al*., 2005; Griffiths & Harrod, 2007), bioenergetics (Kitchell *et al*., 1977; Kitchell & Crowder, 1986; Beauchamp *et al*., 1989) and yield (Schlesinger & Regier, 1982; Hlohowskyj *et al*., 1996; Lara *et al*., 2009) models.

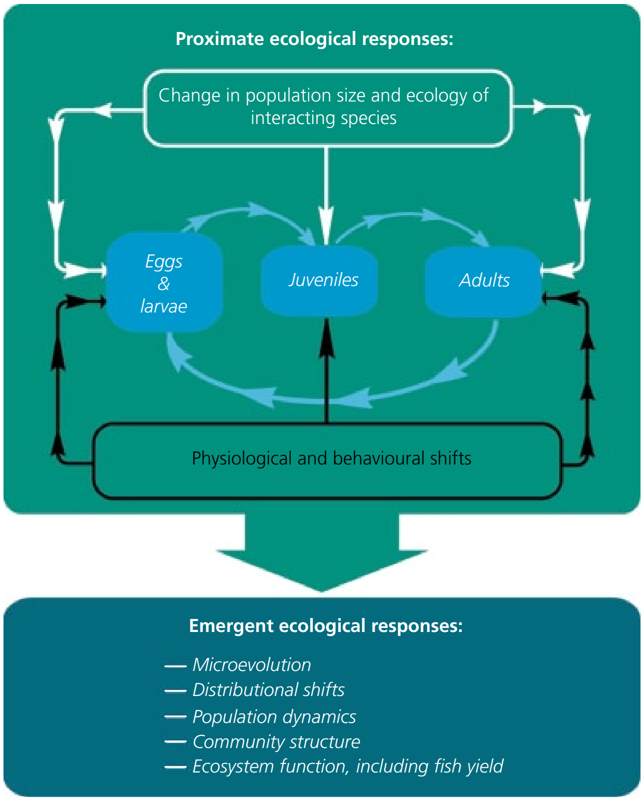

Figure 7.3.1 Potential ecological responses of individual fishes to climate change. As changes in abiotic conditions affect molecular and cellular process, the physiology and behaviour of individual fishes shift and their performance in intra- and interspecific interactions changes, resulting in climate change driving emergent ecological responses, *e.g.* changes in ecosystem function, community structure and fishery yields. Adapted from Harley *et al.* (2006). © John Wiley & Sons.

Such approaches provide a useful means to give a broad understanding how freshwater fishes and fisheries will respond to climate change (Shuter & Meisner, 1992; Hlohowskyj *et al*., 1996). Correctly predicting ecological responses to climate change (*e.g.* responses of fish populations supporting fisheries or the behaviour of fishers), however, is complex and even more so than the already complicated science of climatic modelling. This reflects the fact that the links between cause and effect are typically provided by a range of interacting environmental variables, which are also directly or indirectly influenced by climatic variables, *e.g.* temperature and precipitation (Sharp, 1987). Hence, biological responses are less predictable than those in physico-chemical or hydrological variables (Hering *et al*., 2010), reducing predictive capacity. Predicting fishery responses to climate change is even more complicated: Sharp (1987) described fisheries as (at least) 4th-order phenomena, as they integrate a series of climate–ecosystem responses which vary as a result of continuous climatic changes.

Jeppesen *et al*. (2010*b*) warned that the IPCC's use to date of purely physical models probably results in severe underestimates of the impacts of climate change, which can be reinforced by biological processes (Moss, 2010*a*). Future climate models will probably include increased biological information (Moss *et al*., 2010) and should include integrated climate–ecosystem monitoring and analysis (Sharp, 1987). Decision-making regarding freshwater fisheries management may be further improved through the use of decision support systems (DSS), computer-based systems that permit non-specialists to work with data and models to produce information to guide the decision-making process (Matthies *et al*., 2007; Jolma *et al*., 2010).

In the absence of such specialized integrative approaches (Sharp, 1987) and if suitable long-term data are available, qualitative estimates of the response of a fishery or particular species to future climatic conditions can be made by comparing previous performance recorded under certain weather conditions (*e.g.* during a hot summer) with the conditions predicted under future climate change (George *et al*., 2010). Although this is obviously a less refined approach, it is a useful first step.

Climate change model outputs have been widely used to forecast the distribution of ecosystems and species under future climatic conditions. With regard to fishes, two broad classes of models are typically used, empirical and process-based models. The empirical approach is based on the concept of the environmental niche or bioclimatic envelope (Araújo & Peterson, 2012), which reflects the empirical association between climate and the known distribution of a particular species to provide an indication of its environmental niche. Here, the presence or absence or abundance of a species is modelled as a function of the climatic space or bioclimatic envelope that individual of that species can tolerate physiologically, *i.e.* its fundamental niche (Morin & Thuiller, 2009). By comparing contemporary distribution data with climatic conditions (Hijmans *et al.*, 2005) and the outputs of climate models, biologists can extrapolate to estimate the probable bioclimatic niche of a species.

This provides a conceptually simple and potentially powerful means to project predicted changes in the distribution of a species by examining shifts in habitat suitability (or unsuitability) under future (or past) climatic conditions (Pearson & Dawson, 2003). This approach has proved to be popular with freshwater fish ecologists providing information on shifts in habitat suitability (Magnuson *et al.*, 1990; Shuter & Meisner, 1992; Lappalainen & Lehtonen, 1997; Magnuson & Destasio, 1997) or across landscapes and regions (Meisner, 1990; Bond *et al.*, 2011; Comte *et al.*, 2013), especially as other environmental factors are included in models, *e.g.* elevation, habitat availability and land use (Xenopoulos *et al.*, 2005; Elith *et al.*, 2010; Isaak *et al.*, 2012*a*).

The bioclimatic envelope approach is subject to considerable criticism: it is correlative, coarse-scaled and based on often implausible assumptions, and importantly, model projections are often extreme and are contradicted by empirical evidence of species distributions (Pearson & Dawson, 2003; Morin & Thuiller, 2009; Araújo & Peterson, 2012). Many bioclimatic envelope models ignore the potentially crucial influence of climate on key factors such as growth, mortality or interspecific interactions (Blois *et al.*, 2013). This is important, as many components of interspecies interactions, *e.g.* key components of the predation cycle (swimming velocity, search rate, handling time and escape probability), are affected by water temperature (Dell *et al.*, 2013). Responses to climate change will probably differ between species and may also differ between populations (Richard & Rypel, 2013), for instance, due to local adaptation (Pearson & Dawson, 2003). Bioclimatic envelope models are typically parameterized from contemporary observations that reflect long-term historical factors, *e.g.* postglacial recolonization (Morin & Thuiller, 2009), and therefore may not be able to accurately project ecological responses to future novel climates (Williams & Jackson, 2007). Indeed, simple bioclimatic envelope models often overestimate the probable future distribution of warm-adapted species while underestimating the distribution of cold-adapted taxa (Hein *et al.*, 2011). Predictions of bioclimatic envelope studies can often be extreme and dramatic (Isaak & Rieman, 2012). Although freshwater fishes have changed their distributions (Comte *et al.*, 2013) and performance (Jeppesen *et al.*, 2012) in response to climate change, to date, there has been little evidence that the most dramatic changes in distributions and extinctions predicted by some studies are taking place (Comte *et al.*, 2013), leading to confusion in terms of targeting limited resources available for management of fisheries or ecosystems.

The other broad classification of models used to examine climate change impacts on species is mechanistic or process-based models. Used far less commonly than their bioclimatic envelope counterparts, this class of models is more complex but includes key biological processes in the model framework (Morin & Thuiller, 2009; Hobday & Lough, 2011) to predict the response of individuals or populations to a range of future climatic conditions (Clark *et al.*, 2001). Rather than simply characterizing shifts in distributions, process-based models can be used to predict key life history or population-level responses to climate change such as growth, mortality and recruitment (Morin & Thuiller, 2009). Again, process-based models are not without criticisms, for instance, the effect of climatic variation on the biological parameter may be poorly characterized, and model structure may be such that other important factors are excluded (Wilsey *et al.*, 2013).

It is likely that fishery professionals and agencies will need to consider a range of modelling approaches to direct management of fisheries under climate change (Moritz & Agudo, 2013). The use of broad bioclimatic envelope models to characterize large-scale range shifts, with the inclusion of key variables such as dispersal networks (Hein *et al.*, 2011), combined with process-based approaches used to examine the response of key species in particular sites can result in increased resolution, greatly improving the accuracy and utility of model projections (Morin & Thuiller, 2009; Wilsey *et al.*, 2013). At the heart of understanding the response of freshwater systems, biota and fisheries to climate change is the collection of high-quality information over the long term (Sharp, 1987; Elliott, 1990; Parr *et al.*, 2003).

Why is climate important to freshwater fishes and fisheries? Proximate and emergent responses

Climate has a strong influence on physical, chemical and biological processes in aquatic ecosystems (De Stasio *et al.*, 1996; Delpla *et al.*, 2009; Teixeira-de Mello *et al.*, 2009). Air and water temperatures are tightly linked (Arai, 1981; Caissie, 2006), and water temperature is the principal driver of the bulk of physicochemical and biological process in aquatic systems (Brett, 1970). This affects both abiotic and biotic conditions: due to the Arrhenius relation, the rate of a given chemical reaction doubles with every temperature increase of 10°C (Regier *et al.*, 1990). As such, almost all biological and chemical processes are influenced by temperature, from the rate of biochemical processes within aquatic organisms to trophic interactions between consumers and their prey (Dell *et al.*, 2013) through to key chemical transformations including dissolution, degradation and evaporation (Regier *et al.*, 1990). There is a long and detailed literature examining thermal effects on fishes, partly reflecting previously concerns regarding thermal pollution issues associated with human activities such as deforestation, regulation of rivers and discharge of industrial cooling waters (Beitinger *et al.*, 2000; Coutant, 2006).

Almost all fishes are obligate poikilotherms or thermal conformers: as such, almost every aspect of the ecology of an individual fish is influenced by the temperature of the surrounding water, leading Brett (1970) to refer to temperature as the master abiotic factor. Furthermore, fishes have specific temperature requirements that often differ considerably both within (*e.g.* between life stages) and between species (Pörtner & Peck, 2010; Souchon & Tissot, 2012). Enzymatic rates are temperature dependent in fishes, and as such, variation in water temperature drives variation of an individual fish's physiological and biochemical (vital) rates (Fry, 1971; Coutant, 1987; Regier *et al.*, 1990). Hence, abiotic shifts in those habitats that support freshwater fishes and their fisheries due to climate change such as changes in water temperature will result in proximate ecological responses (Fig. 7.3.1) by individual fish (Harley *et al.*, 2006) *via* physiological and behavioural shifts. For example, both spawning (Sandström *et al.*, 1997; Warren *et al.*, 2012) and the time taken for eggs to hatch (Rombough, 1997) are regulated by water temperature in many freshwater fishes, highlighting the importance of temperature as a factor regulating fish population dynamics. Once hatched, water temperature influences the activity (Koch & Wieser, 1983), metabolic demand and oxygen requirements (Clarke & Johnston, 1999) and foraging rate (Bergman, 1987) of individual fishes, as well as the availability of their prey (Heath, 2005) and activity of their predators (Vigg & Burley, 1991). These relationships with water temperature are often non-linear (Brett & Groves, 1979; Isaak & Hubert, 2004), complicating our ability to predict responses to climate change.

As might be expected, with such a fundamental influence on the ecology of individual fishes, variation in water temperature affects key life history characteristics including growth (Brett, 1979), maturation (Svedäng *et al.*, 1996), production (Schlesinger & Regier, 1982) and reproductive success (Planque & Frédou, 1999). Due to the overarching ecological importance of temperature, there is evidence for local adaption within freshwater fishes, especially those that show natal homing (Taylor, 1991; Jensen *et al.*, 2008; Eliason *et al.*, 2011), although this is not always the case (Elliott & Elliott, 2010).

There is a strong relationship between water temperature and fish mortality (Fry, 1971, Griffiths & Harrod, 2007), reflecting how predator consumption rates (Vigg & Burley, 1991), as well as resistance to pathogens (Le Morvan *et al.*, 1998) and pollutants (Reid *et al.*, 1997), co-vary with temperature. There can be strong relationships between water temperature and year-class strength and fisheries production, especially in temperate species (Shuter & Meisner, 1992; Lehtonen & Lappalainen, 1995; Jeppesen *et al.*, 2012). For instance, in the North American Great Lakes, Meisner *et al.* (1987) suggested that a 2°C increase in mean air temperature would result in an increased fisheries yield of *c.* 25%. Due to the relatively constant temperatures encountered in the tropics, variation in recruitment success and production in tropical freshwater fishes is typically associated with other climatic features such as precipitation and run-off (Welcomme, 1985).

The combination of these and other factors means that water temperature is a key influence on the biogeographical distribution of freshwater fishes and communities across different geographical locations (Tonn, 1990; Jackson *et al.*, 2001; Cussac *et al.*, 2009) or within a particular freshwater ecosystem (Fry, 1937; Magnuson *et al.*, 1979; Hamrin, 1986).

Fry (1947) outlined five main effects of temperature on fishes: controlling (metabolic and developmental rates), directing (stimulating an orientation response), limiting (affecting activity, movement and distribution), masking (blocking or affecting the expression to other environmental factors) and lethal effects that act either directly to kill the fish or indirectly as a stress effect. The temperature thresholds associated with these different effects differ between species and individuals within a species and even vary at the individual level, *e.g.* with ontogeny or condition.

The work of pioneers such as Fry (1947) and Brett (1956) showed that the response of fishes to a given temperature was strongly dependent on the history of prior exposure, *i.e.* acclimation. This complicates the provision of a single endpoint estimate for a particular species such as a lethal temperature. A very large body of work now exists on the thermal ecology of freshwater fishes (although dominated by northern hemisphere species), based on both laboratory and field studies, and has generated data on a range of ecologically relevant temperatures (Beitinger *et al.*, 2000) for different species, which describe the thermal niche either by preferred, avoidance and lethal temperatures (incipient lethal temperatures and critical maxima and minima) or by temperatures that optimize metabolic or physiological factors such as growth, digestion rate and swimming performance (Alabaster & Lloyd, 1980; Jobling, 1981; Wismer & Christie, 1987; Staaks, 1996; Beitinger *et al.*, 2000; Carveth *et al.*, 2006; Hasnain *et al.*, 2010; Shuter *et al.*, 2012; Souchon & Tissot, 2012). These temperature thresholds and optima can vary within species or even individuals for different activities (growth and maturation) or life stages (Hokanson, 1977) or time of year (Coutant, 1987).

Developing earlier work by Fry (1947, 1971), Magnuson *et al.* (1979) and Magnuson and Destasio (1997) noted that different fishes are not only adapted to particular temperatures and that their ecological performance is generally optimized close to their thermal niche (*i.e.* preferred temperature ± 2 or 5°C) but that individual fishes actively search and compete for those thermal habitats where their metabolic and behavioural performance is optimized. They went on to propose that water temperature could be considered an ecological resource

(Magnuson *et al.*, 1979; Magnuson & Destasio, 1997), with fishes competing for a particular thermal habitat where their fitness is optimized. Fishes from different evolutionary lineages cluster into broad groups regarding their thermal niches, and fishes have been grouped into broad trait-based thermal guilds according to their response, adaption and selection to different water temperatures. North American temperate freshwater fishes were classified by Magnuson *et al.* (1979) into three broad guilds. According to this classification, fishes in the coldwater guild have summer water temperature preferences between 11 and 15°C, coolwater fishes between 21 and 25°C, and members of the warmwater guild between 27 and 31°C. These guilds have been extended to include Arctic fishes (adapted to waters <10°C) (Wrona *et al.*, 2005). Hokanson (1977) outlined a similar system with three broad northern hemisphere temperate guilds: stenothermal, mesothermal and eurythermal fishes, which closely relate to Magnuson *et al.*'s (1979) cold-, cool- and warmwater guilds. The presence of fishes from multiple thermal guilds in a single waterbody increases the complexity of interspecific interactions, with fishes from similar guilds competing not only for habitat but similar food (Crowder *et al.*, 1981) and can also increase potential fishery yield. Changes in water temperature following climate change will affect habitat suitability for individuals, species and thermal guilds (Magnuson & Destasio, 1997), resulting in modified biological interactions and ultimately fisheries yields.

Much of the information on environmental tolerances of freshwater fishes and therefore their vulnerability to shifts in water temperature is from the temperate northern hemisphere (Alabaster & Lloyd, 1980; Wismer & Christie, 1987; Beitinger *et al.*, 2000; Carveth *et al.*, 2006; Souchon & Tissot, 2012). Although many of these fishes have been translocated worldwide and are exploited or invasive elsewhere (Povlsen, 1993; Soto *et al.*, 2001; Strayer, 2010), similar data are urgently needed from native fishes (Morrongiello *et al.*, 2011) including those supporting fisheries across the world either through direct experimentation (Pörtner & Peck, 2010) or by indirectly characterizing thermal boundaries (Eaton *et al.*, 1995).

Following Brett's (1970) characterizations of water temperature as the master abiotic factor, most research on climate change and fishes has focused on temperature. Temperature is just one of the number of climate-associated variables that influence aquatic ecosystems, either individually or together (Nickus *et al.*, 2010). For instance, there is a well-reported and synergistic interaction between temperature and oxygen stress (McBryan *et al.*, 2013). The solubility of oxygen in water is strongly temperature dependent (Weiss, 1970), and increases in water temperature following climate change will lead to a reduction in dissolved oxygen (DO) concentrations, reducing the carrying capacity of aquatic systems; at the extreme, this may result in an increase in the frequency and scale of fish kills (Casselman & Harvey, 1975; Ochumba, 1990; Townsend *et al.*, 1992). Fishes vary considerably in their DO requirements, both between species and different life stages (Doudoroff & Shumway, 1970; Alabaster & Lloyd, 1980), but oxygen demands increase as metabolic rates rise with temperature (Beamish, 1964; Clarke & Johnston, 1999; Pörtner, 2001). Sublethal consequences of reductions in oxygen concentrations following increases in temperature associated with climate change include modification of foraging behaviour (Rahel & Nutzman, 1994; Aku & Tonn, 1999), reproductive success (Muller & Stadelmann, 2004), growth capacity (Brett, 1979) and exposure to predation risk (Headrick & Carline, 1992).

Climate change will influence many other environmental factors, all with the potential to affect freshwater fisheries, *e.g.* cloud cover, ultraviolet radiation (UVR), lake levels, lake thermal structure, ice cover, sea levels, storm surges, precipitation, run-off, wind intensity and patterns, evaporation, river and stream discharge and the intensity and timing of flood events (Kernan *et al.*, 2010; Nickus *et al.*, 2010). Changes in temperature and these and other abiotic factors will drive changes in interspecific interactions (*e.g.* predation, competition and parasitism) (Marcogliese, 2001; Jeppesen *et al.*, 2010*a*; Dell *et al.*, 2013; Hayden *et al.*, 2013*a*), which will in turn affect growth, maturation and production, with subsequent impacts on fisheries yield.

Tropical and subtropical fishes face less variation in water temperature than their temperate counterparts (Lowe-McConnell, 1987; Meisner & Shuter, 1992), limiting the utility of the thermal guild concept across >45% of the world's land mass. Welcomme (1979) and Regier *et al.* (1989) detailed riverine tropical fish guilds based on their relative sensitivity to low DO concentrations: blackfishes are adapted to and are tolerant of low DO concentration, while whitefishes are relatively sensitive to low concentrations and undertake seasonal migrations to avoid low DO concentrations, and greyfishes are intermediate with some physiological adaptation to low DO concentrations (Dudgeon, 2000). This concept was developed further by Welcomme *et al.* (2006) who described a series of riverine fish guilds with common traits. Such trait-based analysis has considerable potential for predicting responses of fishes to climate change (Petchey & Gaston, 2002; Chessman, 2013), *e.g.* by examining how climate change will affect functional diversity (Buisson *et al.*, 2013).

Beyond the fishes that fishers and fishery professionals focus on, climate change will have impacts on the other taxa that freshwater ecosystems depend upon for their function (Woodward *et al.*, 2010). It will impact different trophic levels from viruses (Marcos-López *et al.*, 2010), parasites (Marcogliese, 2001) and primary producers (Mooij *et al.*, 2005; de Senerpont Domis *et al.*, 2013) through to top predators (Moore *et al.*, 2009), including humans (Haines *et al.*, 2006; McMichael *et al.*, 2006; Hsiang *et al.*, 2013). As individual taxa (and life stages) will show different proximate responses to climate change, resulting emergent ecological responses, *e.g.* in community-level interactions such as predator and prey relationships, competition and parasitism following climate change are likely to be complex and difficult to predict with confidence (Harley *et al.*, 2006; Blois *et al.*, 2013), especially following invasion by non-native species (Capdevila-Arguelles & Zilletti, 2008; Britton *et al.*, 2010).

The relative importance of the different top-down and bottom-up processes that influence freshwater production will probably change following climate change (Gyllström *et al.*, 2005; Wrona *et al.*, 2005). As a result, responses to climatic change in freshwater systems may be non-linear and complex (Isaak & Hubert, 2004; Jansen & Hesslein, 2004; Hobday & Lough, 2011) and could be sudden and non-reversible. Although changes in water temperature and physical stressors are likely to have a strong influence on the response of fishes to climate change, some workers have suggested that the primary mechanism by which climate change will impact fish population dynamics is through trophic interactions (Crozier & Hutchings, 2014). Any attempt to make generalized predictions regarding the likely effects of climate change on freshwater fisheries is made even more difficult due to geographical variation in climate, ecosystem function and fish communities (Hlohowskyj *et al.*, 1996; Teixeira-de Mello *et al.*, 2009; Garner *et al.*, 2014) and the humans, industries and economies involved in fisheries (Sharp, 1987; Allison *et al.*, 2007; Daw *et al.*, 2009). Furthermore, there are fundamental differences between freshwater ecosystems (*e.g.* lentic *v.* lotic systems) and the life cycles of the fishes that inhabit them (*e.g.* riverine *v.* lacustrine, pelagic *v.* benthic and main river *v.* floodplain) (Welcomme, 2001; Blanck & Lamouroux, 2007; Welcomme *et al.*, 2010).

Climate and the ecology of fishes over different levels of biological organization: recorded and predicted effects

Holt (1990) noted that the response of individual species to climate change could be summarized as 'shifting in abundance and distribution, by going extinct, or by evolving', but also highlighted that predicting which of these different responses would occur was likely to be extremely arduous. Although difficult, fishery professionals and fishers rightly want to know how climate change will affect the ecosystems and fishes that support particular fisheries or are of conservation concern. It will require research and communication between workers from a wide range of disciplines (Mykles *et al.*, 2010), and it is important to recognize that impacts will act over different levels of biological organization (McCullough *et al.*, 2009; Woodward *et al.*, 2010) from the molecular through to the individual, species and ecosystem level. Climate change has the potential to affect almost all aspects of a fish's ecology, and the current format limits the current author's capacity to do the topic full justice. In order to provide the interested reader with an non-exclusive introduction to the literature, Table 7.3.3 and the following sections provide an outline to the potential and observed impacts of climate change on fishes at the individual, population, species, community and ecosystem level.

Climate change and individual fishes

Natural selection acts principally at the level of the individual (Pianka, 1994), and as such, the impacts of climate change will be greatest at the level of the individual fish (Fig. 7.3.1 and Table 7.3.3). Climate change has the potential to affect almost every component of an individual fish's life ranging from availability and suitability of habitats; the probability of successfully hatching, surviving and reproducing; its metabolic demands; how fast and large it will grow; how much investment it makes in reproduction and growth; how it behaves; what and how much it eats; which habitats it uses; when and where it migrates; which diseases, parasites or pollutants it is exposed to; its probability of being captured by fishers.

Beyond the availability of suitable water to maintain necessary habitats, a principal response of freshwater ecosystems to climate change will be an increase in average water temperature (although some regions will cool). If water temperatures are such that thermal tolerances of particular species are exceeded, individuals of that species will not be able to survive (Preston, 2006; Moyle *et al.*, 2013). Where thermal limits are not exceeded, increases in temperature will have considerable ecological impacts. Freshwater fishes are typically poikilothermic, and their metabolic rates scale directly with water temperature (Gillooly *et al.*, 2001). With mean surface temperatures across the globe predicted to increase between 1 and 6°C by 2100, Bickford *et al.* (2010) predicted that ectotherm metabolic rates will rise between 10 and 75%, with subsequent impacts on food and oxygen consumption, excretion of waste products and the scope for growth and production.

On a global level, the temperature size rule suggests that as waters warm, the average size of fishes is likely to reduce (Daufresne *et al.*, 2009; Sheridan & Bickford, 2011; Ohlberger, 2013), with subsequent ecological impacts including reduced individual reproductive investment (Stearns & Koella, 1986; Birkeland & Dayton, 2005; Lappalainen *et al.*, 2008), increased predation risk (Lundvall *et al.*, 1999) and shifts in diet (Persson, 1988). Conversely, in those regions where individual growth is currently temperature limited, moderate warming and a longer growing season (Rouse *et al.*, 1997) will enhance growth, reproductive investment and production (Reist *et al.*, 2006*a*, *b*). An analysis of otolith growth increments using techniques developed for dendrochronology showed that subarctic lake trout *Salvelinus namaycush* showed increased growth in warmer summers (Black *et al.*, 2012). This suggests that these and other cool-adapted fishes are likely to show a positive response to climate warming to a point where increased metabolic demands outstrip the benefits of warming, assuming that other limiting factors, *e.g.* access to food, do not come into play (Barange & Perry, 2009).

Much of the focus on climate change is how increases in upper temperatures will affect fisheries, but fisheries professionals working in areas where lower temperatures are currently sufficient to cause mortality (Griffiths & Kirkwood, 1995; Sogard, 1997; Lappalainen *et al.*, 2000) may see a relaxation of this selective pressure, with increased numbers of smaller, low-condition

Table 7.3.3 Examples of potential and observed impacts of climate change on freshwater fishes and fisheries at a range of levels of biological organization

Level of organization	Issue
Sub-organismal/individual	• Epigenetic effects (Salinas & Munch, 2012)
	• Heat shock, hypoxia, UV and other stresses (Parsons, 1990; McCarthy & Houlihan, 1997; Iwama, 1998; Lund *et al*., 2002; Bancroft *et al*., 2007; Häder *et al*., 2007; Somero, 2010; Tomanek, 2010)
	• Phenotypic capacity (Pörtner & Peck, 2010; Somero, 2010)
	• Physiology (Gillooly *et al*., 2001; Pörtner & Farrell, 2008; Pankhurst & Munday, 2011; Ohlberger, 2013)
	• Growth rate and body size (Sandström *et al*., 1995; Daufresne *et al*., 2009; Reyjol *et al*., 2009; Sheridan & Bickford, 2011; Ohlberger, 2013)
	• Developmental time (Rombough, 1997; Gillooly *et al*., 2002; Mooij *et al*., 2008; Bryant, 2009; Pankhurst & Munday, 2011)
	• Metabolic rate and energetic requirements for growth and reproduction (Fry, 1971; Shuter & Post, 1990; Clarke & Johnston, 1999; Gillooly *et al*., 2001; Hölker, 2003)
	• Maturation, sex determination, reproductive investment and behaviour (Vlaming, 1972; Hokanson, 1977; Gillet *et al*., 1995; Sandström *et al*., 1997; Jager *et al*., 1999; Gillet & Quétin, 2006; Reyjol *et al*., 2009; Strüssmann *et al*., 2010; Pankhurst & Munday, 2011)
	• Prey availability, foraging capacity and diet (Adams *et al*., 1982; Persson, 1986, 1990; Huusko *et al*., 1996; Taniguchi *et al*., 1998; Humphries *et al*., 1999; Durant *et al*., 2007; Anneville *et al*., 2009; Hayden *et al*., 2013*a, b*)
	• Migration (Cooke *et al*., 2004; Daufresne & Boët, 2007; Bryant, 2009)
	• Mortality (Casselman & Harvey, 1975; Griffiths & Kirkwood, 1995; Lappalainen *et al*., 2000; Petersen & Kitchell, 2001; Charnov & Gillooly, 2004; Griffiths & Harrod, 2007)
	• Predation risk (Adams *et al*., 1982; Bystrom *et al*., 2007)
	• Immune response, disease and parasitism (Snieszko, 1974; Chubb, 1976; Marcogliese, 2001; Croisetière *et al*., 2010; Macnab & Barber, 2012)
	• Susceptibility to angling-associated stress (Huntingford *et al*., 2006; Gale *et al*., 2013)
	• Exposure to stressors and uptake of contaminants (Bullock & Coutts, 1985; Coutant, 1985; Schindler *et al*., 1996; Reid *et al*., 1997; Zagarese & Williamson, 2001; Wrona *et al*., 2006*a*; Reist *et al*., 2006*b*; Häder *et al*., 2007; Schiedek *et al*., 2007; Noyes *et al*., 2009)
Population	• Modification of abiotic cues (Humphries *et al*., 1999; Ahas & Aasa, 2006; Shuter *et al*., 2012)
	• Habitat suitability (Coutant, 1990; Magnuson *et al*., 1990, 1997; De Stasio *et al*., 1996; Lappalainen & Lehtonen, 1997; Hilborn *et al*., 2003; Mohseni *et al*., 2003; Fang *et al*., 2004*a, b, c*; Lyons *et al*., 2010; Elliott & Bell, 2011)
	• Phenotypic shifts (Jensen *et al*., 2008; Hering *et al*., 2010; Strüssmann *et al*., 2010; Gregersen *et al*., 2011; Forster *et al*., 2012; Crozier & Hutchings, 2014)
	• Phenology, *e.g.* of migration, spawning and hatching (Cooke *et al*., 2004; Juanes *et al*., 2004; Ahas & Aasa, 2006; Mooij *et al*., 2008; Bryant, 2009; Wedekind & Kung, 2010; Shuter *et al*., 2012; Warren *et al*., 2012)
	• Life history characteristics (Heibo *et al*., 2005; Jensen *et al*., 2008; Lappalainen *et al*., 2008)
	• Prey availability and foraging capacity (Persson, 1986, 1990; Huusko *et al*., 1996; Humphries *et al*., 1999; Durant *et al*., 2007; Anneville *et al*., 2009; Dell *et al*., 2013; Hayden *et al*., 2013*a, b*)
	• Size and age structure (Gillet *et al*., 1995; Jeppesen *et al*., 2012; Ohlberger, 2013)
	• Sex ratio (Craig *et al*., 1996; Davey & Jellyman, 2005; Ospina-Álvarez & Piferrer, 2008; Baroiller *et al*., 2009; Strüssmann *et al*., 2010; Wedekind *et al*., 2013)
	• Recruitment, population dynamics and potential fishery yield (Lehtonen & Lappalainen, 1995; Lappalainen *et al*., 1997; Grenouillet *et al*., 2001; Casselman, 2002; Isaak & Hubert, 2004; Reist *et al*., 2006*b*; Lehtonen *et al*., 2009; Pörtner & Peck, 2010; Jeppesen *et al*., 2012)
	• Evolution and loss of local adaptation (Merilä, 2012; Crozier & Hutchings, 2014), *e.g.* thermal tolerance (Wohlschlag, 1957; Hubbs, 1964; Holt, 1990; Carvalho, 1993; Jensen *et al*., 2008; Willis & Bhagwat, 2009; Pörtner & Peck, 2010; Eliason *et al*., 2011; McBryan *et al*., 2013; Whitney *et al*., 2013)
	• Distributional shifts and population fragmentation (Rahel *et al*., 1996; Hari *et al*., 2006; Comte & Grenouillet, 2013; Roberts *et al*., 2013)
Species	• Distributional shifts, colonisation, local extirpation and extinction (Johnson & Evans, 1990; Magnuson *et al*., 1990, 1997; Xenopoulos *et al*., 2005; Bystrom *et al*., 2007; Lassalle & Rochard, 2009; Lyons *et al*., 2010; Booth *et al*., 2011; Wenger *et al*., 2011*a, b*; Isaak *et al*., 2012*b*; Comte & Grenouillet, 2013; Comte *et al*., 2013; Moyle *et al*., 2013; Tedesco *et al*., 2013)
	• Intraspecific interactions, *e.g.* selection of particular genotypes (Holt, 1990; Carvalho, 1993; Hutchinson *et al*., 2003; Eliason *et al*., 2011; Whitney *et al*., 2013)
	• Phenotypic shifts (Blanck & Lamouroux, 2007; Forster *et al*., 2012; Crozier & Hutchings, 2014)
Community and ecosystem	• Habitat degradation (Coutant, 1990; Magnuson *et al*., 1990, 1997; De Stasio *et al*., 1996; Lappalainen & Lehtonen, 1997; Mohseni *et al*., 2003; Fang *et al*., 2004*a, b, c*; Lyons *et al*., 2010; Elliott & Bell, 2011; Pratchett *et al*., 2011)
	• Interspecific interactions (De Stasio *et al*., 1996; Jeppesen *et al*., 2010*a*; Blois *et al*., 2013; Dell *et al*., 2013; Hayden *et al*., 2013a)
	• Stenothermal specialist/eurythermal generalist ratio (Daufresne & Boët, 2007; Jeppesen *et al*., 2012)
	• Exposure to pollutants and contaminants (Noyes *et al*., 2009; Paerl & Huisman, 2009; Grimalt *et al*., 2010)
	• Changes in fish community structure (Magnuson *et al*., 1997; Carveth *et al*., 2006; Daufresne & Boët, 2007; Jeppesen *et al*., 2010*a*, 2012; Skeffington *et al*., 2010, Hayden *et al*., 2013*a*) including loss of functional diversity and biotic homogenization (Buisson *et al*., 2013).
	• Invasive species (Johnson & Evans, 1990; Dukes & Mooney, 1999; Bierwagen *et al*., 2008; Capdevila-Arguelles & Zilletti, 2008; Peterson *et al*., 2008; Walther *et al*., 2009; Britton *et al*., 2010; Carpenter *et al*., 2011)
	• Changes in food web structure (Beklioglu *et al*., 2007; Durant *et al*., 2007; Teixeira-de Mello *et al*., 2009; Jeppesen *et al*., 2010*a*; Thackeray *et al*., 2013) and possible switch to increased omnivory in fishes (Jeppesen *et al*., 2010*a*; Moss, 2010*a*)
	• Ecosystem function and provision of goods and services (Regier *et al*., 1990; Wrona *et al*., 2006*b*; Jeppesen *et al*., 2010*a*), *e.g.* production and yield (O'Reilly *et al*., 2003; O'Connor *et al*., 2009) or provision of recreation (Nelson *et al*., 2013)
	• Capacity of protected areas to conserve fishes (Hole *et al*., 2009; Prowse *et al*., 2009; Hermoso & Clavero, 2011; Peterson *et al*., 2013)

individuals surviving the winter. This has implications for fishery performance as well as population- and community-level interactions such as intra- and intraspecific competition and the relative success of invasive species (Johnson & Evans, 1990).

Climate change will change the concentration of ultraviolet (UV) encountered by individual fishes through their life cycle by shifts in stratospheric ozone concentrations, changes in cloud, vegetation and ice cover or modification in water colour or depth, with a wide range of potential ecological impacts (Zagarese & Williamson, 2001; Wrona *et al*., 2006*a*; Bancroft *et al*., 2007; Häder *et al*., 2007). At the individual level, increased UV could lead directly to egg and larval mortality (Williamson *et al*., 1997), as well as adult and juvenile sunburn (Bullock & Coutts, 1985). Indirect impacts of increased UV include oxidative stress, phototoxicity and photosensitization (Zagarese & Williamson, 2001), potentially resulting in reduced individual investment in growth due to investment in cellular and behavioural UV protection (Wrona *et al*., 2006a).

Population-level responses to climate change

In contrast to evolutionary biology, in fisheries biology, the population has historically been the focal entity (Cury *et al*., 2008), and it is likely that population-level responses to climate change will be of most interest to the majority of fishery professionals or fishers. The population-level effects of climate change on freshwater fishes are numerous (Table 7.3.3) and can be considered as emergent properties of individual-level responses (Fig. 7.3.1), which together affect the balance of recruitment, mortality, growth and reproduction of a given fish population. This in turn controls the abundance and the distribution of life history characteristics in a given population of fishes (Pörtner & Peck, 2010) and its subsequent performance as a fishery (Welcomme, 2001). Assessments of population-level responses to climate change are important as they not only provide an indication of the capability of a species to withstand climate change and maintain fisheries throughout its range but also the extent of adaptive scope within a species (McCullough *et al*., 2009), important for predicting responses to future change.

Shuter and Meisner (1992) suggested that habitat suitability ultimately controls abundance at the population level. In terms of climate change, this will probably reflect water availability and temperature, although other factors will also be important, including DO concentrations (Magnuson *et al*., 1997), food availability (Durant *et al*., 2007) and enemy-free space (Gaeta *et al*., 2014) that together permit 'good growth' (Stefan *et al*., 2001). As many species require different habitats throughout their life cycle, maximizing habitat diversity is likely to provide a buffer to climatic change (Hilborn *et al*., 2003).

Population dynamics in some freshwater fishes are driven by intraspecific interactions, for instance, by strong asymmetries in foraging abilities between conspecifics of different sizes (Hamrin & Persson, 1986) or cannibalism of juveniles by large-bodied adults (Claessen *et al*., 2000). Changes in water temperature and the phenology of early life stages may affect the strength of density-dependent regulation, year-class strength and the strength and direction of intraspecific interactions (Skov & Koed, 2004), with subsequent cascading effects on fisheries (Helminen *et al*., 1997).

Freshwater fish populations are constrained in their capacity to migrate to more suitable habitats if conditions become unsuitable. Freshwater habitats are typically part of dendritic river systems (Brown & Swan, 2010), restricting movement to within a given catchment (Hein *et al*., 2011), while some standing waters are completely isolated (Welcomme, 2001), preventing natural migration. Carpenter *et al.* (1992) noted that many major river systems have an east–west drainage pattern, limiting the capacity of riverine fishes in such systems to migrate polewards to avoid thermal stress (Hickling *et al*., 2006), although this is not the case globally (Heino *et al*., 2009). Within a river system, thermal refuges will often be present in river sections located at higher elevations, and the elevational shifts predicted as a response to warming (Meisner, 1990; Jager *et al*., 1999) have been reported from individual populations (Hari *et al*., 2006; Almodóvar *et al*., 2012; Comte & Grenouillet, 2013). Migrations may fail, however, as natural and anthropogenic barriers prevent fish movements (Hein *et al*., 2011; Isaak & Rieman, 2012) or because other features of the habitats located at higher elevations are unsuitable. Hari *et al.* (2006) noted that even if fishes are able to undertake an upward habitat shift, it represents an overall decrease in the population due to the reduction in available habitat (Shuter & Meisner, 1992). Furthermore, as populations of cold-adapted river fishes are forced into isolated thermal refugia, they will probably become subject to increased levels of population fragmentation (Rahel *et al*., 1996; Roberts *et al*., 2013).

Parasites and diseases (Barber & Poulin, 2008) play important roles in regulating fish populations and are sensitive to abiotic conditions. Marcogliese (2001) noted that parasites of freshwater fishes will be affected by climate change, both directly, *e.g.* by shifts in water temperature (Swennen *et al*., 1979), and indirectly, *e.g. via* the effect of climate change on host abundance and distribution (Macnab & Barber, 2012).

Changes in exposure to UV and contaminants associated with climate change (Zagarese & Williamson, 2001; Schiedek *et al*., 2007; Noyes *et al*., 2009) may have multiple population-level effects on fishes. This may include life cycle disruption, where sensitive life stages such as eggs and larvae (Bancroft *et al*., 2007) are lost, even though larger-bodied individuals are not impacted (Williamson *et al*., 1997), resulting in the need for stocking of larger-sized individuals to maintain fisheries operations. The negative impacts of UV on individual growth (Bancroft *et al*., 2007) are likely to result in decreased productivity at the population and community level in those systems where exposure to increased UV concentrations occurs (Wrona *et al*., 2006*a*) with subsequent consequences on fisheries (Reist *et al*., 2006*c*).

Species-level responses

Responses at individual and population level will combine to affect how fish species responds to climate change across their distribution, which will interest those fishery professionals and

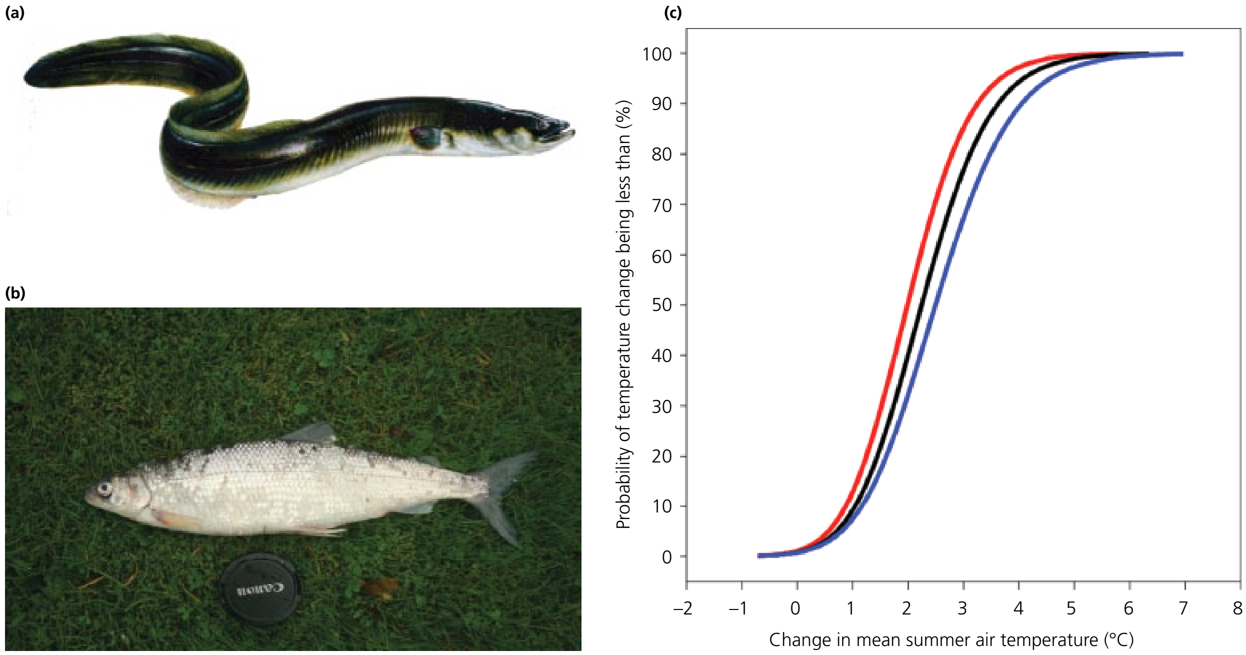

Figure 7.3.2 Winners and losers. Lough Neagh is a large (383 km^2) lake in Northern Ireland that supports a large freshwater fishery that targets the (a) warmwater *Anguilla anguilla* and to a lesser extent (b) *Coregonus autumnalis*. Both species are of conservation concern but are likely to respond very differently to climate change. Currently, summer temperatures are at a threshold for both species: *C. autumnalis* are on a metabolic knife-edge during the hottest summers, while *A. anguilla* growth is currently temperature limited. (c) The probability of different changes in air temperature in the Lough Neagh catchment in the period 2040 to 2069 under three different SRES scenarios (—, low B1; —, medium A1B; —, high A1F1; see text for definition of scenarios). Whatever the scenario, it is clear that summer water temperatures are likely to rise by 1.5–2.5°C from the 1961 to 1990 baseline, probably benefiting the fishery in terms of increased *A. anguilla* growth (assuming that deoxygenation does not become an issue in the extremely eutrophic lake). Due to the lack of a thermal refuge, it is likely that future summers may be too hot for the cold-adapted *C. autumnalis*, and the last viable population of this species in Europe may be lost (Harrod *et al.*, 2002). Data from UKCP09 (http://ukclimateprojections-ui.defra.gov.uk).

fishers working to manage, conserve and exploit fishes at the local, national and international scales. Understanding whether a species will be a winner (*i.e.* resist climate change) or a loser (*i.e.* undergo a decline) under future climates (Fig. 7.3.2) is a complex undertaking (Moritz & Agudo, 2013), with a range of influences at work (Table 7.3.3), further complicated by the potential for widely distributed fishes to show ecosystem-specific growth responses to climatic variation (Richard & Rypel, 2013).

Large zoogeographical differences exist in the distribution of freshwater fishes. Certain species are restricted to particular climatic zones, both globally (Lévêque *et al.*, 2008) and regionally (Cussac *et al.*, 2009), representing the influences of past geological, climatic and evolutionary processes (Heino *et al.*, 2009). In terms of current distribution patterns, fishes are adapted to a number of climate-relevant variables that vary regionally (Schultz, 2002; Chu *et al.*, 2005; Heino *et al.*, 2009), including temperature and precipitation, which are subject to modification by climate change. One way that adaption is expressed is through ecological phenology, and this plays an important role in setting species' zoogeographical boundaries (Shuter & Post, 1990; Shuter *et al.*, 2012). In many temperate fishes, seasonal cycles displayed by fishes (*e.g.* migration, spawning and growth) follow patterns of water temperature or day length (Helfman *et al.*, 2009), although changes in water level associated with snowmelt or seasonal storms can also be an important cue for fishes at higher latitudes or altitudes (Fausch *et al.*, 2001). In tropical systems, seasonality largely reflects rainfall patterns (Welcomme, 1979, 1985; Lowe-McConnell, 1987). The predicted impacts of climate change are such that some of the regional controls on fish distribution will lessen or possibly break down, resulting in widespread redistribution of those freshwater fishes that are currently constrained by climate.

Over the past 30 years, *c.* 70 studies have used various modelling approaches to predict the effect of climate change on the distribution of freshwater fish species (Comte *et al.*, 2013). These models have suggested widespread shifts in the availability of suitable habitat and the future distribution of species, including range expansions and contractions, regional extirpation and even global extinction of some species (Xenopoulos *et al.*, 2005). Overall, these studies have predicted that the range of most coldwater species will probably contract or shift to a higher altitude or latitude, while that of coolwater fishes could expand or contract. Warmwater fishes are generally predicted to expand their distributions.

A far smaller number ($n = 11$) of observational studies have examined shifts in species distributions associated with recent climate change (Comte *et al.*, 2013). Such shifts have occurred as follows: in Great Britain, 15 stream fishes shifted their northern range margin polewards by 47 km and their mean altitude by

33 m over 25 years (Hickling *et al*., 2006). Elsewhere in Europe, brown trout *Salmo trutta* have shifted towards higher elevations in the Pyrenees (Almodóvar *et al*., 2012) and the Swiss Alps (Hari *et al*., 2006), and diadromous fishes have shifted their distributions, with 14 species being lost from catchments across Europe (Lassalle & Rochard, 2009).

Comte *et al.* (2013) examined predicted and observed changes in 183 species of freshwater fishes. Although there was a strong geographical (temperate northern hemisphere) and taxonomic (salmonid) bias, Comte *et al.* (2013) found general support for the predictive studies, with a positive correlation between predicted and observed changes in habitat suitability at the family level. They reported that estimates of observed effects of climate change on habitat suitability were almost eight times higher than those predicted, but are extremely variable. There was no evidence for an overall directional shift in salmonids, even though these are commonly identified as being particularly sensitive to climate change.

Although some predictive studies have suggested that freshwater fishes will show extremely marked responses to climate change, the limited literature published to date does not provide any evidence that this has occurred. This may reflect the influence of several non-exclusive factors including the poor performance of predictive models (Elith *et al*., 2010) or the existence of unrecognized adaption and plasticity in freshwater fishes (Crozier & Hutchings, 2014). Conversely, and more likely, a marked lack of data (Comte *et al*., 2013) and the lag between environmental change and species responses (Magnuson, 1990) mean that changes have or will occur and we lack the necessary statistical power to identify them.

Comte *et al.* (2013) effectively represent the state of our understanding of how freshwater fishes are responding to climate change in terms of redistribution at a global scale. Its value extends beyond a much-needed review and a general reaffirmation of predicted patterns, as it quantifies the geographic bias of studies examining the impact of climate change on freshwater fishes. Of the studies examined, the great majority related to the Palearctic and Nearctic regions, and only a single paper was available in the literature examining distributional changes in each of the Australasian, Oriental, Neotropical and Afrotropical biogeographical realms. In terms of the global distribution of freshwater fishes and fisheries, this is clearly not representative and extremely worrying. As a community, we have been discussing climate change and fishes for more than three decades: this lack of knowledge needs to be forestalled before the worst impacts of climate change are felt.

Many of the regions where data are lacking support elevated levels of endemism, and this may reflect specialization and adaptation to local conditions (Bootsma & Hecky, 2003; Pratchett *et al*., 2011; Filipe *et al*., 2012). Such species may be unable to adapt to climate change (Thieme *et al*., 2010), allowing a foothold to generalist invasive species that are likely to be the winners under climate change (Moyle *et al*., 2013). Conversely, endemic fishes are adapted to deal with considerable abiotic variability and may therefore be able to resist a certain level of climate change (*e.g.* Australia; Costelloe *et al*., 2010; Morrongiello *et al*., 2011).

Given the scale of predicted shifts in precipitation and temperature (Tables 7.3.1 and 7.3.2), the largest impact of climate change on freshwater fisheries during the near future is likely to be felt in systems where water availability falls below a threshold required to support particular species (Xenopoulos *et al*., 2005). The other major impact will be felt by the cold-adapted fishes that natively inhabit rivers and lakes in the northern hemisphere (Sharma *et al*., 2007) and support important fisheries throughout their distribution (Craig, 1984; Reist *et al*., 2006*c*). These fishes are adapted to harsh winter conditions (Brännäs & Wilund, 1992; Shuter *et al*., 2012; Hayden *et al*., 2013*b*) and are extremely sensitive to elevated water temperatures (Fry, 1937; Edsall & Colby, 1970; Lappalainen & Lehtonen, 1997; Lyytikainen *et al*., 1997). How these cold-adapted species will respond to the relaxation of the adverse conditions that drove their evolution is unknown, but they may be susceptible to invasion by cool- or warmwater species previously unable to endure harsh winter conditions (Hayden *et al*., 2013*c*). It is likely that locally adapted coldwater fishes have some inherent adaptive capacity to respond to increased temperatures (Jensen *et al*., 2008). Indeed, extant populations of the most northern freshwater fishes, the Arctic charr *Salvelinus alpinus* and the Arctic cisco *Coregonus autumnalis*, are found far to the south of the Arctic today, suggesting that there is some capacity to adapt in these coldwater fishes, assuming that temperature and oxygen conditions remain suitable (Harrod *et al*., 2002; Winfield *et al*., 2010) and that interactions with cool- and warmwater fishes do not lead to extirpation. Once habitats are lost (Preston, 2006) and species adapted to warmwater are established, however, changes may be such that once widely distributed species are lost from large areas and are relegated to coldwater refugia (*e.g.* high-altitude sections of rivers and mountain lakes) (Skeffington *et al*., 2010). Due to the conservation and fisheries value of these coldwater species, intervention and translocation are likely in order to conserve genetically relevant populations (Rahel *et al*., 2008, Morrongiello *et al*., 2011).

Verdonschot *et al.* (2010) noted that many stream taxa are probably adapted to dynamic conditions that characterize river ecosystems and as such are likely to be resilient to some change, *e.g.* at the habitat scale. They further note that major shifts, such as changes in the phenology of snowmelt and the timing of associated high-flow conditions, may result in the loss of specific taxa. Verdonschot *et al.* (2010) warn that the loss of native taxa combined with more dynamic, less predictable conditions may further increase the suitability of impacted riverine habits to invasion by generalist non-native species (Bierwagen *et al*., 2008; Rahel & Olden, 2008; Britton *et al*., 2010).

The potential for climate change to aid the redistribution and establishment of fishes that are non-native and potentially invasive is of obvious concern (Johnson & Evans, 1990; Rahel & Olden, 2008), especially given their often large impacts on receiving waters (Britton *et al*., 2010; Cucherousset & Olden, 2011). It is clear that many such species have undergone intensive shifts in their distribution in the past century, either through invasion or by intentional human introductions. To date, it has been difficult to model how these species' distributions will respond to climate change, but recent developments show great promise (Elith *et al.*, 2010).

Wide-scale evidence for species-level evolutionary adaptation to climate change is still largely lacking (Merilä, 2012; Crozier & Hutchings, 2014). Evidence for transgenerational plasticity in thermal responses, however, was recently reported from the sheepshead minnow *Cyprinodon variegatus* (Salinas & Munch, 2012). This exciting result suggests that some fish may show epigenetic responses to climate change, allowing parents to rapidly respond to shifts in conditions and influence the fitness of their progeny.

Community- and ecosystem-level responses to climate change

Freshwater fisheries often target multiple species (Allan *et al.*, 2005, Welcomme *et al.*, 2010), and many fishers and fishery professionals are interested in the impacts of climate change at the community or ecosystem level. In terms of how freshwater fisheries will respond to climate change, it is important to recognize that freshwater ecosystems and the fish communities inhabiting them consist of an assemblage of species, populations and individuals that differ regionally (Lévêque *et al.*, 2008; Jeppesen *et al.*, 2010*a*) and that will display their own responses to climate change (Mooij *et al.*, 2005; Woodward *et al.*, 2010; de Senerpont Domis *et al.*, 2013). Understanding such community-level response to climate change is important in terms of successful fisheries management, especially with shifts to increasingly holistic approaches, *e.g.* the ecosystem approach to fisheries management (FAO Fisheries Department, 2003; Beard *et al.*, 2011). Fishery professionals should be aware that inherent differences in community structure and ecosystem function between different climatic regions may limit the utility of studies from dissimilar climatic zones to understand probable vulnerability to climate change (Ibañez *et al.*, 2009; Teixeira-de Mello *et al.*, 2009; Jeppesen *et al.*, 2010*a*; González-Bergonzoni *et al.*, 2012). Furthermore, as climate change breaks down the predictability between species responses to variation in abiotic and biotic drivers, the capacity to predict the future response of a particular ecosystem will lessen (Kundzewicz *et al.*, 2008).

Climate change will affect interspecific interactions such as predation (Jeppesen *et al.*, 2010*a*), competition (Taniguchi *et al.*, 1998), disease (Marcos-López *et al.*, 2010), parasitism (Marcogliese, 2001; Macnab & Barber, 2012) and facilitation (Bruno *et al.*, 2003), both directly through the modification of abiotic conditions and indirectly as the species pool changes (Meisner *et al.*, 1987; Daufresne & Boët, 2007; Jeppesen *et al.*, 2010*a*). Shifts in the competitive abilities (Persson, 1986) and year-class strength of species previously constrained by temperature may have significant impacts where interspecific competition or predation is important in structuring fish communities (Persson, 1988; Byström & García-Berthou, 1999). Although changes in temperature are extremely important in terms of biological interactions (Dell *et al.*, 2013), other factors are important too, for example, predation pressure can increase as water levels fall (Ghent & Hanna, 1999; Gaeta *et al.*, 2014).

The importance of bottom-up processes may change in freshwater ecosystems following climate change, due to changes in physico-chemistry or in taxa at the base of the food web (Durant *et al.*, 2007; de Senerpont Domis *et al.*, 2013), which have the capacity to cascade up to fish communities and the wider ecosystem, leading to changes in ecosystem function (Meyer *et al.*, 1999; Winder & Schindler, 2004*a*; Durant *et al.*, 2007; Thackeray *et al.*, 2010, 2013). Shifts in phenology driven by climate change (Shuter *et al.*, 2012) may affect the variable components of freshwater communities differently, leading to poor or even failed recruitment or even the desynchronization of the entire food webs (Thackeray *et al.*, 2010, 2013) through trophic mismatch (Durant *et al.*, 2007), with potential impacts on fisheries productivity (O'Reilly *et al.*, 2003). Conversely, climate change may affect top-down regulation by fishes (Gyllström *et al.*, 2005), leading to changes in ecosystem function, such as the increased levels of omnivory recorded from warmer lakes (Jeppesen *et al.*, 2010*b*; González-Bergonzoni *et al.*, 2012), with implications for potential fisheries productivity.

The distribution, mobility and availability of contaminants including persistent organic pollutants and heavy metals are likely to shift following climate change (Reid *et al.*, 1997; Schiedek *et al.*, 2007; Noyes *et al.*, 2009; Grimalt *et al.*, 2010), with obvious potential detrimental effects on ecosystem health and fisheries. At an ecosystem level, changes in UV concentrations may also affect the fish community both directly through its negative effect on individual growth (Bancroft *et al.*, 2007), with consequent impacts on productivity (Wrona *et al.*, 2006*a*) and fisheries (Reist *et al.*, 2006*c*), and indirectly through its effects on lower trophic levels including primary producers as well macroinvertebrates and zooplankton (Häder *et al.*, 2007).

The principal impacts of climate change on fisheries at the community and ecosystem level will probably be changes in community structure, as species are lost and gained reflecting their relative capacity to tolerate conditions following climate change, and in fish yield, as the abundance and growth of fishes respond to climate change (Magnuson *et al.*, 1997; MacKenzie *et al.*, 2007; McCullough *et al.*, 2009). Fishery professionals should expect marked shifts in fish community structure in the future. In temperate systems, coldwater species are likely to be lost, and the relative contribution of warmwater fishes to the overall fish community will increase (Taniguchi *et al.*, 1998; Daufresne *et al.*, 2003; Daufresne & Boët, 2007; Jeppesen *et al.*, 2012), including invasive and non-native fishes (Johnson & Evans, 1990; Rahel & Olden, 2008; Walther *et al.*, 2009), with subsequent impacts on ecosystem function (Vander Zanden *et al.*, 1999). These systems, like others elsewhere in the world, probably face a homogenization of community structure and functional diversity (Moyle & Marchetti, 2006; Buisson & Grenouillet, 2009; Pool & Olden, 2012; Buisson *et al.*, 2013).

Invasion of freshwater ecosystems associated with climate change will include both non-native species (Rahel, 2002) and native fishes that were previously unable to maintain populations due to tolerance to local conditions, such as winter temperature or flood regimes (Scott & Helfman, 2001). Some lineages or communities of fishes are ecologically flexible, which provides protection from some effects of climate change and invasive species, *e.g.* in terms of their capacity to shift diet (Bourke *et al.*, 1999) or respond to extreme events (Costelloe *et al.*, 2010). Invasion will undoubtedly lead to ecological changes in many cases (Reinthal & Kling, 1994; Vander Zanden *et al.*, 1999; Wenger *et al.*, 2011*a*) especially as the ecosystem-level impacts of invasive species may be magnified under climate change (Rahel & Olden, 2008). The threats associated with invasive species extend beyond fishes (Dukes & Mooney, 1999; Rahel & Olden, 2008), including phytoplankton (Wiedner *et al.*, 2007), plants (Bickel & Closs, 2008), invertebrates (Jackson *et al.*, 2012) and zooplankton (Strecker & Arnott, 2008). As the proportion of non-native species increases in a system, the threat of invasional meltdown grows (Simberloff & Von Holle, 1999) and may have large potential impacts on fisheries and ecosystem function.

Predicting how ecosystems will respond to climate change is inherently difficult. In the most extreme case, there is the possibility that in the future, fishery professionals and fishers will face climates, freshwater ecosystems and fish communities without current analogues (Williams & Jackson, 2007; Strayer, 2010). As precipitation patterns change and evaporation rates increase, gradual shifts in the overall ecosystem state may occur (Brown *et al.*, 1997; Folke *et al.*, 2004), such as the loss of aquatic systems in arid and semi-arid regions (García-Ruiz *et al.*, 2011; Hermoso & Clavero, 2011; Filipe *et al.*, 2012). Conversely, rapid shifts in ecosystem state may occur as key climatic thresholds are met, such as air temperatures rising above freezing point (ACIA, 2004). In most cases, however, the impacts of climate change will be less marked but will result in shifts in ecosystem-level characteristics, including biological and functional diversity (Buisson *et al.*, 2013) and overall function (Chapin *et al.*, 2000) including the level (O'Reilly *et al.*, 2003) and type of fishery productivity (Meyer *et al.*, 1999; Hamilton, 2010; Jeppesen *et al.*, 2010*a*; Grimm *et al.*, 2013). Shifts in ecosystem function in freshwater ecosystems will not only impact fisheries but will extend to feedbacks affecting the global climate system itself (Hamilton, 2010; Grimm *et al.*, 2013).

Climate change and freshwater habitats

Worldwide, fisheries target fishes inhabiting both natural (rivers, lakes and wetlands) and artificial habitats such as reservoirs (Lowe-McConnell, 1987; Straškraba, 2007). Fresh waters can be widely considered useful sentinels of environmental change (Adrian *et al.*, 2009; Williamson *et al.*, 2008) but vary widely according to their geographical location, *e.g.* by ecoregion (Schultz, 2002), latitude or elevation (Lewis 1996, 2000, 2011; Amarasinghe & Welcomme 2002). Regional differences extend beyond the marked latitudinal and seasonal differences in solar radiation and precipitation (Schultz, 2002). For example, limnological contrasts exist between tropical and temperate lakes (Lewis, 2000), and lake origin also has a large influence on limnology (Welcomme, 2001), as well the type and intensity of human utilization. Within lakes, the impacts of climate change will probably differ between different lake habitats and their fisheries, *e.g.* littoral, pelagic and profundal zones. Rivers are characteristically diverse habitats (Rosgen, 1994), and their form and function can vary both seasonally and across different geographical scales, ranging from the broad, *e.g.* at the level of continental or climatic zones, through to the narrow scale, such as the sub-catchment level (Welcomme, 1985; Minshall, 1988; Ward *et al.*, 2002).

The impacts of climate change on fresh waters will therefore vary both between and within drainage basins, with specific impacts depending on a range of factors including the geographical location, catchment geomorphology (Rosgen, 1994), hydrology (Meyer *et al.*, 1999; Millennium Ecosystem Assessment, 2005; Kundzewicz *et al.*, 2007) and the origins of the water supply (Meyer *et al.*, 1999; Verdonschot *et al.*, 2010). Although responses to threats such as climate change are typically managed at a national level, national boundaries may be poor predictors of the impacts of climate change. Many large lakes and rivers can extend across multiple international borders, and some significant freshwater fisheries are found in systems that straddle different climatic zones (European Environment Agency, 2012*a*) including the great rivers of Eurasia (*e.g.* Ob and Lena) that include Arctic and temperate regions in their catchments, the Mekong which drains the Tibetan Plateau and tropical Southeast Asia (Zhang *et al.*, 2007; Prathumratana *et al.*, 2008) and the Murray–Darling River system which drains temperate and subtropical regions of Australia (Humphries *et al.*, 1999; Pratchett *et al.*, 2011). Even within relatively small geographical areas (*e.g.* England and Wales), rivers can differ in their response to changes in air temperature (Garner *et al.*, 2014).

Jeppesen *et al.* (2012) suggested that the impacts of climate change will likely be most apparent in those systems that have been most impacted by anthropogenic activities (*e.g.* eutrophication). As such, in order for the fishery professional to have a consideration of the probable impacts of climate change on a particular fishery, they will also need to consider the potential for climate change to interact with other stressors associated with human activities (Carpenter *et al.*, 2011), including over-extraction of water (Gleeson *et al.*, 2012), over-exploitation (Allan *et al.*, 2005), habitat degradation (Pratchett *et al.*, 2011), ecosystem modification (Ward, 1998; Allan, 2004), invasive species (Baxter *et al.*, 2007) and reduction in water quality (Tibby & Tiller, 2007; Clews *et al.*, 2010).

Recent climate change has affected freshwater habitats worldwide including shifts in temperature as well as precipitation and wind patterns and intensity, evaporation rates, river flow and lake levels (Carpenter *et al.*, 1992; Shuter & Meisner, 1992; Kundzewicz *et al.*, 2007, 2008; Parry *et al.*, 2007). A summary of observed impacts with direct relevance to freshwater fisheries, based on very broad geographical regions, is given in Table 7.3.4. Note that this is non-exhaustive and is limited by a lack of data for large parts of the world including the Arctic, Asia and Africa.

Table 7.3.4 Summary of observed effects of climate change on key characteristics of freshwater ecosystems at the level of broad climatic regions. Note that this probably oversimplifies the situation, *e.g.* rivers in tropical areas vary significantly according to the particular climatic zone in which they are found (the wet or wet–dry tropics; Latrubesse *et al.*, 2005). Note that for brevity's sake, IPCC chapters or review articles are referred to where possible

Region	Component	Observed changes
Arctic, subarctic and boreal regions (Nijssen *et al.*, 2001; Barnett *et al.*, 2005; Symon *et al.*, 2005; Wrona *et al.*, 2005, 2006*b*; Anisimov *et al.*, 2007; Christensen *et al.*, 2007; Kundzewicz *et al.*, 2007, 2008; Rosenzweig *et al.*, 2007*b*; Trenberth *et al.*, 2007; Bates *et al.*, 2008; Adrian *et al.*, 2009; Kaufman *et al.*, 2009; Moore *et al.*, 2009; Weyhenmeyer *et al.*, 2011; European Environment Agency, 2012*a*; Blunden & Arndt, 2013; Vincent *et al.*, 2013)	Air temperature	• Air temperatures have increased across the region and at a rate (*c.* ×2) and extent greater than the global average (ACIA, 2004; Trenberth *et al.*, 2007) • Overall increase in air temperatures (over land) up to 5°C across the region during 20th century (ACIA, 2004) • Increases have been more marked in winter than summer, *e.g.* winter temperatures increased by 3–4°C in last half century (Alaska, west Canada and interior of North Asia) (ACIA, 2004; Anisimov *et al.*, 2007) • Increased frequency of mild winter days over the past 80 years (Symon *et al.*, 2005) • Reconstruction of 2000 year-long climate record for the Arctic showed that four of the five warmest decades during this period occurred between 1950 and 2000 (Kaufman *et al.*, 2009)
	Precipitation and water availability	• Increased by 8% across the Arctic in the 20th century (although spatially very variable), with an increased contribution of rain *versus* snow (ACIA, 2004)
	Ice and snow	• Decreased snow coverage, with a *c.* 10% decline in the last 30 years across the wider region • Spring melt is occurring earlier (Bates *et al.*, 2008) • Timing of snow-free conditions in Eurasia and North America has advanced by 5–6 days per decade over the past three decades (Anisimov *et al.*, 2007) • Permafrost temperatures are warming and terrestrial permafrost is decreasing with greening (plant colonization) noted in Siberia and North America (ACIA, 2004) • Permafrost temperatures in the Arctic and subarctic have increased by up to 3°C since the 1980s. Permafrost warming also observed on the Tibetan Plateau (Trenberth *et al.*, 2007) • Large loss of glaciers in North America (*c.* 450 km^3) and Russian (100 km^3) Arctic. Scandinavian glaciers increased in volume (ACIA, 2004)
	Extreme weather events	• No evidence of increases in intense storms in the Arctic (Anisimov *et al.*, 2007) • Decreased intense precipitation (northern Russia) • Recent increased frequency of catastrophic floods in Russian Arctic rivers due to earlier break-up of river ice and heavy rain (Bates *et al.*, 2008)
	Rivers	• Increased water temperatures in the Lena River basin between 1935 and 1999 (Trenberth *et al.*, 2007) • During the period 1935 to 1999, run-off and streamflow in Arctic river drainages showed an annual increase of 5%, with increase in winter period between 25% and 90%, reflecting increased melt and thawing permafrost (Bates *et al.*, 2008). Over the previous half century, the combined flow from the six largest Eurasian rivers increased by 7% (Peterson *et al.*, 2002) • Reduced period of river ice cover by up to 3 weeks across the Arctic (ACIA, 2004) and reductions across much of the sub-Arctic (Magnuson *et al.*, 2000; Anisimov *et al.*, 2007; Trenberth *et al.*, 2007), *e.g.* freeze date for the Mackenzie River shifted by 6.1 days per century between 1876 and 1978. Lena River basin showed significant decreases in ice thickness during the cold season (Trenberth *et al.*, 2007)
	Lakes	• Very few direct measures of changes in water temperature in the region as few long-term data sets are available, changes mostly inferred from air temperature or proxies such as diatoms or chironomid head capsules (Battarbee, 2000; Smol & Douglas, 2007). Warming of surface waters, *e.g.* in Lake Baikal increased by 1.2°C since the 1940s (Hampton *et al.*, 2008) and Lake Storsjön 0.16°C per year since 1990 (Adrian *et al.*, 2009) • Widespread decline and loss of shallow lakes between 1973 and 1997 to 2004 across 515 000 km^2 of Siberia linked with raising air and soil temperatures in areas of non-continuous permafrost (Smith *et al.*, 2005). Six per cent decline in regional lake surface area during the period. Contrast with expansion of existing lakes and formation of new lakes in areas of continuous permafrost due to increased ice melt and snowmelt (Siberia, Mongolia and China) (Smith *et al.*, 2005; Ma *et al.*, 2010) • Period of lake ice cover decreased (Magnuson *et al.*, 2000; Anisimov *et al.*, 2007), but level of change varied regionally (Weyhenmeyer *et al.*, 2011). Lake Baikal ice-free season increased by 18 days between 1869 and 2000

(*Continued*)

Table 7.3.4 (*Continued*)

Region	Component	Observed changes
Temperate regions (European Environment Agency, 2012*a*) (Nijssen *et al.*, 2001; Barnett *et al.*, 2005; Milly *et al.*, 2005; Kundzewicz *et al.*, 2007, 2008; Rosenzweig *et al.*, 2007*b*; Trenberth *et al.*, 2007; Bates *et al.*, 2008; Adrian *et al.*, 2009; Báez *et al.*, 2011; Blunden & Arndt, 2013; Dokulil, 2013)	Air temperatures	• Air temperatures have increased across temperate regions • Northern Europe by 0.32°C per decade since the 1960s (Alcamo *et al.*, 2007) • New Zealand mean air temperatures increased by 0.4°C since 1950 (Hennessy *et al.*, 2007) • Mongolia by 1.8°C rise in last six decades, most notably in winter (Cruz *et al.*, 2007). • Japan by 1°C rise in 20th century (Cruz *et al.*, 2007) • Uruguay mean rate increased by 0.08 per decade, and in Argentinian Patagonia, air temperatures increased 1–2°C in 20th century (Magrin *et al.*, 2007) • In south-west Europe, air temperatures have increased on average by 0.34°C per decade since the 1960s (above European average) (Alcamo *et al.*, 2007)
	Precipitation and water availability	• Precipitation patterns variable (Parry *et al.*, 2007) • Increased in some areas, *e.g.* Patagonia and northern Europe and western Norway (up to 70 mm per decade since 1950s), with increased winter precipitation • Increased between 1901 and 2005 over much of North America, Patagonia and North and Central Asia • No measurable change in some areas (Central Asia and Japan) (Cruz *et al.*, 2007) • Decreased precipitation in some areas, *e.g.* by up to 70 mm per decade in the Iberian Peninsula. General decreases in Mediterranean region, South Africa, Chile and south-west United States (Parry *et al.*, 2007; Trenberth *et al.*, 2007) • Droughts in southern Canada and western United States (Bates *et al.*, 2008) • A 50% reduction in precipitation in central Chile over the past 50 years (Magrin *et al.*, 2007) • Reduced proportion of precipitation falling as snow in western North America and Canadian prairies (Field *et al.*, 2007)
	Glacial ice and snow	• Reduced snow and ice cover (*e.g.* in spring in Europe and north-west United States) (Lemke *et al.*, 2007) • Annual duration of snow cover in Central Europe has reduced by *c.* 1 day per year (Lemke *et al.*, 2007) • Glacial retreat (*e.g.* Europe, New Zealand, North America and Patagonia) (Bates *et al.*, 2008)
	Extreme weather events	• Increased length and frequency of heatwaves (Russia, Western Europe and Mongolia) • Increased frequency of hot days (Japan and China) • Reduced numbers of very cold days (Japan and Mongolia) • Increase in intense precipitation events (Europe, America, western Russia, west and south China and Japan) (Bates *et al.*, 2008) • Increase in the number of very wet days (Europe and North America) • Drought frequency and intensity increased, *e.g.* southern Europe, western United States and southern Canada (Field *et al.*, 2007) • Increased number of warm nights and decreases in cold nights (southern South America and Canada)
(Webb, 1996; Daufresne *et al.*, 2003; Milly *et al.*, 2005; Xenopoulos *et al.*, 2005; Preston, 2006; Daufresne & Boët, 2007; Rosenzweig *et al.*, 2007*b*; Trenberth *et al.*, 2007; Bates *et al.*, 2008; Stahl *et al.*, 2010; Rojas *et al.*, 2012; Dokulil, 2013)	Rivers	• Increases in river water temperature between 1 and 3°C (Europe) • Net increases in river temperatures in North America (north-west United States; Eaton & Scheller, 1996; Kaushal *et al.*, 2010; Isaak *et al.*, 2012a) and Europe (Webb, 1996; Daufresne *et al.*, 2003) • North-west United States river temperatures increased by 0.22°C per decade between 1980 and 2009 • Increase in winter (DJF) and spring (MAM) stream temperatures in a small northern stream in the United Kingdom of 0.04 year^{-1} between 1967 and 2000, but no parallel increase in summer and autumn water temperatures (Elliott & Elliott, 2010) • Water temperatures in Europe increased between 0.05 and 0.80°C per decade but some extreme increases, *e.g.* 1.5°C in the Upper Rhône between 1979 and 1981 and 1997 and 1999 • Increased water temperatures compared to end of the 19th century, *e.g.* in southern Europe, water temperatures increased between 1 and 3°C • River flow regimes have changed across temperate zones. Overall increase in winter flows and decrease in summer flows in Europe since the 1960s (Stahl *et al.*, 2010). Reduced flows (southern Europe) (Stahl *et al.*, 2010; European Environment Agency, 2012*a*) • Canadian annual mean streamflow generally decreased since the period 1950–1970 (Zhang *et al.*, 2001). Decreases in monthly mean streamflow for most months, greatest decreases in August and September. Increased streamflow in March and April (Zhang *et al.*, 2001). Southern Canada has seen a *c.* 30% decrease in annual maximum daily streamflow reflecting combined increase in temperature and evaporation with no change in precipitation (Bates *et al.*, 2008) • Streamflow in the Yellow River Basin in China decreased significantly during the latter half of the 20th century (Trenberth *et al.*, 2007) • Earlier snowmelt and associated peak streamflow in the western United States and New England, United States (Trenberth *et al.*, 2007) • Across North America, peak streamflow is 1–4 weeks earlier due to earlier snowmelt (Field *et al.*, 2007) • Duration of riverine ice cover reduced by 12 days per°C over the last two centuries (Europe). Canada: break-up of river ice and the ensuing spring freshet occur significantly earlier, especially in British Columbia (Zhang *et al.*, 2001)

(Kundzewicz *et al.*, 2007; Mooij *et al.*, 2008; Adrian *et al.*, 2009; Schneider *et al.*, 2009; Arvola *et al.*, 2010)	Lakes	• General pattern of increased surface and epilimnetic water temperatures (Bates *et al.*, 2008; Adrian *et al.*, 2009) • Since the 1960s, surface water temperatures have warmed by between 0.2 and 2.0°C in lakes in Europe, North America and Asia (Bates *et al.*, 2008) • Increased lake water temperatures between 0.1 and 1.5°C in 100 different stations across Europe and North America (Bates *et al.*, 2008). Up to 2°C in some Swiss lakes since the 1950s (Hari *et al.*, 2006); 0.2°C per decade in Lake Zurich (Livingstone, 2003). Europe-wide review by Arvola *et al.* (2010) from c. 20 lakes showed that mean surface water temperature increased by 0.4°C per decade in the United Kingdom, Finland and Austria • California and Nevada lakes night surface temperatures increased by 0.1 year^{-1} since 1992 • Lake Superior summer surface water temperatures have increased by 2.5°C over the interval 1979 to 2006 (Austin & Colman, 2007) • Warming in Patagonian lakes (Báez *et al.*, 2011) • Lake Biwa (Japan) increase in water temperatures by 0.08–0.12°C per year between 1980 and 1996 • Surface waters temperature increased by 2°C in shallow eutrophic lakes in the Netherlands between 1961 and 2006 (Mooij *et al.*, 2008) • Loss of lake area and levels due to drought, over-extraction and warming, *e.g.* southern China, North America and Europe (Rosenzweig *et al.*, 2007*a*). Increased lake level in Bosten Lake, Xinjiang, China, reflecting increasing precipitation and snowmelt/ice melt between 1980 and 2000 (Rosenzweig *et al.*, 2007*b*) • Great lakes displayed a slight reduction in average levels but variability increased (MacKay & Seglenieks, 2013) • Duration of lacustrine ice cover decreased, *e.g.* in Laurentian Great Lakes (Field *et al.*, 2007). Mean freeze-up date for northern hemisphere has shifted later by 8.2 days per century between 1843 and 2009 (Magnuson, 2010). Over the same period, the mean date of ice break-up has shifted earlier by 8.6 days per century • Ice cover period reduced by a mean of 12 days per century over the last two centuries (Europe) • Canada (Duguay *et al.*, 2006): analysis of freeze-up and break-up dates for Canadian lakes between 1951 and 2000. Results indicated a general trend towards earlier break-up (particularly in western Canada), but freeze-up exhibited a mix of early and later dates • Increased water column stability with warming, *e.g.* Lake Zurich (Livingstone, 2003). Lake Kinneret deepening of thermocline in 1969–1991
Tropical and subtropical regions (Manton *et al.*, 2001; Nicholson, 2001; Nijssen *et al.*, 2001; O'Reilly *et al.*, 2003; Barnett *et al.*, 2005; Milly *et al.*, 2005; Cruz *et al.*, 2007; Rosenzweig *et al.*, 2007*b*; Kundzewicz *et al.*, 2007, 2008; Trenberth *et al.*, 2007; Bates *et al.*, 2008; Adrian *et al.*, 2009; Beyene *et al.*, 2010; Hamilton, 2010; Tierney *et al.*, 2010; Blunden & Arndt, 2013)	Air temperatures	• General increases in air temperature across different regions • Southeast Asia saw an increase between 0.1 and 0.3°C in the last half of 20th century, with India showing an increase of 0.7°C during the 20th century and 0.6–1.0°C rise in mean temperature in coastal areas of Pakistan since the early 1900s (Cruz *et al.*, 2007) • South Africa 0.14°C per decade between 1961 and 1990. Warming of air temperatures in tropical Africa by 0.26°C per decade since the 1970s (Boko *et al.*, 2007) • Increased mean temperature in Amazonia by 0.08°C per decade. Up to 0.27°C in Ecuador (Magrin *et al.*, 2007)
	Precipitation and water availability	• Varied patterns of precipitation, reflecting local climate • Reduced precipitation in areas already under water stress, *e.g.* West Africa and Southern Asia (7.5% between 1900 and 2005), most noted in the Sahel (20–40% decrease) • Decreasing trends in the annual mean rainfall were observed in the coastal areas and arid plains of Pakistan, north-east India, Indonesia and the Philippines (Bates *et al.*, 2008); West Africa has had a 20–40% decline in annual precipitation since the end of the 1960s (Boko *et al.*, 2007) • Decreases in Indonesia (Cruz *et al.*, 2007) • Sri Lanka: increased trend in summer and decreased trend in winter • Increasingly wet conditions have been observed over the Amazon Basin and south-eastern South America, including Patagonia (Bates *et al.*, 2008) • Since 1970, precipitation has increased by 15% in the Bolivian Amazon (Magrin *et al.*, 2007) • Precipitation increased across several areas of Latin America in southern Brazil, Paraguay, Uruguay, north-east Argentina (Pampas) and parts of Bolivia, north-west Peru, Ecuador and north-west Mexico (Magrin *et al.*, 2007)
	Glacial ice and snow	• Loss of glacial ice and snow, *e.g.* Mount Kilimanjaro, Himalaya–Hindu Kush (currently provide 70% of summer flow in the Ganges) and Andes (Magrin *et al.*, 2007; Bates *et al.*, 2008) • Decreased supply of snowmelt and glacial ice, *e.g.* Colombia, Ecuador and Bolivia (Magrin *et al.*, 2007) • Reduced glacial coverage and change in type of precipitation feeding rivers

(*Continued*)

Table 7.3.4 (*Continued*)

Region	Component	Observed changes
	Extreme weather events	• Increased frequency of extreme weather events in Asia (Cruz *et al.*, 2007) including heavy rainfall. Increase in droughts in Asia (Bates *et al.*, 2008) • Increase in the number of hot days and decrease in the number of cold nights across the tropical Pacific and Southeast Asia between 1961 and 1998 (Cruz *et al.*, 2007) • West African and Indian rainforests increase in intensity of dry season • Latin America: increases in climate extremes including both floods and droughts (Bates *et al.*, 2008) • Increased >50–100-year floods from strong monsoons in Bangladesh (Cruz *et al.*, 2007) • Frequency of hot days and multiple-day heatwaves has increased in India during the past century, with increases in deaths due to heat stress in recent years (Cruz *et al.*, 2007)
	Rivers	• Little data available for river temperatures. Mekong water temperature declined from 1985 to 2002 • No general pattern of homogeneous changes in river flow across the tropics, but some reports of increased streamflow, *e.g.* Amazon, resulting in flooding (extreme river levels in the Amazon in 2011 to 2012). Increased streamflow (50%) also reported in the Rivers Paraná and Paraguay • Niger, Senegal and Zambezi Rivers showed a trend of decreasing flow between 1950 and 1995 (Trenberth *et al.*, 2007)
	Lakes	• Surface and deeper waters have warmed by between 0.2 and 0.7°C over the past century in a series of the East African great lakes including Malawi, Tanganyika and Victoria (Bates *et al.*, 2008; MacIntyre, 2013) • Stratification strengthened in Lake Tanganyika (O'Reilly *et al.*, 2003)

Temperature and the thermal regime of freshwater ecosystems

The temperature of freshwater ecosystems is largely determined by local weather, with air temperature, radiation, cloud cover, humidity and wind affecting the flux of energy across the air–water interface, with a lesser influence of streamflow, catchment topography and other factors including human activities (Caissie, 2006; MacKay *et al.*, 2009; Nickus *et al.*, 2010). Caissie (2006) noted the difficulty of associating recent shifts in river temperature with climate change due to human modification of catchments, including the discharge of heated waters from industry or power generation plants, regulation of lakes and rivers by dams, modification or removal of riparian vegetation and water abstraction (Carpenter *et al.*, 2011).

As climate has changed (Trenberth *et al.*, 2007) and air temperatures have warmed globally, the heat balance of fresh waters has also changed, with warming reported (Table 7.3.4) from rivers and lakes across the globe. Regional net increases in freshwater temperatures have been reported worldwide including North America (Eaton & Scheller, 1996; Isaak *et al.*, 2012*a*), Europe (Livingstone & Dokulil, 2001; Hari *et al.*, 2006), Africa (O'Reilly *et al.*, 2003; Vollmer *et al.*, 2005; Tierney *et al.*, 2010), the Indian subcontinent (Vass *et al.*, 2009) and Australia (Thomson *et al.*, 2012). A global analysis of lake surface water temperatures based on remote sensing from a selection of 167 lakes of size >500 km^2 located across the globe indicated that on average night-time surface water temperatures increased by *c.* 0.05°C year^{-1} between 1985 and 2009 (Schneider & Hook, 2010). A recent European Environment Agency (EEA) report suggests that in three of the great rivers of Europe (the Rivers Rhine, Danube and Meuse), mean annual water temperatures have increased between 1 and 3°C over the last century. The increases in the lower Rhine, however, were partly attributed to thermal effluents, highlighting the complexity of identifying and predicting future responses to climate change and human activities.

Climate modelling provides strong evidence for continued increases in air temperatures in the future (Christensen *et al.*, 2007; Meehl *et al.*, 2007), with global multiple model mean surface temperatures for the period 2089 to 2099 estimated to be between 1.8 and 4.0°C above the baseline (1980 to 1999), depending on the emissions scenario used. When examined in detail, predicted future temperature shifts differ markedly both regionally and seasonally (see Table 7.3.1). Higher latitudes in the northern hemisphere are predicted to warm the most, *e.g.* the median estimated increase in annual air temperature between 1980 to 1990 and 2080 to 2099 for Alaska is 4.5°C (Christensen *et al.*, 2007). Northern latitudes are predicted to show the most warming during winter months (Table 7.3.1), while Central Asia and southern Europe and the Mediterranean basin are predicted to warm the most during summer months.

Table 7.3.5 Predicted change in mean and high (95th percentile) water temperatures for major world rivers between the period 2071 to 2100 and 1971 to 2000

Climatic zone and river	Predicted change in mean water temperature ($\mathrm{dtW}_{\mathrm{mean}}$)	Predicted change in 95th percentile of water temperature (dTW_{95})
Arctic and boreal		
Mackenzie	+1.1°C (1.4)	+2.2°C
Lena	+1.1°C (2.1)	+2.3°C
Ob	+0.9°C (1.3)	+1.2°C
Amur	+1.5°C (2.0)	+2.2°C
Temperate		
Colorado	+1.9°C	+2.6°C
Columbia	+1.6°C	+1.9°C
Danube	+2.1°C	+2.7°C
Loire	+1.6°C	+1.8°C
Mississippi	+2.4°C	+2.7°C
Orange	+1.3°C	+1.0°C
Rhine	+1.9°C	+2.8°C
Rhone	+2.1°C	+2.8°C
Yellow	+1.8°C	+2.3°C
Tropical and subtropical		
Amazon	+0.5°C	+0.7°C
Congo	+1.4°C	+1.2°C
Ganges–Brahmaputra	+1.2°C	+1.5°C
Indus	+1.3°C	+0.8°C
Mekong	+0.9°C	+0.9°C
Murray–Darling	+1.3°C	+1.3°C
Niger	+1.3°C	+1.7°C
Paraná	+1.0°C	+1.2°C

Data from van Vliet *et al.* (2013).

With such future shifts in air temperatures and their tight association with water temperature, freshwater fishes across the world face an overall warmer future, but the scale of temperature shift depends on geographical location (Nohara *et al.*, 2006; van Vliet *et al.*, 2013) and season. Recent predictions of future water temperatures (Table 7.3.5; van Vliet *et al.*, 2013) indicate that some temperate and subtropical regions will see the largest increases in predicted mean water temperature: the United States, Europe, eastern China and parts of southern Africa and Australia (all of which have mean increases >2.8°C). The average estimated increases in mean water temperature are especially high in Europe (2.1°C for the Danube, 1.9°C for the Rhine and 2.1°C for the Rhone) and the United States (2.4°C for the Mississippi and 1.9°C for the Colorado).

Managers and resource users will need to recognize the effect of heterogeneity on vulnerability to climate change. Freshwater systems differ in their geomorphology, limnology and ecology both within and between catchments. As such, the impacts of climate change will not be constant either at a large scale, *i.e.* between different geographical locations (Lewis, 2000, 2008, 2011; Palmer *et al.*, 2008; Johnson *et al.*, 2009), or a more local, *e.g.* within-catchment, scale where different responses are likely to be seen along the upstream–downstream gradient (Buisson & Grenouillet, 2009).

Water availability: precipitation, run-off and water levels

Wherever they are located, by definition, freshwater ecosystems require water to exist, to persist and to support fisheries. Currently, human demand for water is such that by the late 1990s (Postel *et al.*, 1996), it was estimated that >50% of all accessible run-off was captured by humans, and this was predicted to increase by to 70% by 2025. Arnell (1999) predicted that by 2025, *c.* 60% of the world's population would be living in areas subject to water stress (*i.e.* where >20% of available resources were used). The combination of increases in human populations and increased impacts on water resources and aquatic habitats highlights a major challenge for those managing freshwater habitats (Wilby *et al.*, 2010), further complicated by the combined impact of these factors (Malmqvist *et al.*, 2002) with climate change.

Worldwide, marked changes across the hydrological cycle have been associated with climate change (see Table 7.3.4; Bates *et al.*, 2008). These include shifts in the pattern and intensity of precipitation, the timing and intensity of ice and snowmelt as well as changes to soil moisture and run-off (Alcamo *et al.*, 2007; Boko *et al.*, 2007; Cruz *et al.*, 2007; Field *et al.*, 2007; Rosenzweig *et al.*, 2007*a*). Furthermore, as the climate has warmed, atmospheric water vapour concentrations have increased, which has resulted in elevated evaporation rates.

Studies of recent (*c.* past 100 years) changes in river flow have shown mixed results depending on the scale and area studied (Table 7.3.4; Rosenzweig *et al.*, 2007*b*). Recent increases in river flow have been observed in large pan-Arctic rivers (Peterson *et al.*, 2002), and this has been associated with long-term climatic cycles (*e.g.* NAO) and changes in global surface air temperatures. The role of climatic change in this is controversial, as it is difficult to separate the effects of climatic change and regulation for hydroelectrical generation in some of the larger Arctic rivers (Anisimov *et al.*, 2007). Elsewhere, river regulation has probably dampened responses to climate change and even possibly increased ecological resilience to climate change, *e.g.* in the Colorado River basin (Hatcher & Jones, 2013).

With continued climatic change and as run-off declines in regions that are currently wet, large lakes will become less common, with large systems probably being dissected into smaller ones. In those regions where run-off is predicted to increase, Tranvik *et al.* (2009) suggested that many small waterbodies will be formed, while small lakes may combine to form new, larger lakes. In all geographic regions, the size distribution will be dominated by small lakes (Downing *et al.*, 2006).

The hydrological changes observed to date (Table 7.3.4) are predicted to continue under future climate change, and many regions will probably undergo marked reductions or increased variability in precipitation (Christensen *et al.*, 2007); this will not only affect the availability of water for aquatic habitats (Barnett *et al.*, 2005; Milly *et al.*, 2005; Immerzeel *et al.*, 2010; Hermoso & Clavero, 2011; van Vliet *et al.*, 2013), but in concert with increased air temperatures will result in enhanced evaporation rates (Baettig *et al.*, 2007; Bates *et al.*, 2008; Kundzewicz *et al.*, 2008). Water availability and river discharge (Table 7.3.6) are projected to fall in waters supporting fisheries in parts of Europe, Asia, Africa, the Americas and Australasia (Nohara *et al.*, 2006; Palmer *et al.*, 2008). The frequency of extreme weather events is predicted to increase, including heatwaves and periods of extreme rainfall (Christensen *et al.*, 2007).

Table 7.3.6 Effects of climate change on river flow: Percentage changes in predicted mean (dQ_{mean}), low (dQ_{10}) and high (dQ_{95}) river flows for the period 2071 to 2100 compared to the period 1971 to 2000 based on averages calculated from six general circulation model (GCM) experiments (A2 and B1 scenarios). NS, non-significant ($P > 0.05$) difference between the two periods. Note marked decrease in low flows

Climatic region and river	Predicted change in mean flow (dQ_{mean})	Predicted change in low flows (dQ_{10})	Predicted change in high flows (dQ_{95})
Arctic and boreal			
Mackenzie	+22%	+24%	+20%
Lena	+48%	+31%	+55%
Ob	+17%	+5% (ns)	+21%
Amur	+23%	+10% (ns)	+27%
Temperate			
Colorado	−1% (NS)	−15% (NS)	+2% (NS)
Columbia	+25% (NS)	−8% (NS)	+20% (NS)
Danube	−20%	−43%	−14% (NS)
Loire	−23% (NS)	−53%	−7% (NS)
Missiikssippi	−6% (NS)	−20%	−3% (NS)
Rhine	−8% (NS)	−37%	+1% (NS)
Rhone	−11% (NS)	−46%	+1% (NS)
Orange	+8% (NS)	1% (NS)	+11% (NS)
Yellow	+23% (NS)	+10% (NS)	+28% (NS)
Tropical and subtropical			
Amazon	+21%	+12% (NS)	+23%
Congo	+20%	+12% (NS)	+24%
Ganges–Brahmaputra	+4%	−13% (NS)	+5% (NS)
Indus	+65%	+30% (NS)	+78%
Mekong	+3%	−22% (NS)	+7% (NS)
Murray–Darling	−10% (NS)	−25%	−8% (NS)
Niger	+9%	−1% (NS)	+11% (MS)
Paraná	+12% (NS)	2% (NS)	+16% (NS)

Data from van Vliet *et al.* (2013).

The impact of changed water availability on freshwater fisheries worldwide is further complicated by the fact that some of the most fishery-dependent countries are located in arid or semi-arid regions. Freshwater fisheries can provide income and employment to significant numbers of people in these water-stressed regions (Allison *et al.*, 2009; Sacchi, 2011) including important inland fisheries in the Mediterranean region and the Niger Inland Delta in Mali, Lake Chad and the small lakes and wetlands of the dry African Rift Valley (Allison *et al.*, 2007). Such semi-arid and arid regions are particularly at risk to the impacts of climate change on freshwater systems, due to existing water stress, increased water use, reduced precipitation (Table 7.3.2), limited capacity for groundwater recharge and increased population growth (Kundzewicz *et al.*, 2007, 2008).

Increased water temperatures combined with longer periods of low flows will affect DO concentrations and other physio-chemical factors, including concentrations of nutrients and pollutants (Delpla *et al.*, 2009; Noyes *et al.*, 2009; Carpenter *et al.*, 2011). Extreme weather events such as heavy rainfall may impact receiving waters through inputs of contaminants or sediments (Whitehead *et al.*, 2009), with subsequent consequences for fisheries (Ochumba, 1990; Vondracek *et al.*, 2003).

Some studies examining the future ecological consequences of climate change suggest impacts may be extreme, for example, regarding loss of species. A well-cited article by Xenopoulos *et al.* (2005) modelled the likely future consequences of reductions in river discharge on freshwater fish diversity due to climate change and increasing human extraction of water. They predicted that in 30% of the world's rivers, up to 22% of fishes would become extinct by 2070. A recent modelling study (Tedesco *et al.*, 2013) suggested that reduced water availability will lead to an 18 times increase in background extinction rates in the 10% of catchments most affected by climate change. Of the >1000 catchments examined by Tedesco *et al.* (2013), however, only 20 (1.9%) were predicted to experience extirpations of fishes that could be attributed to climate change through reduced water availability. The authors not only highlighted that their results contrasted greatly with the often alarming predictions regarding climate change-driven extinctions for freshwater fishes (Xenopoulos *et al.*, 2005) but that conservation action should be directed at the current anthropogenic threats that have and continue to drive biodiversity loss.

Climate change is widely predicted to affect catchment hydrodynamics following shifts in the intensity, timing and even type of precipitation (Milly *et al.*, 2005; de Wit & Stankiewicz, 2006; Bates *et al.*, 2008). This will in turn affect erosion and weathering in the catchment as well as discharge patterns in rivers and the concentration of dissolved and non-dissolved substances including nutrients, pollutants and sediments. In catchments that drain glaciated or snow-covered areas (*e.g.* the Andes, Himalayas and Hindu Kush), river flow is maintained during warm dry periods by glacial melt or snowmelt (Barnett *et al.*, 2005; Bates *et al.*, 2008; Hamilton, 2010). Loss of glaciers or earlier melting of snow will change the supply of water to often large river systems.

There is strong evidence that river flow has shown recent shifts in response to climate change (Table 7.3.4). Variation in flow is a characteristic feature of natural flowing waters worldwide and is tightly linked to the ecology and phenology of riverine taxa (Moss, 2010*b*), but the changes are such that they are likely to have ecological impacts. Base flows are sufficient to provide suitable habitats and conditions (*e.g.* temperatures and DO concentrations) for aquatic and riparian taxa and allow movement of migratory fishes. Low flows typically take place during periods of low inputs from precipitation or snowmelt and ice melt and can lead to reductions in water quality, as temperatures increase and DO concentrations fall. As water residence times are extended under low flows, dilution capacity falls, further impacting water quality and increasing the probability of algal growth. Low flows also have positive ecological implications, for example, they permit the recruitment of riparian or floodplain vegetation (Gregory *et al.*, 1991) that have positive implications for fish stocks, *e.g.* through the provision of cover (Tabacchi *et al.*, 1998) or energetic subsidies (Zeug & Winemiller, 2008).

Increases in flow above the base or low levels, *e.g.* following pulses associated with small floods, play an important role in structuring the physical structure of the river channel and redistributing bed materials, as well as restoring water quality by flushing away pollutants, waste products and fine silts. Larger flood pulses following seasonal events such as ice or snowmelt (Arnell, 1999; Immerzeel *et al.*, 2010) are important as they not only recharge floodplain water tables but also deposit materials from upstream that provide habitats (*e.g.* large woody debris, gravels, cobbles and boulders) and food for fishes and other aquatic taxa. Large floods provide key migratory and reproductive cues for aquatic taxa, while also leading to the flooding and inundation that fertilize the floodplain while opening up spawning and nursery habitats for juveniles and feeding habitats for adults. Extreme floods may lead to marked changes in channel morphology; loss of key habitats both in channel and in adjacent areas, *e.g.* riparian vegetation (Poff, 2002), which provides shade, source of food and woody debris (Wilby *et al.*, 2010); as well as the formation of new habitats such as oxbow lakes. Changes in the timing or intensity of floods (Malmqvist *et al.*, 2002) will affect those species that are adapted to particular hydrodynamic patterns and environmental cues (Lytle & Poff, 2004). Increased winter precipitation may lead to more scouring and loss of spawning habitat, *e.g.* in redd-spawning salmonids (Bryant, 2009; Goode *et al.*, 2013).

Current predictions (Milly *et al.*, 2005; Nohara *et al.*, 2006; Kundzewicz *et al.*, 2008; van Vliet *et al.*, 2013) indicate that by the mid-21st century, there will be marked changes in water availability and river run-off globally (Table 7.3.6). Average annual river run-off and water availability are projected to increase between 10 and 40% at high latitudes and in the wet tropics (*i.e.* those regions located in the area between *c.* 30° north and south of the Equator) but to decrease between 10% and 30% across the mid-latitudes and in the dry tropics. The effects of climate change on the hydrology of rivers (*e.g.* discharge and timing and intensity of floods) and standing waters (*e.g.* water level and residence times) will largely reflect changes in the type, intensity, timing and volume of precipitation, as well as the rate and timing of snow-and glacial-melt (Kundzewicz *et al.*, 2008; Verdonschot *et al.*, 2010; Carpenter *et al.*, 2011; Hatcher & Jones, 2013). Many rivers draining glaciated regions, particularly in the Asian high mountain ranges and the South American Andes, are sustained by glacier melt during warm and dry periods, and warming will probably see a rise in river flow in the near future, followed by a marked reduction as glaciers are lost (Vass *et al.*, 2009; Hamilton, 2010; Immerzeel *et al.*, 2010). Immerzeel *et al.* (2010) suggest that the Brahmaputra and Indus River basins are particularly susceptible to reductions of flow. Evapotranspiration will also be affected locally, through changes in temperature, wind, solar radiation and atmospheric humidity and wind. This will probably counter the effects of small increases in precipitation but amplify effects of reduced precipitation on surface waters (Kundzewicz *et al.*, 2007).

Lake hydrology: renewal and water levels

Climate change has and will continue to affect natural fluctuations in lake volume, water levels and hydraulic retention times (the rate at which lake waters renew themselves) (Carpenter *et al.*, 1992; Schindler *et al.*, 1996; George *et al.*, 2007), affecting chemical and nutrient cycling (Jeppesen *et al.*, 2010*b*). Variation in lake volume and water level has implications for freshwater fisheries including its impacts on primary productivity (Turner *et al.*, 2005) and access to spawning or foraging habitats (Gaboury & Patalas, 1984). Over larger timescales, variation in water levels has acted as a driver for speciation (Sturmbauer *et al.*, 2001). Some lakes, including the African Great Lakes, are very sensitive to small changes in climate, as they receive very little water from riverine inputs, and high year-round temperatures and evaporation rates can lead to shifts in lake levels (Bootsma & Hecky, 2003).

Variation in water levels affects how humans use fresh waters (MacKay & Seglenieks, 2013); at the most extreme, fisheries will be lost if water levels fall sufficiently, but fisheries will probably be affected under future climate conditions as even relatively small changes in water level can effect fish yields (Hickley *et al.*, 2002) and even boat access (Magnuson *et al.*, 1997). If water levels are not suitable for fishing, fishers may be forced to switch to other economic activities, *e.g.* farming (Sarch & Birkett, 2000; Allison et al., 2001).

When hydraulic retention times decrease (*e.g.* with increased precipitation), nutrient levels are likely to be enhanced, possibly leading to algal blooms (de Senerpont Domis *et al.*, 2013); conversely, if retention times become extended, nutrient uptake may be such that water column concentrations fall, enhancing the release of some nutrients (*e.g.* phosphorus) from sediments (Beklioglu *et al.*, 2007). This may also lead to changes in phytoplankton communities, *e.g.* with selection for those taxa that can thrive under low-nutrient conditions (Jeppesen *et al.*, 2005), with bottom-up impacts on fishery production.

Palaeolimnological measurements of variation in lake size and water level are routinely used by palaeoecologists to reconstruct past climate change (Battarbee, 2000; Schwalb, 2003). Variation in such characteristics also provides a useful means to examine contemporary climate change (Mason *et al.*, 1994; Magnuson *et al.*, 1997), especially in non-regulated lakes (Adrian *et al.*, 2009). Recent studies using remote sensing have revealed marked changes in lake surface areas associated with climate change and human activities (Smith *et al.*, 2005; Ma *et al.*, 2010). Ma *et al.* (2010) reported that lakes from China and Tibet had shrunk, with *c.* 250 lakes being lost from northern areas (inner Mongolia), while *c.* 60 new lakes appeared mostly on the Tibetan Plateau. A comparative study of remote sensing data of Siberian lakes from the early 1970s and late 1990s by Smith *et al.* (2005) revealed that in areas of non-continuous permafrost, there had been a marked loss of lakes with surface areas >40 ha; conversely, they showed that the number of lakes had increased in areas of continuous permafrost. Tranvik *et al.* (2009) modelled the global distribution and size distribution of lakes in 2050 based on predicted run-off data under the IPCC B1 scenario. They showed that the although the total global area of lakes will probably remain similar, the regional distribution of lakes will change with a decline in abundance reflecting reduced run-off in much of North America, Western Europe, Asia, Australia and New Zealand. Predictions for South America and Africa are more varied with net increases and decreases predicted for different regions. Lakes that are currently permanent in arid and semi-arid regions are likely to shrink and may even become ephemeral in the future (Parry *et al.*, 2007).

At a markedly different scale, a recent study (Gaeta *et al.*, 2014) highlighted that the ecological effects of lowered lake level extend beyond simple changes in the volume of water. The ecotone that combines the littoral zone of a lake with adjacent terrestrial habitats represents an important source of energy and nutrients, *e.g.* leaf litter (France, 1996), as well as the structured habitat for lake fishes and their prey provided by coarse woody debris such as fallen trees. Gaeta *et al.* (2014) showed that over the period of a prolonged drought during which lake levels fell by 1.1 m, >75% of coarse wooden debris was lost from the littoral zone. This loss of structured littoral habitat was associated with a crash in yellow perch *Perca flavescens* and markedly reduced growth performance in their main predator, the largemouth bass *Micropterus salmoides*. Although other unmeasured factors may have been responsible for the loss of *P. flavescens* and the reduction in *M. salmoides* growth, this study highlights that changes in lake levels driven by climate change may have large biological consequences at the scale of a single lake.

Lake mixing and thermal structure

Lakes vary considerably in the relative intensity of water column mixing (Hutchinson & Löffler, 1956; Lewis, 1983, 2000): in fresh water, stratification is typically thermal, with the timing and amount of mixing varying broadly by latitude (Lewis, 2000; de Senerpont Domis *et al.*, 2013). The relative amount of mixing is related with both climatic, *e.g.* solar radiation and wind (Wetzel, 2001), and physical factors, such as lake size and fetch, as well as the presence of inflowing waters (Lampert & Sommer, 2007), with a strong influence of latitude (Hutchinson & Löffler, 1956). Where thermal stratification takes place, warmer, thermally homogeneous surface waters (the epilimnion) overlay lower cooler waters (hypolimnion), with the two water masses separated by a region (metalimnion) where water temperatures change rapidly (thermocline). There are reports from temperate and tropical regions of increased thermal and hydrodynamic stability in lakes with stratifying periods starting earlier and extending by several weeks (Livingstone, 2003; O'Reilly *et al.*, 2003; George *et al.*, 2007; Arvola *et al.*, 2010).

The physical process of mixing, or conversely the presence of stratification, has major impacts on the ecology of a waterbody and its fisheries. Mixing or stratification of the water column affects lake physico-chemistry including nutrient transfer, as well as phytoplankton productivity (Lampert & Sommer, 2007) and community structure, with periods of extended stratification associated with the increased probability of cyanobacteria (Paerl & Huisman, 2009; de Senerpont Domis *et al.*, 2013). Stratification affects primary production (de Senerpont Domis *et al.*, 2013), and reduced upwelling of nutrient-rich waters in the East African lakes associated with recent climate change has been associated with a reduction in fisheries yield of *c.* 30% (O'Reilly *et al.*, 2003).

The presence and extent of thermal stratification affect the availability and quality of habitats for fishes and other taxa (Coutant, 1985; Harrod & Grey, 2006; Jones *et al.*, 2008). The presence of different thermal masses within a single body of water permits fishes belonging to different thermal guilds to coexist in many temperate lakes (Barange & Perry, 2009), increasing fishery potential. Stratification can also have sublethal or lethal effects: cooler hypolimnetic waters can become deoxygenated during summer months in stratified temperate lakes, forcing coldwater fishes into warmer surface waters, where temperatures may be such to restrict growth through metabolic stress or, in extreme cases, even cause death (Aku & Tonn, 1997; Lappalainen & Lehtonen, 1997), a process known as thermal squeeze (Coutant, 1985). Periods of lake turnover, *i.e.* when stratification breaks down, can also lead to rapid deoxygenation of the water column and can cause fish kills with obvious consequences for fisheries (Aku & Tonn, 1997; Vondracek *et al.*, 2003).

Climate change has reportedly resulted in changes in the thermal structure of lakes worldwide (Table 7.3.4). Such impacts are predicted to continue in the future, with shifts in the extent and phenology of mixing with associated impacts on primary producers and their consumers (Shuter & Meisner, 1992; De Stasio *et al.*, 1996; Boehrer & Schultze, 2008; de Senerpont Domis *et al.*, 2013), and will probably affect freshwater fisheries. Changes to lake productivity have obvious potential impacts on overall fisheries yields (O'Reilly *et al.*, 2003), but changes in stratification are likely to selectively impact those fishes that currently rely on access to well-oxygenated hypolimnetic waters to act as a coldwater thermal refugia during summer periods such as the coldwater coregonids and salmonids that support fisheries in the northern hemisphere (Magnuson *et al.*, 1990; Schindler *et al.*, 1990; Shuter *et al.*, 2012).

Ice cover

Where conditions are suitable, such as higher latitudes and altitudes, lakes and rivers naturally freeze, driving fishers to develop several specialized gears to exploit fishes from under the ice (Gabriele *et al.*, 2005). The extent and timing of ice cover varies between geographical locations and reflects local lake and river characteristics (Weyhenmeyer *et al.*, 2011). As air and water temperatures have shifted, the distribution, extent and phenology of ice cover have changed on lakes and rivers worldwide (Table 7.3.4; Magnuson *et al.*, 2000; Hampton *et al.*, 2008; Magnuson, 2010; Weyhenmeyer *et al.*, 2011). The dates of freeze-over and ice thaw, the thickness of the ice and the length of the ice cover have changed in lakes and rivers across the northern hemisphere (Magnuson *et al.*, 2000; Hinzman *et al.*, 2005; Moore *et al.*, 2009). Examining records from the period 1846 to 1995 over which air temperatures increased by *c.* 1.2 per 100 years, Magnuson *et al.* (2000) showed that the timing of freezing was delayed by *c.* 6 days per 100 years, while the date of ice break-up advanced by *c.* 7 days per 100 years. They also noted that in the late 20th century, there was an increase in inter-annual variability in freeze and break-up dates.

Ice cover (and its break-up) has marked physical, chemical and ecological impacts for lentic and lotic ecosystems (Scrimgeour *et al.*, 1994; Bayley, 1995; Prowse *et al.*, 2006; Magnuson, 2010), as well as for fishes and those exploiting them (Lehtonen & Lappalainen, 1995; Jackson *et al.*, 2001; Reist *et al.*, 2006*a*; Hayden *et al.*, 2013*b*). Extended periods of ice cover not only affects habitat availability and quality for fishes (Craig, 1989) but restrict access to fishes and potential markets by fishers (Prowse *et al.*, 2006). Ice cover can, under certain conditions, lead to fish kills through deoxygenation, with obvious fisheries implications (Greenbank, 1945; Barica & Mathias, 1979). As climate change leads to reduced ice thickness and less snow cover, algal production under the ice will increase, allowing more oxygen production and potentially reducing fish kills (Wrona *et al.*, 2005).

Future warming is predicted to further affect ice cover and the fish communities resident in affected systems (Magnuson *et al.*, 1997; Stefan & Fang, 1997; Fang & Stefan, 1999, 2009; Stefan *et al.*, 2001), with ice cover being reduced or even lost from many freshwater ecosystems, although variability will be marked between systems (Weyhenmeyer *et al.*, 2011). Previous climatic shifts in the northern hemisphere were associated with marked changes in the phenology of ice cover of rivers and lakes (Shuter *et al.*, 2012). The response of freshwater fisheries to changes in ice cover will depend on the geographical location as well as the physical characteristics of the waterbody (Weyhenmeyer *et al.*, 2011); it will also affect fishes differently according to their thermal guild and preferred habitats (Hayden *et al.*, 2013*a*). Current and future warming will result in shortened winter seasons in higher latitudes (Kundzewicz *et al.*, 2007; Meehl *et al.*, 2007); this will result in changes in winter phenology (Shuter *et al.*, 2012) which plays a fundamental role in the life cycle of many cold- and coolwater fishes. Reductions in ice cover, in tandem with warming of surface waters, will probably lead to increased fish growth (Nyberg *et al.*, 2001), production and access to fishes. Combined with a reduction in winterkills, these are generally positive outcomes from a fisheries perspective, but the loss of ice-adapted fishes (Magnuson, 2010) may result in shifts to fish communities including less preferred species (Hayden *et al.*, 2013*b, c*).

Water quality

Climate change has and will continue to affect the physicochemistry of freshwater ecosystems beyond the thermal changes that Caissie (2006) considered a source of thermal pollution on a global scale. Warming and changes in water availability in fresh waters will also impact water quality (Tibby & Tiller, 2007; Prathumratana *et al.*, 2008; Delpla *et al.*, 2009; Grimalt *et al.*, 2010), with changes in the mobility and dilution of pollutants and contaminants (Wrona *et al.*, 2006*a*; Whitehead *et al.*, 2009) and DO concentrations (Arnell, 1998; Fang & Stefan, 2009; Hamilton, 2010) which are key to habitat quality for freshwater fishes (Doudoroff & Shumway, 1970; Alabaster & Lloyd, 1980; Pörtner & Peck, 2010). The potential effect of climate change on water quality may differ between countries of different development states (Kundzewicz *et al.*, 2008). Beyond the potential to drive variation in fish production, community structure and fishery yield (Welcomme, 1985; Jackson *et al.*, 2001),the increased mobilization of pollutants associated with climate change (Grimalt *et al.*, 2010) may limit the suitability of fishes for sale and human consumption (Schiedek *et al.*, 2007; Noyes *et al.*, 2009; Grimalt *et al.*, 2010).

Climate change, energy and nutrient availability

The ecosystems and associated food webs that support freshwater fisheries represent a complex arrangement of dynamic interactions between abiotic and biotic factors, many of which are sensitive to climate change (Meyer *et al.*, 1999; Wrona *et al.*, 2006*b*; Hamilton, 2010). Although fresh waters cover a relatively small proportion of the earth's surface, they can play a significant role in global biogeochemical cycling, for instance, the carbon and nitrogen cycles (Vitousek *et al.*, 1997; Cole *et al.*, 2007; Moss, 2012), and store carbon at a greater rate than marine habitats. Climate change has, and will, continue to qualitatively and quantitatively affect both carbon and nitrogen cycles in freshwater systems (Denman *et al.*, 2007; Tranvik *et al.*, 2009; Jeppesen *et al.*, 2010*b*; Yvon-Durocher *et al.*, 2010; Bastviken *et al.*, 2011; Moss, 2012), *e.g.* the quantity and the manner by which energy (carbon) and nutrients (*e.g.* nitrogen and phosphorus) are fixed, transformed, stored and transported in and through lakes, rivers and wetlands (Porcal *et al.*, 2009; Tranvik *et al.*, 2009; Moss, 2012), many of which have implications for fisheries.

Fishery production will probably change due to climatic effects on community structure and the abundance of certain species (Jeppesen *et al.*, 2010*a, b*), but through food web processes (Cury & Pauly, 2000), as fisheries rely on the flow of energy and nutrients from lower trophic levels to fishes (Woodward *et al.*, 2010). Fish consume primary producers and consumers, assimilating energy and nutrients, which are ultimately synthesized as somatic tissues and are available to humans and other piscivores. Climate change has the potential to not only affect predator–prey relationships (Bystrom *et al.*, 2007; Jeppesen *et al.*, 2010*a*) but also the phenology, origin and level of the basal resources (energy and nutrients) (O'Reilly *et al.*, 2003; Winder & Schindler, 2004*b*; Thackeray *et al.*, 2010) that support the production of higher trophic levels such as fishes (Baulch *et al.*, 2005). For example, the energy (carbon) that underpins fish production can originate from a complex mix of photosynthetic (Hecky & Hesslein, 1995; Jones *et al.*, 1998; Grey *et al.*, 2001; Pace *et al.*, 2004) or even chemosynthetic (Grey *et al.*, 2004; Ravinet *et al.*, 2009; Jones & Grey, 2011) processes.

As well as the autochthonous carbon produced through primary production within a given ecosystem, fresh waters also receive subsidies of allochthonous carbon from the surrounding catchment, which can play an important role in the ecology and dynamics of fresh waters (Grey *et al.*, 2001), including energetic subsidies to higher trophic levels such as fishes (Jones *et al.*, 1998). Terrestrial carbon entering fresh waters is largely received (Porcal *et al.*, 2009; Tranvik *et al.*, 2009) as either dissolved inorganic carbon (DIC) or dissolved organic carbon (DOC), while inputs of both particulate organic carbon (POC) and particulate inorganic carbon make a lower contribution. The relative importance of these different inputs varies with latitude, catchment type and hydrology and has already shown a measurable response to climate change (Monteith *et al.*, 2007; Nickus *et al.*, 2010). For instance, some temperate freshwater systems (Monteith *et al.*, 2007) are receiving increased inputs of terrestrial-derived organic matter, including DOC from the surrounding catchment through so-called browning. Increases in DOC export to fresh water have been associated with multiple aspects of climate change including shifts in atmospheric chemistry and deposition, changes in precipitation, drought and warming (Monteith *et al.*, 2007; Porcal *et al.*, 2009).

The increased presence of DOC in fresh waters has marked implications that extend across levels of biological organization and has potential positive and negative implications for fisheries. Due to effects on water transparency and its capacity to absorb UV radiation, DOC can reduce UV damage in sensitive taxa and life stages, *e.g.* fish eggs and larvae (Williamson *et al.*, 1997; Reist *et al.*, 2006*c*; Häder *et al.*, 2007). DOC has complex interactions with heavy metals, but increased DOC concentrations can result in reduced metal toxicity (Porcal *et al.*, 2009). Significant inputs of DOC can affect food webs; primary productivity can be reduced at the whole lake scale due to the attenuating effect of DOC on sunlight (Roulet & Moore, 2006); conversely, terrestrial-derived DOC can provide a trophic subsidy to consumers in freshwater systems, including fishes (Jones *et al.*, 1998; Pace *et al.*, 2004). Future changes in catchment conditions will probably affect the export of DOC to fresh waters, with drier conditions leading to less run-off and increased DOC inputs and run-off under wetter conditions (Porcal *et al.*, 2009).

The nitrogen cycle is not only integral to life on earth (Galloway *et al.*, 2008), but plays an integral role in climate systems (Denman *et al.*, 2007). As humans have modified landscapes and the global nitrogen cycle, for example, through food production and energy production (Vitousek *et al.*, 1997; Galloway *et al.*, 2008; Moss, 2012), ecosystems have responded (Vitousek *et al.*, 1997; Anderson & Cabana, 2005) to increased availability of this and other nutrients such as phosphorus, which has been released into aquatic systems from agricultural, industrial and domestic sources. In many fisheries, mild eutrophication associated with nutrient additions is typically thought to have positive impact on fish yield, but increased levels of eutrophication are typically associated with habitat degradation and a reduction in fishery quality due to shifts away from preferred high-value species (Hasler, 1947; Nümann, 1972; Jeppesen *et al.*, 2005).

Predicting how climate change will impact the flow of energy and nutrients through an ecosystem will be difficult as the effects will vary according to the climate change scenario, ecosystem type as well as latitude and elevation (Wrona *et al.*, 2006*b*; de Senerpont Domis *et al.*, 2013), leading to a continuum of potential states under future warming (Seitzinger *et al.*, 2010, Moss, 2012). Some general observations, however, can be made to inform fisheries professionals, who will need to consider the likelihood of impacts on particular fisheries on a case-by-case basis.

Within lotic ecosystems (Meyer *et al.*, 1999; Whitehead *et al.*, 2009; Hamilton, 2010), as precipitation, run-off and river flow are affected by climate change (van Vliet *et al.*, 2013), the timing and extent of flooding will shift. This, combined with changes in water temperature, will modify the supply of nutrients and the relative contribution of allochthonous (*e.g.* benthic algae and macrophytes) and autochthonous (*e.g.* leaf litter and other terrestrial-derived materials) carbon to riverine fishes (Vannote *et al.*, 1980; Junk *et al.*, 1989; Junk, 2002; Hamilton, 2010; Hering *et al.*, 2010). As water temperatures rise, the decomposition rate of organic matter derived from terrestrial habitats and nitrogen flux in run-off will increase, resulting in higher nutrient concentrations (Hering *et al.*, 2010). In scenarios where river flows are reduced, effluents will be subject to less dilution, leading to increased nutrient concentrations in rivers. Under such a scenario, enhanced eutrophication of rivers can be expected and strengthened by high water retention time during periods of low flow. Denitrification, however, is likely to be enhanced during periods of low flows and increased water temperatures, resulting in loss of nitrogen to the atmosphere, although Moss (2012) notes that in tropical areas at least, nitrogen fixation may also increase.

In lentic systems, climate change will both modify internal processes such as lake hydrodynamics as well as their interactions with the wider catchment (Magnuson *et al.*, 1997; George, 2010; Moss, 2012). This will alter the relative contribution of energy and nutrients derived from either benthic or pelagic habitats within the system (Schindler & Scheuerell, 2002; Vadeboncoeur *et al.*, 2002; Vander Zanden & Vadeboncoeur, 2002) or *via* terrestrial-derived sources (Solomon *et al.*, 2011) to lake fisheries. De Senerpoint Domis *et al.* (2013) provide a detailed and useful summary of the predicted impacts of climate change on lake productivity globally, including shifts in nutrient dynamics, primary producer seasonal dynamics, community structure and biomass. Their predictions regarding increased production in tropical lakes following future increases in precipitation were criticized (Sarmento *et al.*, 2013), largely as the latter group of authors felt that the more likely scenario for many tropical lakes, *e.g.* in East Africa, was one of reduced productivity due to increased thermal stability (O'Reilly *et al.*, 2003; Tierney *et al.*, 2010). Predictions of changes in primary producer community structure extend to an increased risk of harmful cyanobacterial blooms in certain ecosystems, *e.g.* eutrophic lakes or rivers (Paerl & Huisman, 2009), as water temperatures rise and water column mixing is reduced. This will affect not only nutrient dynamics, with a consequent impact on fish productivity, but has the further risk of tainting of fish flesh and, in extreme cases, causing fish kills. Under such extreme cases, access to fisheries may also be restricted, due to risks to human health (Paerl & Huisman, 2009).

Salinity

Salinity acts a major filter of aquatic biodiversity (Gasith & Resh, 1999), including fishes (Nelson, 2006), with increased salinities selecting against non-tolerant stenohaline fishes. Changes in salinity can therefore have drastic effects on habitat suitability, abundance and production of fishes (Blanco *et al.*, 2007; Jeppesen *et al.*, 2010*a*, 2012) with consequences for freshwater fisheries. Salinization of fresh waters is an ongoing environmental issue in arid and semi-arid areas across the globe (Williams, 1999; Kundzewicz *et al.*, 2007; García-Ruiz *et al.*, 2011). The process has extremely negative consequences for fresh waters and the goods and services they provide to human societies and is typically associated with saline intrusion of aquifers due to over-extraction of groundwater for irrigation, as well as changes in land use, sea level rise and desertification (Williams, 1999), and will be greatly exacerbated by climate change (Kundzewicz *et al.*, 2007, 2008). In extreme cases, salinization is likely to lead to the loss of freshwater fishes from the community and a shift to euryhaline fishes, many of which may be generalist and non-native (Rahel & Olden, 2008). An extreme example of the impact of salinization on a 'freshwater' fishery is provided by the Aral Sea. Here, salinization associated with the development of large-scale irrigation schemes to improve agriculture in this arid region resulted in catastrophic degradation and loss of lake habitats (Zholdasova, 1997; Butorina, 2007). In turn, there was a change from an endemic-dominated to a non-native-dominated fish community and a complete loss of the commercial fishery (Zholdasova, 1997).

Conversely, increased precipitation associated with climate change will result in some currently brackish water habitats becoming increasingly fresh water, such as the Baltic Sea (Stigebrandt & Gustafsson, 2003), which will allow increased reproduction and production of freshwater fishes that are currently limited by salinity (Härmä *et al*., 2008) with subsequent impacts on fish communities and fisheries (MacKenzie *et al*., 2007).

Climate change impacts on fishers and fisheries

A main challenge for fishery professionals under a scenario of climate change is to maximize or optimize fishery production, without negatively impacting biodiversity or the provision of ecosystem goods and services. Like other socio-economic sectors (Wilbanks *et al*., 2007), the different subcomponents (commercial, artisanal and recreational) of freshwater fisheries are vulnerable to climate change (Ford *et al*., 2006; Daw *et al*., 2009) and face threats, as well as future opportunities, to which they must adapt (Badjeck *et al*., 2010; De Young *et al*., 2012). Climate change has already affected freshwater fish production (O'Reilly *et al*., 2003), and the inertia residual in the climate system is such that even if emissions stopped totally tomorrow, fisheries would be exposed to continued climate change for most of the next century (Meehl *et al*., 2007). Throughout this chapter, the difficulties in predicting the response of freshwater ecosystems and fishes to climate change have been repeatedly stated. Extending predictions to fisheries themselves adds another layer of complexity, due to the uncertainties regarding how fishers and associated socio-economic systems will respond to climate change (Sharp, 1987; Allison *et al*., 2007; Plagányi *et al*., 2011).

The response of the fishes targeted by fisheries to climate change will be extremely variable and will vary regionally, taxonomically and according to habitat type; furthermore, changes may be gradual or abrupt. Climate change may lead fishes targeted by freshwater fisheries to increase or decrease (or even become extirpated; Xenopoulos *et al*., 2005) in a particular region or fishery, for their population dynamics to become more or less variable (Jeppesen *et al*., 2012), for community structure to change (Jeppesen *et al*., 2010a) and for growth seasons to be extended or even truncated (Lappalainen & Lehtonen, 1997), affecting fishery yields. Managers need to be ready to incorporate changes in fish distributions into their plans (Link *et al*., 2011), with cold- and coolwater fishes moving polewards (Comte *et al*., 2013) or to higher elevations (Hari *et al*., 2006; Comte & Grenouillet, 2013) or conversely not (VanDerWal *et al*., 2012). Fishers may lose access to traditional fisheries but gain access to new fisheries (Ford *et al*., 2006; De Young *et al*., 2012). Changes in contaminant or parasite dynamics may mean that although fishes are present, they are unsuitable for sale (Marcogliese, 2001; Noyes *et al*., 2009; Grimalt *et al*., 2010). The efficiency of fishing gears will change, and the fishing knowledge built up over generations may become ineffective (Silvano & Valbo-Jørgensen, 2008). The demand for fishery products and access to fisheries as a source of employment, protein and recreation will change (Badjeck *et al*., 2010), as will the array of environmental challenges facing fresh waters (Meyer *et al*., 1999; Schindler, 2001; van Vliet *et al*., 2013).

Adapting to climate change will mean trade-offs between biological resources and socio-economic drivers (Koehn *et al*., 2011), and management schemes will need to be adaptive allowing management responses to be robust to unexpected outcomes (Plagányi *et al*., 2011). In order to maximize adaptive capacity in the freshwater fishery sector, governments may need to invest in education for fishers and fishery managers and provide funding for commercial and artisanal fishers and, as air temperatures increase, to ensure that suitable cold storage and transport systems are available for fishery products (Young & Muir, 2008). Clearly, fishery professionals potentially have a busy time ahead, but in the short term, ongoing non-climate challenges, *e.g.* changes in markets, demographics, overexploitation and governance regimes, as well as reduced water availability, may have a greater effect on fisheries than climate change (Nijssen *et al*., 2001; Daw *et al*., 2009).

Fisheries of all types continue to have significant negative impacts on the environment (Cooke & Cowx, 2006), and there is a need for sustainability in artisanal (Allison *et al*., 2001), commercial (FAO Fisheries Department, 2003) and recreational (FAO, 2012) sectors. This is particularly important when the impacts of human population growth are considered and the need for food security (Wheeler & von Braun, 2013). As human populations grow and undergo redistribution, their impacts on fresh waters extend beyond a simple increased demand for fishes (and access to fisheries) and will include disruptions to the hydrological cycle, changes in land use and pollution (Whitehead *et al*., 2009).

As climate change impacts fisheries worldwide, countries, industries, communities, families and individuals will be affected differently (Wilbanks *et al*., 2007; Allison *et al*., 2009; Badjeck *et al*., 2010). At a community level, the risks and rewards, as well as the capacity to adapt to climate change itself, are unevenly distributed both across and within fishing communities (Daw *et al*., 2009). This reflects variation in the availability of education, material resources and technology, but also governmental and non-governmental structures and networks. A series of authors have noted that vulnerability to the impacts of climate change (and other non-climate drivers of change in fisheries) can be reduced through the development of adaptive capacity (Allison *et al*., 2007; Badjeck *et al*., 2010; Wilby *et al*., 2010; Plagányi *et al*., 2011), and Daw *et al*. (2009) called for government intervention to develop adaptive capacity within vulnerable communities. This reflects the fact that freshwater fisheries can often be operated by socially vulnerable parts of society, *i.e.* they may be low-income and indigenous peoples (Anisimov *et al*., 2007; Hennessy *et al*., 2007; Lynn *et al*., 2013), who already have reduced access to employment, health services and infrastructure (Field *et al*., 2007).

Fishers living in or close to poverty are likely to be particularly vulnerable to climate change (Cruz *et al*., 2007; Hennessy *et al*., 2007) as they may be facing a poverty trap, *i.e.* they are financially unable to adapt or diversify to the changes forced on them by climate change (Cinner *et al.*, 2009). Those parts of society with strong cultural links to the traditional use of freshwater resources such as indigenous peoples may face the most difficult transition in terms of adapting to future conditions (Anisimov *et al.*, 2007).

Managers and policymakers need therefore to consider the socio-economic context of the different groups and individuals involved in fisheries and how this will affect their capacity to adapt to climate change. Badjeck *et al.* (2010) identified that fishery managers and policymakers needed to develop approaches and policies that strengthened the fishers' livelihood asset base, *i.e.* to diversify and develop the means by which fishers make their livelihood. Furthermore, they suggested that managers should be aware of the potential opportunities offered by climate change such as increased yields (Wrona *et al.*, 2005).

Understanding the responses of fishers and their cultures, communities and households to gradual change or sudden events, *e.g.* changes in the availability of fishes, new legislation, past environmental change and extreme weather events, can provide important information to policymakers on existing adaptive strategies that might minimize vulnerability to climate change and maintain fishery-associated livelihoods (Allison *et al.*, 2001; Berkes & Jolly, 2001). Studies examining traditional ecological knowledge (Silvano & Valbo-Jørgensen, 2008) and traditional management systems (Neiland *et al.*, 2000*b*) from areas that have historically encountered climatic variation such as arid zones have particular value. Allison *et al.* (2007) provided an excellent case study from Lake Chilwa in southern Malawi, which, under favourable (*i.e.* high water level) conditions, provides half of all fish production in Malawi, while during periods of low water, fish yields fall. Allison *et al.* (2007) compared how the fisher community of Lake Chilwa responded to major reductions in lake level. They reported on the development of two main strategies among fishers: the first was shown by local residents who engaged in various mixes of farming, trading, wage labour, self-employment as well as fishing, with fishing and fish trading typically providing between 30 and 50% of the total household income. The second strategy was exhibited by migrants to the area who were heavily dependent on fishing and fish trading, with the two activities contributing >80% to their household incomes. This study highlights the fact that groups of stakeholders that will show different responses and vulnerabilities to climate change. This conclusion was supported by Cinner *et al.* (2009), whose work on individual marine fishers in East Africa examined the proportion of fishers that would exit the fishery with magnitude of decline in catch. They showed that those fishers most likely to stop fishing were from higher-income backgrounds and factors such as level of capital investment in the fishery had no significant influence. Cinner *et al.* (2009) revealed that fishers from the poorest households felt unable to exit a fishery under marked decline, *i.e.* they were subject to a poverty trap.

Climate change will lead to a redistribution of fishing activities. In some areas, freshwater systems and their associated fisheries will be lost (Smith *et al.*, 2005), but in other areas, new opportunities for fisheries will appear (Milner *et al.*, 2008). Following climate change in the Arctic, the northern limit for activities such as forestry and agriculture is predicted to shift north by several hundred kilometres by 2050 (ACIA, 2004; Parry *et al.*, 2007). The northern limit for other human activities is also likely to shift north (Stephenson *et al.*, 2011), opening new systems for recreational and commercial fishing (ACIA, 2004; Wrona *et al.*, 2005), as well as the demand for food and alternative employment. Similar but less drastic shifts are likely in southern South America, where invasive salmonids support economically important recreational fisheries (Soto *et al.*, 2001) and will probably extend their range into Patagonia.

Climate change will also affect patterns of tourism, including recreational fisheries, with more northern areas becoming increasingly accessible for tourists (Hamilton *et al.*, 2005), and possible shifts in the distribution of preferred fishes (Link *et al.*, 2011). The current direction of tourism in Europe is predominantly from the north to the south, but climate change will probably lead to the area of favourable climate for tourists moving northwards (European Environment Agency, 2012*a*), allowing increased potential for fisheries to support and target tourist anglers in these areas. Fisheries managers in these regions need to be aware of the potential to develop fisheries but also ensure that their negative impacts (Cooke & Cowx, 2006; Lewin *et al.*, 2006) are limited. Elsewhere, recreational fishery managers will have to re-evaluate the ethics of angling practices in their waters, as water temperature rises and stress from catch–release activities increases (Gale *et al.*, 2013).

As part of the drive to increase sustainability in freshwater fisheries, there is a need to consider the impacts (Cowx & Gerdeaux, 2004; Cooke & Cowx, 2006; Lewin *et al.*, 2006) and the environmental footprint (Wackernagel *et al.*, 1999; Wheeler & von Braun, 2013) of fisheries and associated activities, including greenhouse gas emissions. Although individual behaviour is very varied (Fisher, 1997), anglers typically use motorized transport to access fisheries, and some individuals travel extreme distances (*e.g.* between continents) to fish particular waters or to target particular species. In commercial and artisanal fisheries, significant amounts of energy (typically provided by fossil fuels) is required to travel to and from the fishing ground, to locate and capture the fishes, to process and preserve the catch (Young & Muir, 2008) and for its transportation to the end consumer (Gulbrandsen, 2012). In terms of fish capture, different gears and fishing techniques have different fuel costs (and emissions), but boat speed is the most important factor (Gulbrandsen, 2012). Commercial and artisanal fishers can optimize their speed, fuel consumption and emissions by keeping the boat hull clean to maximize hydrodynamic efficiency and through the installation of an engine tachometer.

Fisheries are notably reliant on climate-sensitive systems and resources (Sharp, 1987; Badjeck *et al.*, 2010), and fishing practices are typically based on knowledge of particular short-term climatic processes (Sharp, 1987), ecosystems and target fishes that are developed over time and passed between fishers (ACIA, 2004), for example, through local ecological knowledge (LEK; Silvano & Valbo-Jørgensen, 2008). As climate change affects the weather, aquatic systems and fishes, their prey and predators, the utility of LEK built up over generations is becoming less valuable (ACIA, 2004), although knowledge from older members of the community who have previously faced environmental extremes may provide increased adaptive capacity (Silvano & Valbo-Jørgensen, 2008).

As well as the impacts of gradual climate change that will affect the freshwater systems and fish communities on which they rely, climate change means that fishers will become increasingly exposed to changes in weather that may lead to the long-term modification of the ecosystem itself but also can increase the risk of injury or even death, *e.g.* due to changes in ice thickness (Ford *et al.*, 2006) or flooding (Haines *et al.*, 2006). Extreme weather events such as storms and floods may damage gears, risk lives (Haines *et al.*, 2006) and restrict fishery operations (European Environment Agency, 2012*a*). For instance, changes in the length of ice cover and ice thickness in Arctic and cold-temperate regions will affect the ease by which fishers can transport equipment and fish catches across lakes and rivers (ACIA, 2004; Wrona *et al.*, 2005) and fishing strategies themselves (Ford *et al.*, 2006). Increased storminess may also expose fishers to increased risk of injury or drowning, and insurance costs and coverage are likely to change (Wilbanks *et al.*, 2007). Loss of permafrost in the Arctic has led to failures in infrastructure which may affect the suitability of the area to support fisher communities (ACIA, 2004).

Changes in temperature may affect the occupational health of fishers and their communities (McMichael *et al.*, 2006; Bates *et al.*, 2008). The associations between climate change and human health are complex and include increased risk of drowning during flood conditions (European Environment Agency, 2012*a*), as well as a raft of potential health issues (McMichael *et al.*, 2006; Bates *et al.*, 2008; Lafferty, 2009; Altizer *et al.*, 2013). Harmful algal blooms (Paerl & Huisman, 2009) have the potential to cause health problems, as well as cause fish kills and restrict access to fishing grounds or even sales of fishes. Increased air temperatures will increase the risk of heat exposure (Hitz & Smith, 2004; Confalonieri *et al.*, 2007). Exposure to increased concentrations of UVR (Reist *et al.*, 2006c; Häder *et al.*, 2007) has a range of associated health impacts that range between UVR-induced sunburn through to increased risk of skin cancers. Conversely, in regions where air temperatures currently restrict fishery-related activities such as in the Arctic, working condition may improve for fishers, with a reduction in cardiovascular and respiratory deaths and the number of cold weather-associated injuries such as frostbite and traffic accidents (Confalonieri *et al.*, 2007). Fishery managers interested in the probable health implications of climate change are directed towards a EEA report (2012*a*) into vulnerability to climate change.

Management

Fisheries management is by its nature a complicated field (Hart & Reynolds, 2008); it aims to maintain fish yields and allow access to fishery resources to a range of often conflicting stakeholders while minimizing the impact of fishery activities on the fishes and ecosystems that support the fisheries. Climate change has the potential to further test the capacity of fishery professionals to manage fisheries. In some areas, there are almost no baseline data (Hlohowskyj *et al.*, 1996), while other freshwater systems extend across climatic (Latrubesse *et al.*, 2005; Anisimov *et al.*, 2007) and political (Welcomme, 2001; Bootsma & Hecky, 2003; Lynch *et al.*, 2010) boundaries, which will complicate the development and maintenance of management activities (Welcomme *et al.*, 2010) under climate change.

Cooke and Cowx (2006) identified four main approaches to freshwater fisheries management: stock enhancement, rehabilitation and habitat manipulation, regulations and the conservation and protection of fishes and fisheries, all of which will potentially require reconsideration as ecosystems, fishes and fisheries respond to climate change (Hennessy *et al.*, 2007). Regulations regarding stocking practices (Britton *et al.*, 2010), catch limits and fishing activities may require rethinking and regular assessment (Cooke & Cowx, 2006), as will controls on thermal discharges (McCullough *et al.*, 2009). The relative importance of different objectives, strategies and management mechanisms for a particular fishery will differ according to the current and future developmental state of a particular region or state (Welcomme, 2001; Welcomme *et al.*, 2010).

Fisheries managers and scientists are increasingly incorporating climate change into assessment, policy and management decisions (Nelson *et al.*, 2013), with studies on the probable implications of climate change for fishery management, *e.g.* North American Great Lakes (Lynch *et al.*, 2010) and conservation (Rahel *et al.*, 2008). Due to the uncertainties involved, fisheries professionals and fishers will have to appreciate the need for flexibility and change in fisheries management (Brander, 2007), especially as they work together to build resilience to climate change (De Young *et al.*, 2012). In terms of efficiency (Dulvy & Allison, 2009; Badjeck *et al.*, 2010), policy reviews and action plans are most needed in the countries whose fisheries sectors are most vulnerable to climate change (Allison *et al.*, 2009). Climate change has the potential to test the capacity of both fisheries professionals and fishers to operate as weather patterns, fish communities and freshwater ecosystems change; however, this can be minimized by the provision of education and upgrading of skills for both fishers and fishery professionals (Badjeck *et al.*, 2010). There is considerable scope for fishery professionals from well-resourced nations to support their colleagues from less resourced nations or regions (Dixon *et al.*, 2003), possibly under the aegis of international organizations such as the FAO (Sharp, 2003; FAO, 2007; Cochrane *et al*., 2009) or the various world fishery societies via the World Council of Fisheries Societies.

MacNeil *et al.* (2010) noted that ultimately the response of marine fisheries (and the societies they support) will reflect their capacity to adapt to climate change *via* planning and implementing effective responses to change. They further noted that although this is driven by physico-chemical and biological processes, the capacity to adapt also reflects cultural, socio-economic and political circumstances. Such observations extend to fresh waters and highlight the need for adaptive management in freshwater fisheries (Brander, 2007). There is an increasing awareness of the advantages of adaptive management in order to allow successful adaptation to climate change (Kundzewicz *et al*., 2007; Wilby *et al*., 2010; Plagányi *et al*., 2011; European Environment Agency, 2012*b*; Stein *et al*., 2013). At the heart of adaptive management is the informed assessment of risk and the inclusion of stakeholders from a range of backgrounds (Wilby *et al*., 2010) to develop and implement management measures that are subject to regular evaluation and modification.

Fishery professionals can play central roles in such management systems, but specialized inputs from other disciplines will become increasingly important including genetics (Reusch & Wood, 2007; Somero, 2010; Salinas & Munch, 2012; Crozier & Hutchings, 2014), climate modelling (Skeffington *et al*., 2010; Plagányi *et al*., 2011) and the social sciences (Welcomme, 2001). A shift to an ecosystem approach to fisheries management (FAO Fisheries Department, 2003) may allow a more adaptive means to deal with the probable impacts of climate change than the single species and stock approach that still dominates fisheries management (Garcia & Cochrane, 2005; Kempf, 2010; Beard *et al*., 2011). Its use, however, is in the early stages of development in the context of freshwater habitats (Beard *et al*., 2011).

As part of adaptive management, fishery professionals need to provide information on how climate change will affect fisheries, extending from individual fisheries through to the regional and global level. This will involve data gathering and prediction making, as well as the production and dissemination of information to inform decision-making and to initiate dialogue regarding vulnerability, adaptation and mitigation with stakeholder groups including fishers, legislators, scientific colleagues and the general public. These data will also be important for the quantitative analysis of how climate change is affecting the planet's ecology (Brown *et al*., 2011). This may take the approach of other biologists who have examined the vulnerability of particular geographical areas, nations, habitats or taxa to climate change (Allison *et al*., 2009; Edelson *et al*., 2011; Moyle *et al*., 2013).

There is a need to examine the vulnerability of different freshwater fisheries sectors to climate change at a range of scales from continental (Hlohowskyj *et al*., 1996), national (Allison *et al*., 2009) and local, including fishing communities themselves (Ford *et al*., 2006; Badjeck *et al*., 2010). As part of the education component of adaptive management, fishery professionals should inform fishers, legislators and other stakeholders of the likely scenario that they and their fishery face (Parry *et al*., 2007) and provide mitigation and adaptation strategies to allow for the ongoing management of fisheries under climate change, including how climate change will affect the availability and quality of water (Kundzewicz *et al*., 2008) and the vulnerability of freshwater fishes (Williams *et al*., 2008), their prey (Jeppesen *et al*., 2010a) and habitats (Gehrke *et al*., 2011) in the area of interest.

Data are required (Evans & Grainger, 2008) both from the fishery itself (*e.g.* yield, effort and socio-economic structures) (Welcomme, 2011) and the abiotic and biotic factors that influence the fishery (Sharp, 1987). There are a number of key variables (Adrian *et al*., 2009; Hering *et al*., 2010; European Environment Agency, 2012*a*) that will allow the impacts of climate change on freshwater fisheries to be assessed (Table 7.3.7). Some abiotic data such as water temperature and water depth can be measured automatically through the use of low-cost, miniature data loggers which have the added value that, if installed properly, data collection can be continued even through large flood events that prevent manual collection (Isaak & Horan, 2011). Information will probably have to be collected at the level of the individual fisheries; by doing this and by sharing information,

Table 7.3.7 Key variables for monitoring impacts of climate change

Hydrodynamics	Physico-chemistry	Biotic	Fisheries data (collected *via* both fishery independent surveys and catch surveys)
• Ice cover and date of formation and break-up • Water level • River flow • Duration of stratification	• Water temperature* • Dissolved oxygen concentration* • Sulphate concentration • Dissolved organic carbon concentrations • pH • Conductivity • Total organic carbon • Nutrient concentrations • Secchi depth	• Chlorophyll *a* concentration • Phytoplankton biomass and community composition, including proportion of harmful cyanobacteria • Zooplankton biomass and community/size composition	• Fish community structure • Proportion of invasive species • Population size structure • Maturation size • Phenology of spawning and migration • Diet and trophic level of fishes • Parasite loads • Fishing effort • Fishing yield • Size structure of captured fishes

Data from (Adrian *et al*., 2009; Hering *et al*., 2010; European Environment Agency, 2012*a*).
*Measured through water column in lakes.

particularly in data-deficient regions such as Arctic, arid, Mediterranean, and tropical regions as well as the southern hemisphere as a whole (Meisner & Shuter, 1992; Symon *et al.*, 2005; Rosenzweig *et al.*, 2007*b*; Hamilton, 2010; Comte *et al.*, 2013), fishery professionals will be able work towards understanding how fisheries respond to climate change at a regional and global level. Some baseline data may be available, but if not, then fishery professionals should initiate data collection before the worst effects of climate change impact freshwater fisheries. It must be recognized, however, that baseline conditions have probably already been impacted by climate change (Nõges *et al.*, 2007; Hermoso & Clavero, 2013; Logez & Pont, 2013). As in all monitoring programmes, statistical power needs to be considered (Underwood, 1996). If managers do not have the required equipment or knowledge to undertake such monitoring, then fisheries agencies or local universities may be able to help. With the widespread popularity of recreational angling in many parts of the world, there is the potential to utilize citizen science schemes to collect some data (Dickinson *et al.*, 2010; Booth *et al.*, 2011). Finally, there is a strong argument for storage of data in openly available data repositories (Whitlock, 2011), as it will greatly aid the analyses required to understand local, regional and global responses to climate change.

The principle that the past is the key to the future behaviour of a particular system (Kundzewicz *et al.*, 2008) or fishery will become less valid as the impact of climate change increases. Analyses of past behaviour are essential, but as freshwater ecosystems change and move towards regime shifts (Folke *et al.*, 2004), fishery managers, scientists and fishers will need to communicate with colleagues from other regions where such conditions are current. In some case, there may be no homologous systems; here managers, scientists and fishers will have to follow a precautionary principle. Management practices and infrastructure (*e.g.* the supply of suitable water; Kundzewicz *et al.*, 2007, 2008) will have to deal with increased uncertainty, and adaptability will have to be at the core of management and practice in freshwater fisheries. Such changes in management practices will not come without cost and may lead to certain fisheries becoming unsustainable.

Although the links between the burning of fossil fuels and anthropogenic climate change are well recognized (Trenberth *et al.*, 2007), human societies will remain reliant on this form of energy in the future and will continue to seek and exploit new sources, with impacts on freshwater ecosystems and fisheries. Recent developments in shale gas extraction (fracking) will continue, resulting in the widespread extraction of natural gas across the globe, with subsequent environmental impacts (Vidic *et al.*, 2013). Exploitation of oil and gas resources in the Arctic will continue and may intensify as permafrost melts and conditions become less harsh (European Environment Agency, 2012*a*), subsequently increasing the probability of pollution incidents.

As some human societies work to minimize carbon emissions and the environmental impact of their activities, there has been and will continue to be a shift to the use of renewable energy (Dincer, 2000). Although an important means to limit emissions and counter climate change, such technologies are not without significant environmental impacts (Abbasi & Abbasi, 2000), some of which may impact freshwater fisheries. The most obvious is hydropower, which has long had been recognized (Rosenberg *et al.*, 1997; Baxter, 1977) as detrimental to fisheries due to indirect (habitat degradation, changes in flow regimes and disruption of spawning connectivity) and direct (fish mortalities through turbine passage) impacts on fishes. Any increased use of hydropower will result in continued impacts on fishes and the fisheries they support. Conversely, although hydrological regulation associated with hydropower leads to marked changes in ecosystem function and fish community structure (Baxter, 1977; Dudgeon, 2000), it also offers the opportunity for the development of new fisheries (Petrere, 1996; Witte *et al.*, 2009).

Climate change will drive changes in the transmission of disease (Daszak *et al.*, 2001) and fish parasites (Marcogliese, 2001; Macnab & Barber, 2012), both of which have clear potential to affect freshwater fisheries (Barber & Poulin, 2008; Marcos-López *et al.*, 2010). Apart from the monitoring required to fulfil national and international food quality standards (Ababouch, 2006; Unnevehr, 2008), there is a need for maintenance (or development) of suitable cold-storage facilities (Young & Muir, 2008) as well as biosecurity standards (*e.g.* of fish movements and stocking) (Subasinghe, 2005; Scarfe *et al.*, 2006; Håstein *et al.*, 2008). This will require the training and employment of skilled staff or access to suitable specialist assistance from regional fisheries agencies.

The value of long-term monitoring on understanding the impacts of environmental change climate change has been repeatedly highlighted (Magnuson, 1990, 2010; Elliott, 1990). Without long-term data, we would not have been able to track shifts in air and water temperatures, in river flows and lake levels (Table 7.3.4) or the responses of fishes to climate change (O'Reilly *et al.*, 2003; Hickling *et al.*, 2006; Jeppesen *et al.*, 2012). As scientists and citizens, it is essential that we not only act to minimize our individual and collective impacts on the planet, but we also need to ensure that governments maintain support for long-term data collection in the face of calls for austerity or drives to applied science. The future management and conservation of freshwater fisheries depends on it.

References

Ababouch, L. (2006). Assuring fish safety and quality in international fish trade. *Marine Pollution Bulletin* **53,** 561–568.

Abbasi, S. A. & Abbasi, N. (2000). The likely adverse environmental impacts of renewable energy sources. *Applied Energy* **65,** 121–144.

ACIA (2004). *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge: Cambridge University Press.

Adams, S. M., Mclean, R. B. & Huffman, M. M. (1982). Structuring of a predator population through temperature-mediated effects on prey availability. *Canadian Journal of Fisheries and Aquatic Sciences* **39,** 1175–1184.

Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., Livingstone, D. M., Sommaruga, R., Straile, D. & Van Donk, E. (2009). Lakes as sentinels of climate change. *Limnology and Oceanography* **54,** 2283.

Ahas, R. & Aasa, A. (2006). The effects of climate change on the phenology of selected Estonian plant, bird and fish populations. *International Journal of Biometeorology* **51,** 17–26.

Aku, P. M. K. & Tonn, W. M. (1997). Changes in population structure, growth, and biomass of cisco (*Coregonus artedi*) during hypolimnetic oxygenation of a deep, eutrophic lake, Amisk Lake, Alberta. *Canadian Journal of Fisheries and Aquatic Sciences* **54,** 2196–2206.

Aku, P. M. K. & Tonn, W. M. (1999). Effects of hypolimnetic oxygenation on the food resources and feeding ecology of cisco in Amisk Lake, Alberta. *Transactions of the American Fisheries Society* **128,** 17–30.

Alabaster, J. S. & Lloyd, R. (1980). *Water Quality Criteria for Freshwater Fishes*. London: Butterworth Scientific.

Alcamo, J., Moreno, J. M., Nováky, B., Bindi, M., Corobov, R., Devoy, R. J. N., Giannakopoulos, C., Martin, E., Olesen, J. E. & Shvidenko, A. (2007). Europe. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E., eds), pp.541–580. Cambridge: Cambridge University Press.

Allan, J. D. (2004). Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics* **35,** 257–284.

Allan, J. D., Abell, R., Hogan, Z. E. B., Revenga, C., Taylor, B. W., Welcomme, R. L. & Winemiller, K. (2005). Overfishing of inland waters. *BioScience* **55,** 1041–1051.

Allison, E. H., Ellis, F., Mvula, P. M. & Mathieu, L. F. (2001). Fisheries management and uncertainty: The causes and consequences of variability in inland fisheries in Africa, with special reference to Malawi. In *Proceedings of the Lake Malawi Fisheries Management Symposium, Lilongwe, Malawi* (Weyl, O. L. F. & Weyl, M. V., eds), pp. 66–79. Lilongwe: National Aquatic Resource Management Programme.

Allison, E. H., Andrew, N. L. & Oliver, J. (2007). Enhancing the resilience of inland fisheries and aquaculture systems to climate change. *Journal of Semi-Arid Tropical Agricultural Research* **4,** 1–35.

Allison, E. H., Perry, A. L., Badjeck, M.-C., Neil Adger, W., Brown, K., Conway, D., Halls, A. S., Pilling, G. M., Reynolds, J. D., Andrew, N. L. & Dulvy, N. K. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries* **10,** 173–196.

Almodóvar, A., Nicola, G. G., Ayllón, D. & Elvira, B. (2012). Global warming threatens the persistence of Mediterranean brown trout. *Global Change Biology* **18,** 1549–1560.

Altizer, S., Ostfeld, R. S., Johnson, P. T. J., Kutz, S. & Harvell, C. D. (2013). Climate change and infectious diseases: From evidence to a predictive framework. *Science* **341,** 514–519.

Amarasekera, K. N., Lee, R. F., Williams, E. R. & Eltahir, E. A. B. (1997). ENSO and the natural variability in the flow of tropical rivers. *Journal of Hydrology* **200,** 24–39.

Amarasinghe, U. S. & Welcomme, R. L. (2002). An analysis of fish species richness in natural lakes. *Environmental Biology of Fishes* **65,** 327–339.

Anderson, C. & Cabana, G. (2005). δ^{15}N in riverine food webs: Effects of N inputs from agricultural watersheds. *Canadian Journal of Fisheries and Aquatic Sciences* **62,** 333–340.

Anisimov, O. A., Vaughan, D. G., Callaghan, T. V., Furgal, C., Marchant, H., Prowse, T. D., Vilhjálmsson, H. & Walsh, J. E. (2007). Polar regions (Arctic and Antarctic). In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, C. E. & Hanson, C. E., eds), pp. 655–685. Cambridge: Cambridge University Press.

Anneville, O., Souissi, S., Molinero, J. C. & Gerdeaux, D. (2009). Influences of human activity and climate on the stock-recruitment dynamics of whitefish, *Coregonus lavaretus*, in Lake Geneva. *Fisheries Management and Ecology* **16,** 492–500.

April, J., Hanner, R. H., Mayden, R. L. & Bernatchez, L. (2013). Metabolic rate and climatic fluctuations shape continental wide pattern of genetic divergence and biodiversity in fishes. *PLoS One,* **8,** e70296.

Arai, T. (1981). Climatic and geomorphological influences on lake temperature. *Verhandlungen der Internationale Vereinigung für Theoretische und Angewandte Limnologie* **21,** 130–134.

Araújo, M. B. & Peterson, A. T. (2012). Uses and misuses of bioclimatic envelope modeling. *Ecology* **93,** 1527–1539.

Arnell, N. W. (1998). Climate change and water resources in Britain. *Climatic Change* **39,** 83–110.

Arnell, N. W. (1999). Climate change and global water resources. *Global Environmental Change* **9,** S31–S49.

Arvola, L., George, G., Livingstone, D. M., Järvinen, M., Blenckner, T., Dokulil, M. T., Jennings, E., Aonghusa, C. N., Nõges, P., Nõges, T. & Weyhenmeyer, G. A. (2010). The impact of the changing climate on the thermal characteristics of lakes. In *The Impact of Climate Change on European Lakes* (George, D. G., ed.), pp. 85–102. London: Springer.

Austin, J. A. & Colman, S. M. (2007). Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. *Geophysical Research Letters* **34,** L06604.

Badjeck, M.-C., Allison, E. H., Halls, A. S. & Dulvy, N. K. (2010). Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy* **34,** 375–383.

Baettig, M. B., Wild, M. & Imboden, D. M. (2007). A climate change index: Where climate change may be most prominent in the 21st century. *Geophysical Research Letters* **34,** L01705.

Báez, V. H., Aigo, J. D. C. & Cussac, V. E. (2011). Climate change and fish culture in Patagonia: Present situation and perspectives. *Aquaculture Research* **42,** 787–796.

Bancroft, B. A., Baker, N. J. & Blaustein, A. R. (2007). Effects of UVB radiation on marine and freshwater organisms: A synthesis through meta-analysis. *Ecology Letters* **10,** 332–345.

Barange, M. & Perry, R. I. (2009). Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* (Cochrane, K., de Young, C., Soto, D. & Bahri, T., eds), pp. 7–106. Rome: FAO.

Barber, I. & Poulin, R. (2008). Interactions between fish parasites and disease. In *Handbook of Fish Biology and Fisheries* (Hart, P. J. B. & Reynolds, J. D., eds), pp. 359–389. Oxford: Blackwell Publishing Ltd.

Barica, J. & Mathias, J. A. (1979). Oxygen depletion and winterkill risk in small prairie lakes under extended ice cover. *Journal of the Fisheries Research Board of Canada* **36,** 980–986.

Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438,** 303–309.

Baroiller, J. F., D'Cotta, H., Bezault, E., Wessels, S. & Hoerstgen-Schwark, G. (2009). Tilapia sex determination: Where temperature and genetics meet. *Comparative Biochemistry and Physiology A* **153,** 30–38.

Barrow, E. & Hulme, M. (1997). Describing the surface climate of the British Isles. In *Climates of the British Isles: Present, Past and Future* (Hulme, M. & Barrow, E., eds), pp. 33–62. London: Routledge.

Bastviken, D., Tranvik, L. J., Downing, J. A., Crill, P. M. & Enrich-Prast, A. (2011). Freshwater methane emissions offset the continental carbon sink. *Science* **331,** 50.

Bates, B. C., Kundzewicz, Z. W., Wu, S. & Palutikof, J. P. (Eds) (2008). *Climate Change and Water. Technical Paper VI of the Intergovernmental Panel on Climate Change*. Geneva: IPCC Secretariat.

Battarbee, R. W. (2000). Palaeolimnological approaches to climate change, with special regard to the biological record. *Quaternary Science Reviews* **19,** 107–124.

Battarbee, R. W. (2010). Aquatic ecosystem variability and climate change – A palaeoecological perspective. In *Climate Change Impacts on Freshwater Ecosystems* (Kernan, M., Battarbee, R. W. & Moss, B., eds), pp. 15–37. Oxford: Wiley-Blackwell.

Baulch, H. M., Schindler, D. W., Turner, M. A., Findlay, D. L., Paterson, M. J. & Vinebrooke, R. D. (2005). Effects of warming on benthic communities in a boreal lake: Implications of climate change. *Limnology and Oceanography* **50,** 1377–1392.

Baxter, R. M. (1977). Environmental effects of dams and impoundments. *Annual Review of Ecology and Systematics* **8,** 255–283.

Baxter, C., Fausch, K., Murakami, M. & Chapman, P. (2007). Invading rainbow trout usurp a terrestrial prey subsidy from native charr and reduce their growth and abundance. *Oecologia* **153,** 461–470.

Bayley, P. B. (1995). Understanding large river: Floodplain ecosystems. *BioScience* **45,** 153–158.

Beamish, F. W. H. (1964). Respiration of fishes with special emphasis on standard oxygen consumption: II Influences of weight and temperature on respiration of several species. *Canadian Journal of Zoology* **42,** 177–188.

Beard, T. D., Arlinghaus, R., Cooke, S. J., McIntyre, P. B., De Silva, S., Bartley, D. & Cowx, I. G. (2011). Ecosystem approach to inland fisheries: Research needs and implementation strategies. *Biology Letters* **7,** 481–483.

Beauchamp, D. A., Stewart, D. J. & Thomas, G. L. (1989). Corroboration of a bioenergetics model for sockeye salmon. *Transactions of the American Fisheries Society* **118,** 597–607.

Beitinger, T. L., Bennett, W. A. & McCauley, R. W. (2000). Temperature tolerances of North American freshwater fishes exposed to dynamic changes in temperature. *Environmental Biology of Fishes* **58,** 237–275.

Beklioglu, M., Romo, S., Kagalou, I., Quintana, X. & Bécares, E. (2007). State of the art in the functioning of shallow Mediterranean lakes: Workshop conclusions. *Hydrobiologia* **584,** 317–326.

Bell, J. D., Johnson, J. E. & Hobday, A. J. (Eds) (2011). *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Noumea, New Caledonia: Secretariat of the Pacific Community.

Bergman, E. (1987). Temperature-dependent differences in foraging ability of two percids, *Perca fluviatilis* and *Gymnocephalus cernuus*. *Environmental Biology of Fishes* **19,** 45–53.

Berkes, F. & Jolly, D. (2001). Adapting to climate change: Social-ecological resilience in a Canadian western Arctic community. *Conservation Ecology* **5,** article18. http://www.consecol.org/vol5/iss2/art18/

Beyene, T., Lettenmaier, D. & Kabat, P. (2010). Hydrologic impacts of climate change on the Nile River Basin: Implications of the 2007 IPCC scenarios. *Climatic Change* **100,** 433–461.

Bickel, T. O. & Closs, G. P. (2008). Fish distribution and diet in relation to the invasive macrophyte *Lagarosiphon major* in the littoral zone of Lake Dunstan, New Zealand. *Ecology of Freshwater Fish* **17,** 10–19.

Bickford, D., Howard, S., Ng, D. J. & Sheridan, J. (2010). Impacts of climate change on the amphibians and reptiles of Southeast Asia. *Biodiversity and Conservation* **19,** 1043–1062.

Bierwagen, B. G., Rahel, F. J. & Thomas, R. (2008). A synthesis of climate-change effects on aquatic invasive species. *Conservation Biology* **22,** 518–520.

Birkeland, C. & Dayton, P. K. (2005). The importance in fishery management of leaving the big ones. *Trends in Ecology and Evolution* **20,** 356–358.

Black, B. A., Biela, V. R., Zimmerman, C. E. & Brown, R. J. (2012). Lake trout otolith chronologies as multidecadal indicators of high-latitude freshwater ecosystems. *Polar Biology* **36,** 147–153.

Blanck, A. & Lamouroux, N. (2007). Large-scale intraspecific variation in life-history traits of European freshwater fish. *Journal of Biogeography* **34,** 862–875.

Blanco, J. A., Narváez Barandica, J. C. & Viloria, E. A. (2007). ENSO and the rise and fall of a tilapia fishery in northern Colombia. *Fisheries Research* **88,** 100–108.

Blenckner, T., Adrian, R., Livingstone, D. M., Jennings, E., Weyhenmeyer, G. A., George, D. G., Jankowski, T., Järvinen, M., Aonghusa, C. N., Nõges, T., Straile, D. & Teubner, K. (2007). Large-scale climatic signatures in lakes across Europe: A meta-analysis. *Global Change Biology* **13,** 1314–1326.

Blenckner, T., Elliott, A., Markensten, H., Pers, C. & Thackeray, S. (2010). Modeling the effects of climate change on the seasonal dynamics of phytoplankton. In *The Impact of Climate Change on European Lakes* (George, D. G., ed.), pp. 275–292 London: Springer.

Blois, J. L., Zarnetske, P. L., Fitzpatrick, M. C. & Finnegan, S. (2013). Climate Change and the past, present, and future of biotic interactions. *Science* **341,** 499–504.

Blunden, J. & Arndt, D. S. (2013). State of the Climate in 2012. *Bulletin of the American Meteorological Society* **94,** S1–S238.

Boehrer, B. & Schultze, M. (2008). Stratification of lakes. *Reviews of Geophysics* **46,** RG2005.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. & Yanda, P. (2007). Africa. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 433–467 Cambridge: Cambridge University Press.

Bond, N., Thomson, J., Reich, P. & Stein, J. (2011). Using species distribution models to infer potential climate change-induced range shifts of freshwater fish in south-eastern Australia. *Marine and Freshwater Research* **62,** 1043–1061.

Booth, D. J., Bond, N. & Macreadie, P. (2011). Detecting range shifts among Australian fishes in response to climate change. *Marine and Freshwater Research* **62,** 1027–1042.

Bootsma, H. A. & Hecky, R. E. (2003). A comparative introduction to the biology and limnology of the African Great Lakes. *Journal of Great Lakes Research* **29,** 3–18.

Bourke, P., Magnan, P. & Rodríguez, M. (1999). Phenotypic responses of lacustrine brook charr in relation to the intensity of interspecific competition. *Evolutionary Ecology* **13,** 19–31.

Brander, K. M. (2007). Global fish production and climate change. *Proceedings of the National Academy of Sciences* **104,** 19709–19714.

Brännäs, E. & Wilund, B.-S. (1992). Low temperature growth potential of Arctic charr and rainbow trout. *Nordic Journal of Freshwater Research* **67,** 77–81.

Brett, J. R. (1956). Some principles in the thermal requirements of fishes. *Quarterly Review of Biology* **31,** 75–87.

Brett, J. R. (1970). Environmental factors, part I. Temperature. In *Marine Ecology* (Kinne, O., ed.), pp. 515–560. London: John Wiley & Sons, Ltd.

Brett, J. R. (1979). Environmental factors and growth. In *Fish Physiology* Vol. VIII (Hoar, W. S., Randall, D. J. & Brett, J. R., eds), pp. 599–675. New York, NY: Academic Press.

Brett, J. R. & Groves, T. D. D. (1979). Physiological energetics. In *Fish Physiology*, Vol. VIII (Hoar, W. S., Randall, D. J. & Brett, J. R., eds), pp. 279–352. New York, NY: Academic Press.

Britton, J. R., Cucherousset, J., Davies, G. D., Godard, M. J. & Copp, G. H. (2010). Non-native fishes and climate change: Predicting species responses to warming temperatures in a temperate region. *Freshwater Biology* **55,** 1130–1141.

Brooker, M. P., Morris, D. L. & Hemsworth, R. J. (1977). Mass mortalities of adult salmon, *Salmo salar*, in the R. Wye, 1976. *Journal of Applied Ecology* **14,** 409–417.

Brown, B. L. & Swan, C. M. (2010). Dendritic network structure constrains metacommunity properties in riverine ecosystems. *Journal of Animal Ecology* **79,** 571–580.

Brown, J. H., Valone, T. J. & Curtin, C. G. (1997). Reorganization of an arid ecosystem in response to recent climate change. *Proceedings of the National Academy of Sciences of the United States of America* **94,** 9729–9733.

Brown, C. J., Schoeman, D. S., Sydeman, W. J., Brander, K., Buckley, L. B., Burrows, M., Duarte, C. M., Moore, P. J., Pandolfi, J. M., Poloczanska, E., Venables, W. & Richardson, A. J. (2011). Quantitative approaches in climate change ecology. *Global Change Biology* **17,** 3697–3713.

Bruno, J. F., Stachowicz, J. J. & Bertness, M. D. (2003). Inclusion of facilitation into ecological theory. *Trends in Ecology & Evolution* **18,** 119–125.

Bryant, M. D. (2009). Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. *Climatic Change* **95,** 169–193.

Buisson, L. & Grenouillet, G. (2009). Contrasted impacts of climate change on stream fish assemblages along an environmental gradient. *Diversity and Distributions* **15,** 613–626.

Buisson, L., Grenouillet, G., Villéger, S., Canal, J. & Laffaille, P. (2013). Toward a loss of functional diversity in stream fish assemblages under climate change. *Global Change Biology* **19,** 387–400.

Bullock, A. M. & Coutts, R. R. (1985). The impact of solar ultraviolet radiation upon the skin of rainbow trout, *Salmo gairdneri* Richardson, farmed at high altitude in Bolivia. *Journal of Fish Diseases* **8,** 263–272.

Butorina, L. G. (2007). Lake Baikal and other Great Lakes of Asia. In *The Lakes Handbook:* Vol. II (O'Sullivan, P. E. & Reynolds, C. S., eds), pp. 179–199. Oxford: Blackwell Science Ltd.

Byström, P. & García-Berthou, E. (1999). Density dependent growth and size specific competitive interactions in young fish. *Oikos* **86,** 217–232.

Bystrom, P. A. R., Karlsson, J. A. N., Nilsson, P. E. R., Van Kooten, T., Ask, J. & Olofsson, F. (2007). Substitution of top predators: Effects of pike invasion in a subarctic lake. *Freshwater Biology* **52,** 1271–1280.

Caissie, D. (2006). The thermal regime of rivers: A review. *Freshwater Biology* **51,** 1389–1406.

Carpenter, S. R., Fisher, S. G., Grimm, N. B. & Kitchell, J. F. (1992). Global change and freshwater ecosystems. *Annual Review of Ecology and Systematics* **23,** 119–140.

Carpenter, S. R., Stanley, E. H. & Vander Zanden, M. J. (2011). State of the World's freshwater ecosystems: Physical, chemical, and biological changes. *Annual Review of Environment and Resources* **36,** 75–99.

Carvalho, G. R. (1993). Evolutionary aspects of fish distribution: Genetic variability and adaptation. *Journal of Fish Biology* **43,** 53–73.

Carveth, C. J., Widmer, A. M. & Bonar, S. A. (2006). Comparison of upper thermal tolerances of native and nonnative fish species in Arizona. *Transactions of the American Fisheries Society* **135,** 1433–1440.

Casselman, J. M. (2002). Effects of temperature, global extremes, and climate change on year-class production of warmwater, coolwater, and coldwater fishes in the Great Lakes Basin. *American Fisheries Society Symposium* **32,** 20–21.

Casselman, J. M. & Harvey, H. H. (1975). Selective fish mortality resulting from low winter oxygen. *Verhandlungen der Internationale Vereinigung für Theoretische und Angewandte Limnologie* **19,** 2418–2429.

Chapin, F. S., Zavaleta, E. S., Eviner, V. T., Naylor, R. L., Vitousek, P. M., Reynolds, H. L., Hooper, D. U., Lavorel, S., Sala, O. E., Hobbie, S. E., Mack, M. C. & Díaz, S. (2000). Consequences of changing biodiversity. *Nature* **405,** 234–242.

Charnov, E. L. & Gillooly, J. F. (2004). Size and temperature in the evolution of fish life histories. *Integrative and Comparative Biology* **44,** 494–497.

Chatters, J. C., Butler, V. L., Scott, M. J., Anderson, D. M. & Neitzel, D. A. (1995). A paleoscience approach to estimating the effects of climatic warming on salmonid fisheries of the Columbia River basin. *Canadian Special Publication of Fisheries and Aquatic Sciences* **121,** 489–496.

Chessman, B. C. (2013). Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes. *Biological Conservation* **160,** 40–49.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W.-T., Laprise, R., Rueda, V. M., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., Sarr, A. & Whetton, P. (2007). Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L., eds), pp. 847–940. Cambridge: Cambridge University Press.

Chu, C., Mandrak, N. E. & Minns, C. K. (2005). Potential impacts of climate change on the distributions of several common and rare freshwater fishes in Canada. *Diversity & Distributions* **11,** 299–310.

Chubb, J. C. (1976). Seasonal occurrence of helminths in freshwater fishes. Part II: Trematodes. *Advances in Parasitology* **17,** 111–131.

Cinner, J. E., Daw, T. & McClanahan, T. R. (2009). Socioeconomic factors that affect artisanal fishers' readiness to exit a declining fishery. *Conservation Biology* **23,** 124–130.

Claessen, D., De Roos, A. M. & Persson, L. (2000). Dwarfs and giants: Cannibalism and competition in size-structured populations. *American Naturalist* **155,** 219–237.

Clark, M. E., Rose, K. A., Levine, D. A. & Hargrove, W. W. (2001). Predicting climate change effects on Appalachian trout: Combining GIS and individual-based modeling. *Ecological Applications* **11,** 161–178.

Clarke, A. & Johnston, N. M. (1999). Scaling of metabolic rate with body mass and temperature in teleost fish. *Journal of Animal Ecology* **68,** 893–905.

Clews, E., Durance, I., Vaughan, I. P. & Ormerod, S. J. (2010). Juvenile salmonid populations in a temperate river system track synoptic trends in climate. *Global Change Biology* **16,** 3271–3283.

Cochrane, K., De Young, C., Soto, D. & Bahri, T. (Eds) (2009). *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge*. Rome: FAO.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J. & Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* **10,** 172–185.

Comte, L. & Grenouillet, G. (2013). Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography* **36,** 1236–1246.

Comte, L., Buisson, L., Daufresne, M. & Grenouillet, G. (2013). Climate-induced changes in the distribution of freshwater fish: Observed and predicted trends. *Freshwater Biology* **58,** 625–639.

Confalonieri, U., Menne, B., Akhtar, R., Ebi, K. L., Hauengue, M., Kovats, R. S., Revich, B. & Woodward, A. (2007). Human health. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 391–431 Cambridge: Cambridge University Press.

Conover, D. O. (1992). Seasonality and the scheduling of life history at different latitudes. *Journal of Fish Biology* **41,** 161–178.

Cook, J., Nuccitelli, D., Green, S. A., Richardson, M., Winkler, B., Painting, R., Way, R., Jacobs, J. & Skuce, A. (2013). Quantifying the consensus on anthropogenic global warming in the scientific literature. *Environmental Research Letters* **8,** 024024.

Cooke, S. J. & Cowx, I. G. (2006). Contrasting recreational and commercial fishing: Searching for common issues to promote unified conservation of fisheries resources and aquatic environments. *Biological Conservation* **128,** 93–108.

Cooke, S. J., Hinch, S. G., Farrell, A. P., Lapointe, M. F., Jones, S. R. M., Macdonald, J. S., Patterson, D. A., Healey, M. C. & Van Der Kraak, G. (2004). Abnormal migration timing and high *en route* mortality of sockeye salmon in the Fraser River, British Columbia. *Fisheries* **29,** 22–33.

Costelloe, J. F., Reid, J. R. W., Pritchard, J. C., Puckridge, J. T., Bailey, V. E. & Hudson, P. J. (2010). Are alien fish disadvantaged by extremely variable flow regimes in arid-zone rivers? *Marine and Freshwater Research* **61,** 857–863.

Coutant, C. C. (1985). Striped bass, temperature and dissolved oxygen: A speculative hypothesis for environmental risk. *Transactions of the American Fisheries Society* **114,** 31–61.

Coutant, C. C. (1987). Thermal preference: When does an asset become a liability. *Environmental Biology of Fishes* **18,** 161–172.

Coutant, C. C. (1990). Temperature-oxygen habitat for freshwater and coastal striped bass in a changing climate. *Transactions of the American Fisheries Society* **119,** 240–253.

Coutant, C. C. (2006). Thermal effects on fish ecology. In *Encyclopedia of Environmental Engineering*, Vol. II (Pfafflin, J. R. & Ziegler, E. N., eds). London, UK: CRC, Taylor & Francis.

Cowx, I. G. & Gerdeaux, D. (2004). The effects of fisheries management practises on freshwater ecosystems. *Fisheries Management and Ecology* **11,** 145–151.

Craig, P. C. (1984). Fish use of coastal waters of the Alaskan Beaufort Sea: A review. *Transactions of the American Fisheries Society* **113,** 265–282.

Craig, P. C. (1989). An introduction to anadromous fishes in the Alaskan Arctic. In *Research Advances on Anadromous Fish in Arctic Alaska and Canada***,** pp. 27–54. Fairbanks, AK: Institute of Arctic Biology, University of Alaska Fairbanks.

Craig, J. K., Foote, C. J. & Wood, C. C. (1996). Evidence for temperature-dependent sex determination in sockeye salmon (*Oncorhynchus nerka*). *Canadian Journal of Fisheries and Aquatic Sciences* **53,** 141–147.

Croisetière, S., Bernatchez, L. & Belhumeur, P. (2010). Temperature and length-dependent modulation of the MH class IIβ gene expression in brook charr (*Salvelinus fontinalis*) by a cis-acting minisatellite. *Molecular Immunology* **47,** 1817–1829.

Crowder, L. B., Magnuson, J. J. & Brandt, S. B. (1981). Complementarity in the use of food and thermal habitat by Lake Michigan fishes. *Canadian Journal of Fisheries and Aquatic Sciences* **38,** 662–668.

Crowley, T. J. (1983). The geologic record of climate change. *Reviews of Geophysics and Space Physics* **24,** 828–877.

Crozier, L. G. & Hutchings, J. A. (2014). Plastic and evolutionary responses to climate change in fish. *Evolutionary Applications* **7,** 68–87.

Cruz, R. V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C. & Huu Ninh, N. (2007). Asia. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 469–506 Cambridge: Cambridge University Press.

Cucherousset, J. & Olden, J. D. (2011). Ecological impacts of non-native freshwater fishes. *Fisheries* **36,** 215–230.

Cury, P. & Pauly, D. (2000). Patterns and propensities in reproduction and growth of marine fishes. *Ecological Research* **15,** 101–106.

Cury, P. M., Shin, Y.-J., Planque, B., Durant, J. M., Fromentin, J.-M., Kramer-Schadt, S., Stenseth, N. C., Travers, M. & Grimm, V. (2008). Ecosystem oceanography for global change in fisheries. *Trends in Ecology & Evolution* **23,** 338–346.

Cussac, V. E., Fernández, D. A., Gómez, S. E. & López, H. L. (2009). Fishes of southern South America: A story driven by temperature. *Fish Physiology and Biochemistry* **35,** 29–42.

Daszak, P., Cunningham, A. A. & Hyatt, A. D. (2001). Anthropogenic environmental change and the emergence of infectious diseases in wildlife. *Acta Tropica* **78,** 103–116.

Daufresne, M. & Boët, P. (2007). Climate change impacts on structure and diversity of fish communities in rivers. *Global Change Biology* **13,** 2467–2478.

Daufresne, M., Roger, M. C., Capra, H. & Lamouroux, N. (2003). Long-term changes within the invertebrate and fish communities of the Upper Rhône River: Effects of climatic factors. *Global Change Biology* **10,** 124–140.

Daufresne, M., Lengfellner, K. & Sommer, U. (2009). Global warming benefits the small in aquatic ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* **106,** 12788-12793.

Davey, A. & Jellyman, D. (2005). Sex determination in freshwater eels and management options for manipulation of sex. *Reviews in Fish Biology and Fisheries* **15,** 37–52.

Daw, T., Adger, W. N., Brown, K. & Badjeck, M.-C. (2009). Climate change and capture fisheries: Potential impacts, adaptation and mitigation. In *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* (Cochrane, K., De Young, C., Soto, D. & Bahri, T., eds), pp. 107–150 Rome: FAO.

De Stasio, B. T., Jr., Hill, D. K., Kleinhans, J. M., Nibbelink, N. P. & Magnuson, J. J. (1996). Potential effects of global climate change on small north-temperate lakes: Physics, fish, and plankton. *Limnology and Oceanography* **41,** 1136–1149.

De Young, C., Soto, D., Bahri, T. & Brown, D. (2012). Building resilience for adaptation to climate change in the fisheries and aquaculture sector. In *Building Resilience for Adaptation to Climate Change in the Agriculture Sector: Proceedings of a Joint FAO/OECD Workshop 23–24 April 2012* (Meybeck, A., Lankoski, J., Redfern, S., Azzu, N. & Gitz, V., eds), pp. 103–116 Rome: FAO.

Deangelis, D. L. & Cushman, R. M. (1990). Potential application of models in forecasting the effects of climate changes on fisheries. *Transactions of the American Fisheries Society* **119,** 224–239.

Defeo, O., Castrejón, M., Ortega, L., Kuhn, A. M., Gutiérrez, N. L. & Castilla, J. C. (2013). Impacts of climate variability on Latin American small-scale fisheries. *Ecology and Society* **18**, 30. doi 10.5751/es-05971-180430.

Dell, A. I., Pawar, S. & Savage, V. M. (2013). Temperature dependence of trophic interactions are driven by asymmetry of species responses and foraging strategy. *Journal of Animal Ecology* **83**, 70–84.

Delpla, I., Jung, A. V., Baures, E., Clement, M. & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. *Environment International* **35,** 1225–1233.

Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Da Silva Dias, P. L., Wofsy, S. C., Zhang, X. (2007). Couplings between changes in the climate system and biogeochemistry. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L., eds), pp. 357–390 Cambridge: Cambridge University Press.

Dickinson, J. L., Zuckerberg, B. & Bonter, D. N. (2010). Citizen science as an ecological research tool: Challenges and benefits. *Annual Review of Ecology, Evolution, and Systematics* **41,** 149–172.

Dincer, I. (2000). Renewable energy and sustainable development: A crucial review. *Renewable and Sustainable Energy Reviews* **4,** 157–175.

Dixon, R. K., Smith, J. & Guill, S. (2003). Life on the edge: Vulnerability and adaptation of African ecosystems to global climate change. *Mitigation and Adaptation Strategies for Global Change* **8,** 93–113.

Dokulil, M. T. (2013). Impact of climate warming on European inland waters. *Inland Waters* **4,** 27–40.

Doudoroff, P. & Shumway, D. L. (1970). *Dissolved Oxygen Requirements of Freshwater Fishes*. Rome: Food and Agriculture Organization of the United Nations.

Downing, J. A., Prairie, Y. T., Cole, J. J., Duarte, C. M., Tranvik, L. J., Striegl, R. G., McDowell, W. H., Kortelainen, P., Caraco, N. F., Melack, J. M. & Middelburg, J. J. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography* **51,** 2388–2397.

Dudgeon, D. (2000). Large-scale hydrological changes in tropical Asia: Prospects for riverine biodiversity. *BioScience* **50,** 793–806.

Duguay, C. R., Prowse, T. D., Bonsal, B. R., Brown, R. D., Lacroix, M. P. & Ménard, P. (2006). Recent trends in Canadian lake ice cover. *Hydrological Processes* **20,** 781–801.

Dukes, J. S. & Mooney, H. A. (1999). Does global change increase the success of biological invaders? *Trends in Ecology and Evolution* **14,** 135–139.

Dulvy, N. & Allison, E. (2009). A place at the table? *Nature Reports Climate Change* **3,** 68–70.

Durant, J. M., Hjermann, D. Ø., Ottersen, G. & Stenseth, N. C. (2007). Climate and the match or mismatch between predator requirements and resource availability. *Climate Research* **33,** 271–283.

Eaton, J. G. & Scheller, R. M. (1996). Effects of climate warming on fish thermal habitat in streams of the United States. *Limnology and Oceanography* **41,** 1109–1115.

Eaton, J. G., McCormick, J. H., Goodno, B. E., O'Brien, D. G., Stefany, H. G., Hondzo, M. & Scheller, R. M. (1995). A field information-based system for estimating fish temperature tolerances. *Fisheries* **20,** 10–18.

Edelson, N. A., Glick, P. & Stein, B. A. (Eds) (2011). *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment*. Washington, DC: National Wildlife Federation.

Edsall, T. A. & Colby, P. J. (1970). Temperature tolerance of young-of-the-year Cisco, *Coregonus artedii*. *Transactions of the American Fisheries Society* **99,** 526–531.

Eliason, E. J., Clark, T. D., Hague, M. J., Hanson, L. M., Gallagher, Z. S., Jeffries, K. M., Gale, M. K., Patterson, D. A., Hinch, S. G. & Farrell, A. P. (2011). Differences in thermal tolerance among sockeye salmon populations. *Science* **332,** 109–112.

Elith, J., Kearney, M. & Phillips, S. (2010). The art of modelling range-shifting species. *Methods in Ecology and Evolution* **1,** 330–342.

Elliott, J. M. (1990). The need for long-term investigations in ecology and the contribution of the Freshwater Biological Association. *Freshwater Biology* **23,** 1–5.

Elliott, J. A. & Bell, V. A. (2011). Predicting the potential long-term influence of climate change on vendace (*Coregonus albula*) habitat in Bassenthwaite Lake, U.K. *Freshwater Biology* **56,** 395–405.

Elliott, J. M. & Elliott, J. A. (2010). Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: Predicting the effects of climate change. *Journal of Fish Biology* **77,** 1793–1817.

Elliott, J. M., Hurley, M. A. & Maberly, S. C. (2000). The emergence period of sea trout fry in a Lake District stream correlates with the North Atlantic Oscillation. *Journal of Fish Biology* **56,** 208–210.

Elmer, K. R., Lehtonen, T. K., Kautt, A. F., Harrod, C. & Meyer, A. (2010). Rapid sympatric ecological differentiation of crater lake cichlid fishes within historic times. *BMC Biology* **8,** 60.

Enfield, D. B., Mestas-Nuñez, A. M. & Trimble, P. J. (2001). The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* **28,** 2077–2080.

European Environment Agency (2012*a*). *Climate Change, Impacts and Vulnerability in Europe 2012: An Indicator Based Report*. Copenhagen: European Environment Agency.

European Environment Agency (2012*b*). *Water Resources in Europe in the Context of Vulnerability: EEA 2012 State of Water Assessment.* Copenhagen: European Environment Agency.

Evans, M. S. (2007). The North American great lakes: A Laurentian Great Lakes focus. In *The Lakes Handbook*, Vol. 2: Lake Restoration and Rehabilitation (O'Sullivan.P.E. & Reynolds, C.S., eds), pp. 65–75. Oxford: Blackwell Science Ltd.

Evans, D. & Grainger, R. (2008). Gathering data for resource monitoring and fisheries management. In *Handbook of Fish Biology and Fisheries* (Hart, P. J. B. & Reynolds, J. D., eds), pp. 84–102. Oxford: Blackwell Science Ltd.

Fang, X. & Stefan, H. G. (1999). Projections of climate change effects on water temperature characteristics of small lakes in the contiguous U.S. *Climatic Change* **42,** 377–412.

Fang, X. & Stefan, H. G. (2009). Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous United States under past and future climate scenarios. *Limnology and Oceanography* **54,** 2359–2370.

Fang, X., Stefan, H. G., Eaton, J. G., McCormick, J. H. & Alam, S. R. (2004*a*). Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 1. Cool-water fish in the contiguous US. *Ecological Modelling* **172,** 13–37.

Fang, X., Stefan, H. G., Eaton, J. G., McCormick, J. H. & Alam, S. R. (2004*b*). Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 2. Cold-water fish in the contiguous US. *Ecological Modelling* **172,** 39–54.

Fang, X., Stefan, H. G., Eaton, J. G., McCormick, J. H. & Alam, S. R. (2004*c*). Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 3. Warm-water fish in the contiguous US. *Ecological Modelling* **172,** 55–68.

FAO (2007). *Building Adaptive Capacity to Climate Change. Policies to Sustain Livelihoods and Fisheries*. Rome: FAO Sustainable Fisheries Livelihoods Programme.

FAO (2012). *Recreational Fisheries*. Rome: FAO Sustainable Fisheries Livelihoods Programme.

FAO Fisheries and Aquaculture Department (2012). *The State of World Fisheries and Aquaculture 2012*. Rome: Food and Agriculture Organization of the United Nations.

FAO Fisheries Department (2003). *The Ecosystem Approach to Fisheries*. Rome: Food and Agriculture Organization of the United Nations.

Fausch, K. D., Taniguchi, Y., Nakano, S., Grossman, G. D. & Townsend, C. R. (2001). Flood disturbance regimes influence rainbow trout invasion success among five Holarctic regions. *Ecological Applications* **11,** 1438–1455.

Ficke, A., Myrick, C. & Hansen, L. (2007). Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries* **17,** 581–613.

Field, C. B., Mortsch, L. D., Brklacich, M., Forbes, D. L., Kovacs, P., Patz, J. A., Running, S. W. & Scott, M. J. (2007). North America. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 617–652 Cambridge: Cambridge University Press.

Filipe, A., Lawrence, J. & Bonada, N. (2012). Vulnerability of stream biota to climate change in mediterranean climate regions: A synthesis of ecological responses and conservation challenges. *Hydrobiologia* **719**, 331–351.

Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., Rounsevell, M. D. A., Dube, O. P., Tarazona, J. & Velichko, A. A. (2007). Ecosystems, their properties, goods and services. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 211–272. Cambridge: Cambridge University Press.

Fisher, M. R. (1997). Segmentation of the angler population by catch preference, participation, and experience: A management-oriented application of recreation specialization. *North American Journal of Fisheries Management* **17,** 1–10.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L. & Holling, C. (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics* **35,** 557–581.

Ford, J. D., Smit, B. & Wandel, J. (2006). Vulnerability to climate change in the Arctic: A case study from Arctic Bay, Canada. *Global Environmental Change* **16,** 145–160.

Forster, J., Hirst, A. G. & Atkinson, D. (2012). Warming-induced reductions in body size are greater in aquatic than terrestrial species. *Proceedings of the National Academy of Sciences* **109,** 19310–19314.

Frame, D. J. & Stone, D. A. (2012). Assessment of the first consensus prediction on climate change. *Nature Climate Change* **3**, 357–359.

France, R. L. (1996). Scope for use of stable carbon isotopes in discerning the incorporation of forest detritus into aquatic foodwebs. *Hydrobiologia* **325,** 219–222.

Friedland, K. D., Hansen, L. P., Dunkley, D. A. & Maclean, J. C. (2000). Linkage between ocean climate, post-smolt growth, and survival of Atlantic salmon (Salmo salar L.) in the North Sea area. *ICES Journal of Marine Science* **57,** 419–429.

Friedland, K. D., Reddin, D. G., McMenemy, J. R. & Drinkwater, K. F. (2003). Multidecadal trends in North American Atlantic salmon (*Salmo salar*) stocks and climate trends relative to juvenile survival. *Canadian Journal of Fisheries and Aquatic Sciences* **60,** 563–583.

Fry, F. E. J. (1937). The summer migration of the cisco, *Leucichthys artedi* (Le Sueur), in Lake Nipissing, Ontario. *Publications of the Ontario Fisheries Research Laboratory* **55,** 1–91.

Fry, F. E. J. (1947). Effects of the environment on animal activity. *University of Toronto Studies in Biology Series* **55,** 1–62.

Fry, F. E. J. (1971). The effect of environmental factors on the physiology of fish. In *Fish Physiology,* Vol. VI *Environmental Relations and Behavior* (Hoar, W. S. & Randall, D. J., eds), pp. 1–98. New York, NY: Academic Press.

Gaboury, M. N. & Patalas, J. W. (1984). Influence of water level drawdown on the fish populations of Cross Lake, Manitoba. *Canadian Journal of Fisheries and Aquatic Sciences* **41,** 118–125.

Gabriele, O., Lange, K., Dahm, E. & Wendt, T. (2005). *Fish Catching Methods of the World*, 4th edn. Oxford: Blackwell Publishing.

Gaeta, J. W., Sass, G. G. & Carpenter, S. R. (2014). Drought-driven lake level decline: Effects on coarse woody habitat and fishes. *Canadian Journal of Fisheries and Aquatic Sciences* **71**, 315–325.

Gale, M. K., Hinch, S. G. & Donaldson, M. R. (2013). The role of temperature in the capture and release of fish. *Fish and Fisheries* **14,** 1–33.

Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z., Freney, J. R., Martinelli, L. A., Seitzinger, S. P. & Sutton, M. A. (2008). Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* **320,** 889–892.

Garcia, S. M. & Cochrane, K. L. (2005). Ecosystem approach to fisheries: A review of implementation guidelines. *ICES Journal of Marine Science: Journal du Conseil* **62,** 311–318.

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta–Martínez, T. & Beguería, S. (2011). Mediterranean water resources in a global change scenario. *Earth-Science Reviews* **105,** 121–139.

Garner, G., Hannah, D. M., Sadler, J. P. & Orr, H. G. (2014). River temperature regimes of England and Wales: Spatial patterns, inter-annual variability and climatic sensitivity. *Hydrological Processes* **28,** 5583–5598. Doi: 10.1002/hyp.9992.

Gasith, A. & Resh, V. H. (1999). Streams in Mediterranean climate regions: Abiotic influences and biotic responses to predictable seasonal events. *Annual Review of Ecology and Systematics* **30,** 51–81.

Gehrke, P. C., Sheaves, M. J., Terry, J. P., Boseto, D. T., Ellison, J. C., Figa, B. S. & Wani, J. (2011). Vulnerability of freshwater and estuarine fish habitats in the tropical Pacific to climate change. In *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* (Bell, J. D., Johnson, J. E. & Hobday, A. J., eds), pp. 369–431. Noumea: Secretariat of the Pacific Community.

George, D. G. (Ed.) 2010. *The Impact of Climate Change on European Lakes*. London: Springer.

George, D. G., Maberly, S. C. & Hewitt, D. P. (2004). The influence of the North Atlantic Oscillation on the physical, chemical and biological characteristics of four lakes in the English Lake District. *Freshwater Biology* **49,** 760–774.

George, G., Hurley, M. & Hewitt, D. (2007). The impact of climate change on the physical characteristics of the larger lakes in the English Lake District. *Freshwater Biology* **52,** 1647–1666.

George, D. G., Jennings, E. & Allott, N. (2010). The impact of climate change on lakes in Britain and Ireland. In *The Impact of Climate Change on European Lakes* (George, D. G., ed.). London: Springer.

Ghent, A. W. & Hanna, B. P. (1999). Statistical assessment of Huntsman's 3-y salmon-rainfall correlation and other potential correlations, in the Miramichi fishery, New Brunswick. *The American Midland Naturalist* **142,** 110–128.

Gillet, C. & Quétin, P. (2006). Effect of temperature changes on the reproductive cycle of roach in Lake Geneva from 1983 to 2001. *Journal of Fish Biology* **69,** 518–534.

Gillet, C., Dubois, J. P. & Bonnet, S. (1995). Influence of temperature and size of females on the timing of spawning of perch, *Perca fluviatilis*, in Lake Geneva from 1984 to 1993. *Environmental Biology of Fishes* **42,** 355–363.

Gillooly, J. F., Brown, J. H., West, G. B., Savage, V. M. & Charnov, E. L. (2001). Effects of size and temperature on metabolic rate. *Science* **293,** 2248–2251.

Gillooly, J. F., Charnov, E. L., West, G. B., Savage, V. M. & Brown, J. H. (2002). Effects of size and temperature on developmental time. *Nature* **417,** 70–73.

Gleeson, T., Wada, Y., Bierkens, M. F. P. & Van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature* **488,** 197–200.

Goldman, C. R., Kumagai, M. & Robarts, R. D. (Eds) (2013). *Climatic Change and Global Warming of Inland Waters: Impacts and Mitigation for Ecosystems and Societies*. Oxford: Wiley-Blackwell.

González-Bergonzoni, I., Meerhoff, M., Davidson, T., Teixeira-De Mello, F., Baattrup-Pedersen, A. & Jeppesen, E. (2012). Meta-analysis shows a consistent and strong latitudinal pattern in fish omnivory across ecosystems. *Ecosystems* **15,** 492–503.

Goode, J. R., Buffington, J. M., Tonina, D., Isaak, D. J., Thurow, R. F., Wenger, S., Nagel, D., Luce, C., Tetzlaff, D. & Soulsby, C. (2013). Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. *Hydrological Processes* **27,** 750–765.

Graham, C. T. & Harrod, C. (2009). Implications of climate change for the fishes of the British Isles. *Journal of Fish Biology* **74,** 1143–1205.

Greenbank, J. (1945). Limnological conditions in ice-covered lakes, especially as related to winter-kill of fish. *Ecological Monographs* **15,** 343–392.

Gregersen, F., Vøllestad, L. A., Østbye, K., Aass, P. & Hegge, O. (2011). Temperature and food-level effects on reproductive investment and egg mass in vendace, *Coregonus albula*. *Fisheries Management and Ecology* **18,** 263–269.

Gregory, S. V., Swanson, F. J., McKee, W. A. & Cummins, K. W. (1991). An ecosystem perspective of riparian zones. *BioScience* **41,** 540–551.

Grenouillet, G., Hugueny, B., Carrel, G. A., Olivier, J. M. & Pont, D. (2001). Large-scale synchrony and inter-annual variability in roach recruitment in the Rhône River: The relative role of climatic factors and density-dependent processes. *Freshwater Biology* **46,** 11–26.

Grey, J., Jones, R. I. & Sleep, D. (2001). Seasonal changes in the importance of allochthonous organic matter to the diet of zooplankton in Loch Ness indicated by stable isotope analysis. *Limnology and Oceanography* **46,** 505–513.

Grey, J., Kelly, A. & Jones, R. I. (2004). High intraspecific variability in carbon and nitrogen stable isotope ratios of lake chironomid larvae. *Limnology and Oceanography* **49,** 239–244.

Griffiths, D. & Harrod, C. (2007). Natural mortality, growth parameters, and environmental temperature in fishes revisited. *Canadian Journal of Fisheries and Aquatic Sciences* **64,** 249–255.

Griffiths, D. & Kirkwood, R. C. (1995). Seasonal variation in growth, mortality and fat stores of roach and perch in Lough Neagh, Northern Ireland. *Journal of Fish Biology* **47,** 537–554.

Grimalt, J. O., Catalan, J., Fernandez, P., Piña, B. & Munthe, J. (2010). Distribution of persistent organic pollutants and mercury in freshwater ecosystems under changing climate conditions. In *Climate Change Impacts on Freshwater Ecosystems* (Kernan, M., Battarbee, R. W. & Moss, B., eds), pp. 180–202. Oxford: Wiley-Blackwell.

Grimm, N. B., Chapin, F. S., Bierwagen, B., Gonzalez, P., Groffman, P. M., Luo, Y., Melton, F., Nadelhoffer, K., Pairis, A., Raymond, P. A., Schimel, J. & Williamson, C. E. (2013). The impacts of climate change on ecosystem structure and function. *Frontiers in Ecology and the Environment* **11,** 474–482.

Gulbrandsen, O. (2012). *Fuel Savings for Small Fishing Vessels: A Manual*. Rome: Food and Agriculture Organization of the United Nations

Gyllström, M., Hansson, L. A., Jeppesen, E., Garcia-criado, F., Gross, E., Irvine, K., Kairesalo, T., Kornijow, R., Miracle, M. & Nykänen, M. (2005). The role of climate in shaping zooplankton communities of shallow lakes. *Limnology & Oceanography* **50,** 2008–2021.

Häder, D. P., Kumar, H. D., Smith, R. C. & Worrest, R. C. (2007). Effects of solar UV radiation on aquatic ecosystems and interactions with climate change. *Photochemical & Photobiological Sciences* **6,** 267–285.

Haines, A., Kovats, R. S., Campbell-Lendrum, D. & Corvalan, C. (2006). Climate change and human health: Impacts, vulnerability, and mitigation. *The Lancet* **367,** 2101–2109.

Hamilton, S. K. (2010). Biogeochemical implications of climate change for tropical rivers and floodplains. *Hydrobiologia* **657,** 19–35.

Hamilton, J. M., Maddison, D. J. & Tol, R. S. J. (2005). Climate change and international tourism: A simulation study. *Global Environmental Change* **15,** 253–266.

Hampton, S. E., Izmest'eva, L. R., Moore, M. V., Katz, S. L., Dennis, B. & Silow, E. A. (2008). Sixty years of environmental change in the world's largest freshwater lake – Lake Baikal, Siberia. *Global Change Biology* **14,** 1947–1958.

Hamrin, S. F. (1986). Vertical distribution and habitat partitioning between different size classes of vendace, *Coregonus albula*, in thermally stratified lakes. *Canadian Journal of Fisheries and Aquatic Sciences* **43,** 1617–1625.

Hamrin, S. F. & Persson, L. (1986). Asymmetrical competition between age classes as a factor causing population oscillations in an obligate planktivorous fish species. *Oikos* **47,** 223–232.

Hari, R. E., Livingstone, D. M., Siber, R., Burkhardt-Holm, P. & Guttinger, H. (2006). Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams. *Global Change Biology* **12,** 10–26.

Harley, C. D. G., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J. B., Thornber, C. S., Rodriguez, L. F., Tomanek, L. & Williams, S. L. (2006). The impacts of climate change in coastal marine systems. *Ecology Letters* **9,** 228–241.

Härmä, M., Lappalainen, A. & Urho, L. (2008). Reproduction areas of roach (*Rutilus rutilus*) in the northern Baltic Sea: Potential effects of climate change. *Canadian Journal of Fisheries and Aquatic Sciences* **65,** 2678–2688.

Harrod, C. & Grey, J. (2006). Isotopic variation complicates analysis of trophic relations within the fish community of Plußsee: A small, deep, stratifying lake. *Archiv für Hydrobiologie* **167,** 281–299.

Harrod, C., Griffiths, D., Rosell, R. & Mccarthy, T. K. (2002). Current status of the pollan (*Coregonus autumnalis Pallas* 1776) in Ireland. *Archiv für Hydrobiologie Beiheft: Ergebnisse der Limnologie* **57,** 627–638.

Hart, P. J. B. & Reynolds, J. D. (2008). The human dimension of fisheries science. In *Handbook of Fish Biology and Fisheries* (Hart, P. J. B. & Reynolds, J. D., eds), pp. 1–10. Oxford: Blackwell Science Ltd.

Hasler, A. D. (1947). Eutrophication of lakes by domestic drainage. *Ecology* **28,** 383–395.

Hasnain, S. S., Minns, C. K. & Shuter, B. J. (2010). *Key Ecological Temperature Metrics for Canadian Freshwater Fishes*. Sault Ste Marie, ON: Applied Research and Development Branch, Ministry of Natural Resources.

Håstein, I., Binde, M., Hine, M., Johnsen, S., Lillehaug, A., Olesen, N. J., Purvis, N., Scarfe, A. D. & Wright, B. (2008). National biosecurity approaches, plans and programmes in response to diseases in farmed aquatic animals: Evolution, effectiveness and the way forward. *Revue Scientifique Et Technique-Office International Des Epizooties* **27,** 125–145.

Hatcher, K. L. & Jones, J. A. (2013). Climate and streamflow trends in the Columbia River Basin: Evidence for ecological and engineering resilience to climate change. *Atmosphere-Ocean* **51,** 436–455.

Hayden, B., Harrod, C. & Kahilainen, K. K. (2013*a*). Lake morphometry and resource polymorphism determine niche segregation between cool- and cold-water adapted fish. *Ecology* **95**, 538–552.

Hayden, B., Harrod, C. & Kahilainen, K. K. (2013*b*). The effects of winter ice cover on the trophic ecology of whitefish (*Coregonus lavaretus* L.) in subarctic lakes. *Ecology of Freshwater Fish* **22,** 192–201.

Hayden, B., Holopainen, T., Amundsen, P.-A., Eloranta, A. P., Knudsen, R., Præbel, K. & Kahilainen, K. K. (2013*c*). Interactions between invading benthivorous fish and native whitefish in subarctic lakes. *Freshwater Biology* **58,** 1234–1250.

Headrick, M. R. & Carline, R. F. (1992). Restricted summer habitat and growth of northern pike in two southern Ohio impoundments. *Transactions of the American Fisheries Society* **122,** 228–236.

Heath, M. R. (2005). Changes in the structure and function of the North Sea fish foodwebs, 1973-2000. *ICES Journal of Marine Science* **62,** 847–868.

Hecky, R. E. & Hesslein, R. H. (1995). Contributions of benthic algae to lake food webs as revealed by stable isotope analysis. *Journal of the North American Benthological Society* **14,** 631–653.

Heibo, E., Magnhagen, C. & Vøllestad, L. A. (2005). Latitudinal variation in life-history traits in Eurasian perch. *Ecology* **86,** 3377–3386.

Hein, C. L., Öhlund, G. & Englund, G. (2011). Dispersal through stream networks: Modelling climate-driven range expansions of fishes. *Diversity and Distributions* **17,** 641–651.

Heino, J., Virkkala, R. & Toivonen, H. (2009). Climate change and freshwater biodiversity: Detected patterns, future trends and adaptations in northern regions. *Biological Reviews* **84,** 39–54.

Helfman, G. S., Collette, B. B., Facey, D. E. & Bowen, B. W. (2009). *The Diversity of Fishes*, 2nd edn. Oxford: Blackwell Science.

Helminen, H., Sarvala, J. & Karjalainen, J. (1997). Patterns in vendace recruitment in Lake Pyhäjärvi, south-west Finland. *Journal of Fish Biology* **51** (Suppl. A)**,** 303–316.

Hendry, A. (2001). Adaptive divergence and the evolution of reproductive isolation in the wild: An empirical demonstration using introduced sockeye salmon. *Genetica* **112–113,** 515–534.

Hennessy, K., Fitzharris, B., Bates, B. C., Harvey, N., Howden, S. M., Hughes, L., Salinger, J. & Warrick, R. (2007). Australia and New Zealand. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 507–540. Cambridge: Cambridge University Press.

Hering, D., Haidekker, A., Schmidt-Kloiber, A., Barker, T., Buisson, L., Graf, W., Gäel Grenouillet, Lorenz, A., Sandin, L. & Stendera, S. (2010). Monitoring the responses of freshwater ecosystems to climate change. In *Climate Change Impacts on Freshwater Ecosystems* (Kernan, M., Battarbee, R. W. & Moss, B., eds), pp. 84–118. Oxford: Wiley-Blackwell.

Hermoso, V. & Clavero, M. (2011). Threatening processes and conservation management of endemic freshwater fish in the Mediterranean basin: A review. *Marine and Freshwater Research* **62,** 244–254.

Hermoso, V. & Clavero, M. (2013). Revisiting ecological integrity 30 years later: Non-native species and the misdiagnosis of freshwater ecosystem health. *Fish and Fisheries* **14,** 416–423.

Hickley, P., Bailey, R., Harper, D., Kundu, R., Muchiri, M., North, R. & Taylor, A. (2002). The status and future of the Lake Naivasha fishery, Kenya. In *Lake Naivasha, Kenya* (Harper, D., Boar, R. R., Everard, M. & Hickley, P., eds), pp. 181–190. Dordrecht: Springer.

Hickling, R., Roy, D. B., Hill, J. K., Fox, R. & Thomas, C. D. (2006). The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology* **12,** 450–455.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G. & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25,** 1965–1978.

Hilborn, R., Quinn, T. P., Schindler, D. E. & Rogers, D. E. (2003). Biocomplexity and fisheries sustainability. *Proceedings of the National Academy of Sciences of the United States of America* **100,** 6564–6568.

Hinzman, L., Bettez, N., Bolton, W. R., Chapin, F. S., Dyurgerov, M., Fastie, C., Griffith, B., Hollister, R., Hope, A., Huntington, H., Jensen, A., Jia, G., Jorgenson, T., Kane, D., Klein, D., Kofinas, G., Lynch, A., Lloyd, A., Mcguire, A. D., Nelson, F., Oechel, W., Osterkamp, T., Racine, C., Romanovsky, V., Stone, R., Stow, D., Sturm, M., Tweedie, C., Vourlitis, G., Walker, M., Walker, D., Webber, P., Welker, J., Winker, K. & Yoshikawa, K. (2005). Evidence and implications of recent climate change in northern Alaska and other Arctic regions. *Climatic Change* **72,** 251–298.

Hitz, S. & Smith, J. (2004). Estimating global impacts from climate change. *Global Environmental Change* **14,** 201–218.

Hlohowskyj, I., Brody, M. S. & Lackey, R. T. (1996). Methods for assessing the vulnerability of African fisheries resources to climate change. *Climate Research* **06,** 97–106.

Hobday, A. J. & Lough, J. M. (2011). Projected climate change in Australian marine and freshwater environments. *Marine and Freshwater Research* **62,** 1000–1014.

Hokanson, K. E. F. (1977). Temperature requirements of some percids and adaptations to the seasonal temperature cycle. *Journal of the Fisheries Research Board of Canada* **34,** 1524–1550.

Hole, D. G., Willis, S. G., Pain, D. J., Fishpool, L. D., Butchart, S. H. M., Collingham, Y. C., Rahbek, C. & Huntley, B. (2009). Projected impacts of climate change on a continent-wide protected area network. *Ecology Letters* **12,** 420–431.

Hölker, F. (2003). The metabolic rate of roach in relation to body size and temperature. *Journal of Fish Biology* **62,** 565–579.

Holmlund, C. M. & Hammer, M. (1999). Ecosystem services generated by fish populations. *Ecological Economics* **29,** 253–268.

Holt, R. D. (1990). The microevolutionary consequences of climate change. *Trends in Ecology and Evolution* **5,** 311–315.

Hsiang, S. M., Burke, M. & Miguel, E. (2013). Quantifying the influence of climate on human conflict. *Science* **341**, 123536.

Hubbs, C. (1964). Effects of thermal fluctuations on the relative survival of greenthroat darter young from stenothermal and eurythermal waters. *Ecology* **45,** 376–379.

Hulme, M. & Barrow, E. (Eds) (1997). *Climates of the British Isles: Present, Past and Future*. London: Routledge.

Humphries, P., King, A. & Koehn, J. (1999). Fish, flows and flood plains: Links between freshwater fishes and their environment in the Murray-Darling River system, Australia. *Environmental Biology of Fishes* **56,** 129–151.

Huntingford, F. A., Adams, C., Braithwaite, V. A., Kadri, S., Pottinger, T. G., Sandoe, P. & Turnbull, J. F. (2006). Current issues in fish welfare. *Journal of Fish Biology* **68,** 332–372.

Hutchinson, G. E. & Löffler, H. (1956). The thermal classification of lakes. *Proceedings of the National Academy of Sciences of the United States of America* **42,** 84–86.

Hutchinson, W. F., Van Oosterhout, C., Rogers, S. I. & Carvalho, G. R. (2003). Temporal analysis of archived samples indicates marked genetic changes in declining North Sea cod (*Gadus morhua*). *Proceedings of the Royal Society B* **270,** 2125–2132.

Huusko, A., Vuorimies, O. & Sutela, T. (1996). Temperature- and light-mediated predation by perch on vendace larvae. *Journal of Fish Biology* **49,** 441–457.

Ibañez, C., Belliard, J., Hughes, R. M., Irz, P., Kamdem-Toham, A., Lamouroux, N., Tedesco, P. A. & Oberdorff, T. (2009). Convergence of temperate and tropical stream fish assemblages. *Ecography* **32,** 658–670.

Immerzeel, W. W., Van Beek, L. P. H. & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science* **328,** 1382–1385.

IPCC (1990). *Climate Change: The IPCC Scientific Assessment*. Cambridge: Cambridge University Press.

IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC.

Isaak, D. J. & Horan, D. L. (2011). An evaluation of underwater epoxies to permanently install temperature sensors in mountain streams. *North American Journal of Fisheries Management* **31,** 134–137.

Isaak, D. J. & Hubert, W. A. (2004). Nonlinear response of trout abundance to summer stream temperatures across a thermally diverse montane landscape. *Transactions of the American Fisheries Society* **133,** 6.

Isaak, D. J. & Rieman, B. E. (2012). Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. *Global Change Biology* **19,** 742–751.

Isaak, D. J., Wollrab, S., Horan, D. & Chandler, G. (2012*a*). Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes. *Climatic Change* **113,** 499–524.

Isaak, D. J., Muhlfeld, C. C., Todd, A. S., Al-Chokhachy, R., Roberts, J., Kershner, J. L., Fausch, K. D. & Hostetler, S. W. (2012*b*). The past as prelude to the future for understanding 21st-century climate effects on Rocky Mountain trout. *Fisheries* **37,** 542–556.

Iwama, G. K. (1998). Stress in fish. *Annals of the New York Academy of Sciences* **851,** 304–310.

Jackson, S. T. & Overpeck, J. T. (2000). Responses of plant populations and communities to environmental changes of the late Quaternary. *Paleobiology* **26,** 194–220.

Jackson, D. A., Peres-Neto, P. R. & Olden, J. D. (2001). What controls who is where in freshwater fish communities: The roles of biotic, abiotic, and spatial factors. *Canadian Journal of Fisheries and Aquatic Sciences* **58,** 157–170.

Jackson, M. C., Donohue, I., Jackson, A. L., Britton, J. R., Harper, D. M. & Grey, J. (2012). Population-level metrics of trophic structure based on stable isotopes and their application to invasion ecology. *PLoS One* **7,** e31757.

Jager, H. I., van Winkle, W. & Holcomb, B. D. (1999). Would hydrologic climate changes in Sierra Nevada streams influence trout persistence? *Transactions of the American Fisheries Society* **128,** 222–240.

Jansen, W. & Hesslein, R. H. (2004). Potential effects of climate warming on fish habitats in temperate zone lakes with special reference to Lake 239 of the Experimental Lakes Area (ELA), North-Western Ontario. *Environmental Biology of Fishes* **70,** 1–22.

Jensen, L. F., Hansen, M. M., Pertoldi, C., Holdensgaard, G., Mensberg, K.-L. D. & Loeschcke, V. (2008). Local adaptation in brown trout early life-history traits: Implications for climate change adaptability. *Proceedings of the Royal Society B* **275,** 2859–2868.

Jeppesen, E., Sondergaard, M., Jensen, J. P., Havens, K. E., Anneville, O., Carvalho, L., Coveney, M. F., Deneke, R., Dokulil, M. T., Foy, B. O. B., Gerdeaux, D., Hampton, S. E., Hilt, S., Kangur, K., Kohler, J. A. N., Lammens, E. H. H. R., Lauridsen, T. L., Manca, M., Miracle, M. R., Moss, B., Noges, P., Persson, G., Phillips, G., Portielje, R. O. B., Romo, S., Schelske, C. L., Straile, D., Tatrai, I., Willen, E. V. A. & Winder, M. (2005). Lake responses to reduced nutrient loading – An analysis of contemporary long-term data from 35 case studies. *Freshwater Biology* **50,** 1747–1771.

Jeppesen, E., Meerhoff, M., Holmgren, K., González-Bergonzoni, I., Teixeira-de Mello, F., Declerck, S. J., Meester, L., Søndergaard, M., Lauridsen, T., Bjerring, R., Conde-Porcuna, J., Mazzeo, N., Iglesias, C., Reizenstein, M., Malmquist, H., Liu, Z., Balayla, D. & Lazzaro, X. (2010*a*). Impacts of climate warming on lake fish community structure and potential effects on ecosystem function. *Hydrobiologia* **646,** 73–90.

Jeppesen, E., Moss, B., Bennion, H., Carvalho, L., Demeester, L., Feuchtmayr, H., Friberg, N., Gessner, M. O., Hefting, M., Lauridsen, T. L., Liboriussen, L., Malmquist, H. J., May, L., Meerhoff, M., Olafsson, J. S., Soons, M. B. & Verhoeven, J. T. A. (2010*b*). Interaction of climate change and eutrophication. In *Climate Change Impacts on Freshwater Ecosystems* (Kernan, M., Battarbee, R. W. & Moss, B., eds), pp. 119–151. Oxford: Wiley-Blackwell.

Jeppesen, E., Mehner, T., Winfield, I., Kangur, K., Sarvala, J., Gerdeaux, D., Rask, M., Malmquist, H., Holmgren, K., Volta, P., Romo, S., Eckmann, R., Sandström, A., Blanco, S., Kangur, A., Ragnarsson Stabo, H., Tarvainen, M., Ventelä, A.-M., Søndergaard, M., Lauridsen, T. & Meerhoff, M. (2012). Impacts of climate warming on the long-term dynamics of key fish species in 24 European lakes. *Hydrobiologia* **694,** 1–39.

Jobling, M. (1981). Temperature tolerance and the final preferendum – Rapid methods for the assessment of optimum growth temperatures. *Journal of Fish Biology* **19,** 439–455.

Johnson, T. B. & Evans, D. O. (1990). Size-dependent winter mortality of young-of-the-year white perch: Climate warming and invasion of the Laurentian Great Lakes. *Transactions of the American Fisheries Society* **119,** 301–313.

Johnson, A. C., Acreman, M. C., Dunbar, M. J., Feist, S. W., Giacomello, A. M., Gozlan, R. E., Hinsley, S. A., Ibbotson, A. T., Jarvie, H. P., Jones, J. I., Longshaw, M., Maberly, S. C., Marsh, T. J., Neal, C., Newman, J. R., Nunn, M. A., Pickup, R. W., Reynard, N. S., Sullivan, C. A., Sumpter, J. P. & Williams, R. J. (2009). The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England. *Science of the Total Environment* **407,** 4787–4798.

Jolma, A., Kokkonen, T., Koivusalo, H., Laine, H. & Tiits, K. (2010). Developing a decision support system for assessing the impact of climate change on lakes. In *The Impact of Climate Change on European Lakes* (George, D. G., ed.), pp. 409–434. London: Springer.

Jones, R. I. & Grey, J. (2011). Biogenic methane in freshwater food webs. *Freshwater Biology* **56,** 213–229.

Jones, R. I., Grey, J., Quarmby, C. & Sleep, D. (1998). An assessment, using stable isotopes, of the importance of allochthonous organic carbon sources to the pelagic food web in Loch Ness. *Proceedings of the Royal Society B* **265,** 105–111.

Jones, I. D., Winfield, I. J. & Carse, F. (2008). Assessment of long-term changes in habitat availability for Arctic charr (*Salvelinus alpinus*) in a temperate lake using oxygen profiles and hydroacoustic surveys. *Freshwater Biology* **53,** 393–402.

Jones, P. D., Kilsby, C. G., Harpham, C., Glenis, V. & Burton, A. (2009). *UK Climate Projections Science Report: Projections of Future Daily Climate for the UK from the Weather Generator*. Newcastle: University of Newcastle.

Jones, I., Sahlberg, J. & Persson, I. (2010). Modelling the impact of climate change on the thermal characteristics of lakes. In *The Impact of Climate Change on European Lakes* (George, D. G., ed.), pp. 102–120. London: Springer.

Jonsson, N. & Jonsson, B. (2004). Size and age of maturity of Atlantic salmon correlate with the North Atlantic Oscillation. *Journal of Fish Biology* **64,** 241–247.

Juanes, F., Gephard, S. & Beland, K. F. (2004). Long-term changes in migration timing of adult Atlantic salmon (*Salmo salar*) at the Southern edge of the species distribution. *Canadian Journal of Fisheries and Aquatic Sciences* **61,** 2392–2400.

Junk, W. J. (2002). Long-term environmental trends and the future of tropical wetlands. *Environmental Conservation* **29,** 414–435.

Junk, W. J., Bayley, P. B. & Sparks, R. E. (1989). The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences* **106,** 110–127.

Junk, W. J., Soares, M. G. M. & Bayley, P. B. (2007). Freshwater fishes of the Amazon River basin: Their biodiversity, fisheries, and habitats. *Aquatic Ecosystem Health & Management* **10,** 153–173.

Karl, T. R. & Trenberth, K. E. (2003). Modern global climate change. *Science* **302,** 1719–1723.

Kaufman, D. S., Schneider, D. P., Mckay, N. P., Ammann, C. M., Bradley, R. S., Briffa, K. R., Miller, G. H., Otto-Bliesner, B. L., Overpeck, J. T., Vinther, B. M. & Members, A. L. K. P. (2009). Recent warming reverses long-term Arctic cooling. *Science* **325,** 1236–1239.

Kaushal, S. S., Likens, G. E., Jaworski, N. A., Pace, M. L., Sides, A. M., Seekell, D., Belt, K. T., Secor, D. H. & Wingate, R. L. (2010). Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment* **8,** 461–466.

Kempf, A. (2010). Ecosystem approach to fisheries in the European context; history and future challenges. *Journal of Applied Ichthyology* **26,** 102–109.

Kernan, M., Battarbee, R. W. & Moss, B. (Eds) (2010). *Climate Change Impacts on Freshwater Ecosystems*. Oxford: Wiley-Blackwell.

Kiehl, J. T. & Trenberth, K. E. (1997). Earth's annual global mean energy budget. *Bulletin of the American Meteorological Society* **78,** 197–208.

Kitchell, J. F. & Crowder, L. B. (1986). Predator-prey interactions in Lake Michigan: Model predictions and recent dynamics. *Environmental Biology of Fishes* **16,** 205–211.

Kitchell, J. F., Stewart, D. J. & Weininger, D. (1977). Applications of a bioenergetics model to yellow perch (*Perca flavescens*) and walleye (*Stizostedion vitreum vitreum*). *Journal of the Fisheries Research Board of Canada* **34,** 1922–1935.

Koch, F. & Wieser, W. (1983). Partitioning of energy in fish: Can reduction of swimming activity compensate for the cost of production? *Journal of Experimental Biology* **107,** 141–146.

Koehn, J. D., Hobday, A. J., Pratchett, M. S. & Gillanders, B. M. (2011). Climate change and Australian marine and freshwater environments, fishes and fisheries: Synthesis and options for adaptation. *Marine and Freshwater Research* **62,** 1148–1164.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z. & Shiklomanov, I. A. (2007). Freshwater resources and their management. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 173–210. Cambridge: Cambridge University Press.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döli, P., Jimenez, B., Miller, K., Oki, T., Şen, Z. & Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal* **53,** 3–10.

Kutzbach, J., Gallimore, R., Harrison, S., Behling, P., Selin, R. & Laarif, F. (1998). Climate and biome simulations for the past 21,000 years. *Quaternary Science Reviews* **17,** 473–506.

Lafferty, K. D. (2009). The ecology of climate change and infectious diseases. *Ecology* **90,** 888–900.

Lampert, W. & Sommer, U. (2007). *Limnoecology: The Ecology of Lakes and Streams*, 2nd edn. Oxford: Oxford University Press.

Lappalainen, J. & Lehtonen, H. (1997). Temperature habitats for freshwater fishes in a warming climate. *Boreal Environment Research* **2,** 69–84.

Lappalainen, J., Lehtonen, H. & Erm, V. (1997). Possible effects of climate warming on the timing of spawning, juvenile abundance and catches of pikeperch, *Stizostedion lucioperca* (L.). *Boreal Environment Research* **2,** 85–91.

Lappalainen, J., Erm, V., Kjellman, J. & Lehtonen, H. (2000). Size-dependent winter mortality of age-0 pikeperch, (*Stizostedion lucioperca*) in Pärnu Bay, the Baltic sea. *Canadian Journal of Fisheries and Aquatic Sciences* **57,** 451–458.

Lappalainen, J., Tarkan, A. S. & Harrod, C. (2008). A meta-analysis of latitudinal variations in life-history traits of roach, *Rutilus rutilus*, over its geographical range: Linear or non-linear relationships? *Freshwater Biology* **53,** 1491–1501.

Lara, G., Encina, L. & Rodríguez –Ruiz, A. (2009). Trophometric index: A predictor for fish density, biomass and production in Mediterranean reservoirs in Spain. *Fisheries Management and Ecology* **16,** 341–351.

Larsson, S., Forseth, T., Berglund, I., Jensen, A. J., Naslund, I., Elliott, J. M. & Jonsson, B. (2005). Thermal adaptation of Arctic charr: Experimental studies of growth in eleven charr populations from Sweden, Norway and Britain. *Freshwater Biology* **50,** 353–368.

Lassalle, G. & Rochard, E. (2009). Impact of twenty-first century climate change on diadromous fish spread over Europe, North Africa and the Middle East. *Global Change Biology* **15,** 1072–1089.

Latrubesse, E. M., Stevaux, J. C. & Sinha, R. (2005). Tropical rivers. *Geomorphology* **70,** 187–206.

Le Morvan, C., Troutaud, D. & Deschaux, P. (1998). Differential effects of temperature on specific and nonspecific immune defences in fish. *Journal of Experimental Biology* **201,** 165–168.

Lehodey, P., Alheit, J., Barange, M., Baumgartner, T., Beaugrand, G., Drinkwater, K., Fromentin, J.-M., Hare, S. R., Ottersen, G., Perry, R. I., Roy, C., Van Der Lingen, C. D. & Werner, F. (2006). Climate variability, fish, and fisheries. *Journal of Climate* **19,** 5009–5030.

Lehtonen, H. & Lappalainen, J. (1995). The effects of climate on the year-class variations of certain freshwater fish species. *Canadian Special Publication of Fisheries and Aquatic Sciences* **121,** 37–44.

Lehtonen, H., Leskinen, E., Selén, R. & Reinikainen, M. (2009). Potential reasons for the changes in the abundance of pike, *Esox lucius*, in the western Gulf of Finland, 1939–2007. *Fisheries Management and Ecology* **16,** 484–491.

Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. H. & Zhang, T. (2007). Observations: Changes in snow, ice and frozen ground. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L., eds), pp. 337–383. Cambridge: Cambridge University Press.

Lévêque, C., Oberdorff, T., Paugy, D., Stiassny, M. L. J. & Tedesco, P. A. (2008). Global diversity of fish (Pisces) in freshwater. In *Freshwater Animal Diversity Assessment* (Balian, E. V., Lévêque, C., Segers, H. & Martens, K., eds), pp. 545–567. Dordrecht: Springer.

Levitus, S., Antonov, J. I., Boyer, T. P. & Stephens, C. (2000). Warming of the World Ocean. *Science* **287,** 2225–2229.

Lewin, W.-C., Arlinghaus, R. & Mehner, T. (2006). Documented and potential biological impacts of recreational fishing: Insights for management and conservation. *Reviews in Fisheries Science* **14,** 305–367.

Lewis, W. M., Jr. (1983). A revised classification of lakes based on mixing. *Canadian Journal of Fisheries and Aquatic Sciences* **40,** 1779–1787.

Lewis, W. M., Jr. (1996). Tropical lakes: How latitude makes a difference. In *Perspectives in Tropical Limnology* (Schiemer, F. & Boland, K. T., eds), pp. 43–64. Amsterdam: SPB Academic Publishers.

Lewis, W. M., Jr. (2000). Basis for the protection and management of tropical lakes. *Lakes and Reservoirs: Research and Management* **5,** 35–48.

Lewis, W. M., Jr (2008). Physical and chemical features of tropical flowing waters. In *Tropical Stream Ecology* (Dudgeon, D., ed.), pp. 1–21. London: Academic Press.

Lewis, W. M., Jr (2011). Global primary production of lakes: 19th Baldi Memorial Lecture. *Inland Waters* **1,** 1–28.

Link, J. S., Nye, J. A. & Hare, J. A. (2011). Guidelines for incorporating fish distribution shifts into a fisheries management context. *Fish and Fisheries* **12,** 461–469.

Livingstone, D. M. (2003). Impact of secular climate change on the thermal structure of a large temperate central European lake. *Climatic Change* **57,** 205–225.

Livingstone, D. M. & Dokulil, M. T. (2001). Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperature and the North Atlantic Oscillation. *Limnology and Oceanography* **46,** 1220–1227.

Logez, M. & Pont, D. (2013). Global warming and potential shift in reference conditions: The case of functional fish-based metrics. *Hydrobiologia* **704,** 417–436.

Lough, J. M. & Hobday, A. J. (2011). Observed climate change in Australian marine and freshwater environments. *Marine and Freshwater Research* **62,** 984–999.

Lowe-McConnell, R. A. (1987). *Ecological Studies in Tropical Fish Communities*. Cambridge: Cambridge University Press.

Lund, S. G., Caissie, D., Cunjak, R. A., Vijayan, M. M. & Tufts, B. L. (2002). The effects of environmental heat stress on heat-shock mRNA and protein expression in Miramichi Atlantic salmon (*Salmo salar*) parr. *Canadian Journal of Fisheries and Aquatic Sciences* **59,** 1553–1562.

Lundvall, D., Svanbäck, R., Persson, L. & Byström, P. (1999). Size-dependent predation in piscivores: Interactions between predator foraging and prey avoidance abilities. *Canadian Journal of Fisheries and Aquatic Sciences* **56,** 1285–1292.

Lynch, A. J., Taylor, W. W. & Smith, K. D. (2010). The influence of changing climate on the ecology and management of selected Laurentian Great Lakes fisheries. *Journal of Fish Biology* **77,** 1764–1782.

Lynn, K., Daigle, J., Hoffman, J., Lake, F., Michelle, N., Ranco, D., Viles, C., Voggesser, G. & Williams, P. (2013). The impacts of climate change on tribal traditional foods. *Climatic Change* **120,** 545–556.

Lyons, J., Stewart, J. S. & Mitro, M. (2010). Predicted effects of climate warming on the distribution of 50 stream fishes in Wisconsin, U.S.A. *Journal of Fish Biology* **77,** 1867–1898.

Lytle, D. A. & Poff, N. L. (2004). Adaptation to natural flow regimes. *Trends in Ecology & Evolution* **19,** 94–100.

Lyytikainen, T., Koskela, J. & Rissanen, I. (1997). Thermal resistance and upper lethal temperatures of underyearling Lake Inari Arctic charr. *Journal of Fish Biology* **51,** 515–525.

Ma, R., Duan, H., Hu, C., Feng, X., Li, A., Ju, W., Jiang, J. & Yang, G. (2010). A half-century of changes in China's lakes: Global warming or human influence? *Geophysical Research Letters* **37,** L24106.

MacIntyre, S. (2013). Climatic variability, mixing dynamics, and ecological consequences in the African Great Lakes. In *Climatic Change and Global Warming of Inland Waters: Impacts and Mitigation for Ecosystems and Societies* (Goldman, C. R., Kumagai, M. & Robarts, R. D., eds), pp. 311–336. Oxford: Wiley-Blackwell.

Mackay, M. & Seglenieks, F. (2013). On the simulation of Laurentian Great Lakes water levels under projections of global climate change. *Climatic Change* **117,** 55–67.

Mackay, M. D., Neale, P. J., Arp, C. D., Domis, L. N. D. S., Fang, X., Gal, G., Joehnk, K. D., Kirillin, G., Lenters, J. D., Litchman, E., Macintyre, S., Marsh, P., Melack, J., Mooij, W. M., Peeters, F., Quesada, A., Schladow, S. G., Schmid, M., Spence, C. & Stokesr, S. L. (2009). Modeling lakes and reservoirs in the climate system. *Limnology and Oceanography* **54,** 2315–2329.

Mackenzie, B. R., Gislason, H., Mollmann, C. & Koster, F. W. (2007). Impact of 21st century climate change on the Baltic Sea fish community and fisheries. *Global Change Biology* **13**, 1348–1367.

MacNab, V. & Barber, I. (2012). Some (worms) like it hot: Fish parasites grow faster in warmer water, and alter host thermal preferences. *Global Change Biology* **18,** 1540–1548.

MacNeil, M. A., Graham, N. A. J., Cinner, J. E., Dulvy, N. K., Loring, P. A., Jennings, S., Polunin, N. V. C., Fisk, A. T. & Mcclanahan, T. R. (2010). Transitional states in marine fisheries: Adapting to predicted global change. *Philosophical Transactions of the Royal Society B* **365,** 3753–3763.

MacQueen, D. J. & Johnston, I. A. (2014). A well-constrained estimate for the timing of the salmonid whole genome duplication reveals major decoupling from species diversification. *Proceedings of the Royal Society B* **281**, 20132881.

Magnuson, J. J. (1990). Long-term ecological research and the invisible present. *BioScience* **40,** 495–501.

Magnuson, J. J. (2010). History and heroes: The thermal niche of fishes and long-term lake ice dynamics. *Journal of Fish Biology* **77,** 1731–1744.

Magnuson, J. J. & Destasio, B. T. (1997). Thermal niche of fishes and global warming. In *Global Warming: Implications for Freshwater and Marine Fish* (Wood, C. M. & McDonald, D. G., eds), pp. 377–408. Cambridge: Cambridge University Press.

Magnuson, J. J., Crowder, L. B. & Medvick, P. A. (1979). Temperature as an ecological resource. *American Zoologist* **19,** 331–343.

Magnuson, J. J., Meisner, J. D. & Hill, D. K. (1990). Potential changes in the thermal habitat of Great Lakes fish after global climate warming. *Transactions of the American Fisheries Society* **119,** 254–264.

Magnuson, J. J., Webster, K. E., Assel, R. A., Bowser, C. J., Dillon, P. J., Eaton, J. G., Evans, H. E., Fee, E. J., Hall, R. I., Mortsch, L. R., Schindler, D. W. & Quinn, F. H. (1997). Potential effects of climate changes on aquatic systems: Laurentian great lakes and precambrian shield region. In *Freshwater Ecosystems and Climate Change in North America: A Regional Assessment* (Cushing, C. E., ed.), pp. 7–53. Chichester: John Wiley & Sons, Ltd.

Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., Kuusisto, E., Granin, N. G., Prowse, T. D., Stewart, K. M. & Vuglinski, V. S. (2000). Historical trends in lake and river ice cover in the Northern Hemisphere. *Science* **289,** 1743–1746.

Magrin, G., Gay García, C., Cruz Choque, D., Giménez, J. C., Moreno, A. R., Nagy, G. J., Nobre, C. & Villamizar, A. (2007). Latin America. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. 541–580. Cambridge: Cambridge University Press.

Maitland, P. S. (1991). Climatic change and fish in northern Europe: Some possible scenarios. *Proceedings of the Institute of Fishery Management Annual Study Course* **22,** 97–110.

Malmqvist, B., Ouml, R. N. & Rundle, S. (2002). Threats to the running water ecosystems of the world. *Environmental Conservation* **29,** 134–153.

Manton, M. J., Della-Marta, P. M., Haylock, M. R., Hennessy, K. J., Nicholls, N., Chambers, L. E., Collins, D. A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T. S., Lefale, P., Leyu, C. H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C. M., Pahalad, J., Plummer, N., Salinger, M. J., Suppiah, R., Tran, V. L., Trewin, B., Tibig, I. & Yee, D. (2001). Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. *International Journal of Climatology* **21,** 269–284.

Marcogliese, D. J. (2001). Implications of climate change for parasitism of animals in the aquatic environment. *Canadian Journal of Zoology* **79,** 1331–1352.

Marcos-López, M., Gale, P., Oidtmann, B. C. & Peeler, E. J. (2010). Assessing the impact of climate change on disease emergence in freshwater fish in the United Kingdom. *Transboundary and Emerging Diseases* **57,** 293–304.

Mason, I. M., Guzkowska, M. A. J., Rapley, C. G. & Street-Perrott, F. A. (1994). The response of lake levels and areas to climatic change. *Climatic Change* **27,** 161–197.

Matthies, M., Giupponi, C. & Ostendorf, B. (2007). Environmental decision support systems: Current issues, methods and tools. *Environmental Modelling & Software* **22,** 123–127.

McBryan, T. L., Anttila, K., Healy, T. M. & Schulte, P. M. (2013). Responses to temperature and hypoxia as interacting stressors in fish: Implications for adaptation to environmental change. *Integrative and Comparative Biology* **53,** 648–659.

McCarthy, I. D. & Houlihan, D. F. (1997). The effect of temperature on protein metabolism in fish: The possible consequences for wild Atlantic salmon (*Salmo salar* L.) stocks in Europe as a result of global warming. In *Global Warming: Implications for Freshwater and Marine Fish* (Wood, C. M. & McDonald, D. G., eds), pp. 51–77. Cambridge: Cambridge University Press.

McCullough, D. A., Bartholow, J. M., Jager, H. I., Beschta, R. L., Cheslak, E. F., Deas, M. L., Ebersole, J. L., Foott, J. S., Johnson, S. L., Marine, K. R., Mesa, M. G., Petersen, J. H., Souchon, Y., Tiffan, K. F. & Wurtsbaugh, W. A. (2009). Research in thermal biology: Burning questions for coldwater stream fishes. *Reviews in Fisheries Science* **17,** 90–115.

McDowall, R. M. (1992). Global climate change and fish and fisheries: What might happen in a temperate oceanic archipelago like New Zealand. *GeoJournal* **28,** 29–37.

McMichael, A. J., Woodruff, R. E. & Hales, S. (2006). Climate change and human health: Present and future risks. *The Lancet* **367,** 859–869.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J. & Zhao Z.-C. (2007). Global climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L., eds), pp. 747–845. Cambridge: Cambridge University Press.

Meisner, J. D. (1990). Effect of climatic warming on the southern margins of the native range of brook trout, *Salvelinus fontinalis*. *Canadian Journal of Fisheries and Aquatic Sciences* **47,** 1065–1070.

Meisner, J. D. & Shuter, B. J. (1992). Assessing potential effects of global climate change on tropical freshwater fishes. *GeoJournal* **28,** 21–27.

Meisner, J. D., Goodier, J. L., Regier, H. A., Shuter, B. J. & Christie, W. J. (1987). An assessment of the effects of climate warming on Great Lakes basin fishes. *Journal of Great Lakes Research* **13,** 340–352.

Merilä, J. (2012). Evolution in response to climate change: In pursuit of the missing evidence. *BioEssays* **34,** 811–818.

Metz, B., Davidson, O. R., Bosch, P. R., Dave, R. & Meyer, L. A. (Eds) (2007). *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge: Cambridge University Press.

Meyer, J. L., Sale, M. J., Mulholland, P. J. & Poff, N. L. (1999). Impacts of climate change on aquatic ecosystem functioning and health. *Journal of the American Water Resources Association* **35,** 1373–1386.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being: Wetlands and Water Synthesis*. Washington, DC: World Resources Institute.

Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438,** 347–350.

Milner, A. M., Robertson, A. L., Monaghan, K. A., Veal, A. J. & Flory, E. A. (2008). Colonization and development of an Alaskan stream community over 28 years. *Frontiers in Ecology and the Environment* **6,** 413–419.

Minshall, G. W. (1988). Stream ecosystem theory: A global perspective. *Journal of the North American Benthological Society* **7,** 263–288.

Mohseni, O., Stefan, H. G. & Eaton, J. G. (2003). Global warming and potential changes in fish habitat in US streams. *Climatic Change* **59,** 389–409.

Monteith, D. T., Stoddard, J. L., Evans, C. D., De Wit, H. A., Forsius, M., Hogasen, T., Wilander, A., Skjelkvale, B. L., Jeffries, D. S., Vuorenmaa, J., Keller, B., Kopacek, J. & Vesely, J. (2007). Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature* **450,** 537–540.

Mooij, W. M., Hülsmann, S., De Senerpont Domis, L. N., Nolet, B. A., Bodelier, P. L. E., Boers, P. C. M., Pires, L. M. D., Gons, H. J., Ibelings, B. W., Noordhuis, R., Portielje, R., Wolfstein, K. & Lammens, E. H. R. R. (2005). The impact of climate change on lakes in the Netherlands: A review. *Aquatic Ecology* **39,** 381–400.

Mooij, W. M., De Senerpont Domis, L. N. & Hülsmann, S. (2008). The impact of climate warming on water temperature, timing of hatching and young-of-the-year growth of fish in shallow lakes in the Netherlands. *Journal of Sea Research* **60,** 32–43.

Moore, M. V., Hampton, S. E., Izmest'eva, L. R., Silow, E. A., Peshkova, E. V. & Pavlov, B. K. (2009). Climate Change and the World's "Sacred Sea"—Lake Baikal, Siberia. *BioScience* **59,** 405–417.

Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., Sanchez, J. J., Kaiser, L. R., Stender, Y. O., Anderson, J. M., Ambrosino, C. M., Fernandez-Silva, I., Giuseffi, L. M. & Giambelluca, T. W. (2013). The projected timing of climate departure from recent variability. *Nature* **502,** 183–187.

Morin, X. & Thuiller, W. (2009). Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology* **90,** 1301–1313.

Moritz, C. & Agudo, R. (2013). The future of species under climate change: Resilience or decline? *Science* **341,** 504–508.

Morrongiello, J. R., Beatty, S. J., Bennett, J. C., Crook, D. A., Ikedife, D. N. E. N., Kennard, M. J., Kerezsy, A., Lintermans, M., Mcneil, D. G., Pusey, B. J. & Rayner, T. (2011). Climate change and its implications for Australia's freshwater fish. *Marine and Freshwater Research* **62,** 1082–1098.

Moss, B. (2010*a*). Climate change, nutrient pollution and the bargain of Dr Faustus. *Freshwater Biology* **55,** 175–187.

Moss, B. (2010*b*). *Ecology of Freshwaters: A View for the Twenty-First Century*, 4th edn. Oxford: John-Wiley & Sons, Ltd.

Moss, B. (2012). Cogs in the endless machine: Lakes, climate change and nutrient cycles: A review. *Science of the Total Environment* **434,** 130–142.

Moss, B., Mckee, D., Atkinson, D., Collings, S. E., Eaton, J. W., Gill, A. B., Harvey, I., Hatton, K., Heyes, T. & Wilson, D. (2003). How important is climate? Effects of warming, nutrient addition and fish on phytoplankton in shallow lake microcosms. *Journal of Applied Ecology* **40,** 782–792.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. & Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature* **463,** 747–756.

Moss, B., Kosten, S., Meerhof, M., Battarbee, R., Jeppesen, E., Mazzeo, N., Havens, K., Lacerot, G., Liu, Z., Meester, L. D., Paerl, H. & Scheffer, M. (2011). Allied attack: Climate change and eutrophication. *Inland Waters* **1,** 101–105.

Moyle, P. B. & Marchetti, M. P. (2006). Predicting invasion success: Freshwater fishes in California as a model. *BioScience* **56,** 515–524.

Moyle, P. B., Kiernan, J. D., Crain, P. K. & Quiñones, R. M. (2013). Climate change vulnerability of native and alien freshwater fishes of California: A systematic assessment approach. *PLoS One* **8,** e63883.

Muller, R. & Stadelmann, P. (2004). Fish habitat requirements as the basis for rehabilitation of eutrophic lakes by oxygenation. *Fisheries Management and Ecology* **11,** 251–260.

Mykles, D. L., Ghalambor, C. K., Stillman, J. H. & Tomanek, L. (2010). Grand challenges in comparative physiology: Integration across disciplines and across levels of biological organization. *Integrative and Comparative Biology* **50,** 6–16.

Nakicenovic, N. & Swart, R. (Eds) (2000). *Special Report on Emissions Scenarios*. Cambridge: Cambridge University Press.

Neiland, A. E. (1992). *Artisanal Fisheries of the Chad Basin in Africa, An Overview of Research and Annotated Bibliography 1920–1990*, pp. 1–89. Rome: FAO.

Neiland, A. E., Jaffry, S., Ladu, B. M. B., Sarch, M. T. & Madakan, S. P. (2000a). Inland fisheries of North East Nigeria including the Upper River Benue, Lake Chad and the Nguru–Gashua wetlands: I. Characterisation and analysis of planning suppositions. *Fisheries Research* **48,** 229–243.

Neiland, A. E., Weeks, J., Madakan, S. P. & Ladu, B. M. B. (2000b). Inland fisheries of North East Nigeria including the Upper River Benue, Lake Chad and the Nguru–Gashua wetlands: II. Fisheries management at village level. *Fisheries Research* **48,** 245–261.

Nelson, J. S. (2006). *Fishes of the World*. Hoboken, NJ: John Wiley & Sons, Inc.

Nelson, E. J., Kareiva, P., Ruckelshaus, M., Arkema, K., Geller, G., Girvetz, E., Goodrich, D., Matzek, V., Pinsky, M., Reid, W., Saunders, M., Semmens, D. & Tallis, H. (2013). Climate change's impact on key ecosystem services and the human well-being they support in the US. *Frontiers in Ecology and the Environment* **11,** 483–893.

Nicholson, S. E. (2001). Climatic and environmental change in Africa during the last two centuries. *Climate Research* **17,** 123–144.

Nickus, U., Bishop, K., Erlandsson, M., Evans, C. D., Forsius, M., Laudon, H., Livingstone, D. M., Monteith, D. & Thies, H. (2010). Direct impacts of climate change on freshwater ecosystems. In *Climate Change Impacts on Freshwater Ecosystems* (Kernan, M., Battarbee, R. W. & Moss, B., eds), pp. 38–64. Oxford: Wiley-Blackwell.

Nijssen, B., O'Donnell, G., Hamlet, A. & Lettenmaier, D. (2001). Hydrologic sensitivity of global rivers to climate change. *Climatic Change* **50,** 143–175.

Nilsson, C., Reidy, C. A., Dynesius, M. & Revenga, C. (2005). Fragmentation and flow regulation of the World's large river systems. *Science* **308,** 405–408.

Nõges, P., Bund, W., Cardoso, A. & Heiskanen, A.-S. (2007). Impact of climatic variability on parameters used in typology and ecological quality assessment of surface waters – Implications on the Water Framework Directive. *Hydrobiologia* **584,** 373–379.

Nohara, D., Kitoh, A., Hosaka, M. & Oki, T. (2006). Impact of climate change on river discharge projected by multimodel ensemble. *Journal of Hydrometeorology* **7,** 1076–1089.

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., Erwin, K. N. & Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. *Environment International* **35,** 971–986.

Nümann, W. (1972). The Bodensee: Effects of exploitation and eutrophication on the salmonid community. *Journal of the Fisheries Research Board of Canada* **29,** 833–847.

Nunn, A. D., Harvey, J. P., Britton, J. R., Frear, P. A. & Cowx, I. G. (2007). Fish, climate and the Gulf Stream: The influence of abiotic factors on the recruitment success of cyprinid fishes in lowland rivers. *Freshwater Biology* **52,** 1576–1586.

Nyberg, P., Bergstrand, E., Degerman, E. & Enderlein, O. (2001). Recruitment of pelagic fish in an unstable climate: Studies in Sweden's four largest lakes. *Ambio* **30,** 559–564.

O'Connor, M. I., Piehler, M. F., Leech, D. M., Anton, A. & Bruno, J. F. (2009). Warming and resource availability shift food web structure and metabolism. *PLoS Biology* **7,** e1000178.

O'Reilly, C. M., Alin, S. R., Plisnier, P.-D., Cohen, A. S. & McKee, B. A. (2003). Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature* **424,** 766–768.

Ochumba, P. O. (1990). Massive fish kills within the Nyanza Gulf of Lake Victoria, Kenya. *Hydrobiologia* **208,** 93–99.

Ohlberger, J. (2013). Climate warming and ectotherm body size – From individual physiology to community ecology. *Functional Ecology* **27,** 991–1001.

Ospina-Álvarez, N. & Piferrer, F. (2008). Temperature-dependent sex determination in fish revisited: Prevalence, a single sex ratio response pattern, and possible effects of climate change. *PLoS One* **3,** e2837.

Ottersen, G., Planque, B., Belgrano, A., Post, E., Reiid, P. C. & Stenseth, N. C. (2001). Ecological effects of the North Atlantic Oscillation. *Oecologia* **128,** 1–14.

Ottersen, G., Alheit, J., Drinkwater, K. F., Friedland, K. D., Hagen, E. & Stenseth, N. C. (2004). The response of fish populations to ocean climate fluctuations. In *Marine Ecosystems and Climate Variation* (Stenseth, N. C., Ottersen, G., Hurrell, J. W. & Belgrano, A., eds), pp. 73–94. Oxford: Oxford University Press.

Pace, M. L., Cole, J. J., Carpenter, S. R., Kitchell, J. F., Hodgson, J. R., Van De Bogert, M. C., Bade, D. L., Kritzberg, E. S. & Bastviken, D. (2004). Whole-lake carbon-13 additions reveal terrestrial support of aquatic food webs. *Nature* **427,** 240–243.

Paerl, H. W. & Huisman, J. (2009). Climate change: A catalyst for global expansion of harmful cyanobacterial blooms. *Environmental Microbiology Reports* **1,** 27–37.

Palmer, M. A., Reidy Liermann, C. A., Nilsson, C., Flörke, M., Alcamo, J., Lake, P. S. & Bond, N. (2008). Climate change and the world's river basins: Anticipating management options. *Frontiers in Ecology and the Environment* **6,** 81–89.

Pankhurst, N. W. & Munday, P. L. (2011). Effects of climate change on fish reproduction and early life history stages. *Marine and Freshwater Research* **62,** 1015–1026.

Parmesan, C. & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421,** 37–42.

Parr, T. W., Sier, A. R. J., Battarbee, R. W., Mackay, A. & Burgess, J. (2003). Detecting environmental change: Science and society-perspectives on long-term research and monitoring in the 21st century. *The Science of the Total Environment* **310,** 1–8.

Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E. (Eds) (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

Parsons, P. A. (1990). The metabolic cost of multiple environmental stresses: Implications for climatic change and conservation. *Trends in Ecology and Evolution* **5,** 315–317.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., Watson, R. & Zeller, D. (2002). Towards sustainability in world fisheries. *Nature* **418,** 689–695.

Pearson, R. G. & Dawson, T. P. (2003). Predicting the impacts of climate change on the distribution of species: Are bioclimate envelope models useful? *Global Ecology and Biogeography* **12,** 361–371.

Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P. W., Fernandez-Manjarrés, J. F., Araújo, M. B., Balvanera, P., Biggs, R., Cheung, W. W. L., Chini, L., Cooper, H. D., Gilman, E. L., Guénette, S., Hurtt, G. C., Huntington, H. P., Mace, G. M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R. J., Sumaila, U. R. & Walpole, M. (2010). Scenarios for Global biodiversity in the 21st Century. *Science* **330,** 1496–1501.

Persson, L. (1986). Temperature-induced shift in foraging ability in two fish species, roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*): Implications for coexistence between poikilotherms. *Journal of Animal Ecology* **55,** 829–839.

Persson, L. (1988). Asymmetries in competitive and predatory interactions in fish populations. In *Size Structured Populations, Ecology and Evolution* (Ebenman, B. & Persson, L., eds), 203–218. Berlin: Springer-Verlag.

Persson, L. (1990). Juvenile competitive bottlenecks: The perch (*Perca fluviatilis*)-roach (*Rutilus rutilus*) interaction. *Ecology* **71,** 44–56.

Petchey, O. L. & Gaston, K. J. (2002). Functional diversity (FD), species richness and community composition. *Ecology Letters* **5,** 402–411.

Petersen, J. H. & Kitchell, J. F. (2001). Climate regimes and water temperature changes in the Columbia River: Bioenergetic implication for predators of juvenile salmon. *Canadian Journal of Fisheries and Aquatic Sciences* **58**, 1831–1841.

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A. & Rahmstorf, S. (2002). Increasing river discharge to the Arctic Ocean. *Science* **298,** 2171–2173.

Peterson, A. T., Stewart, A., Mohamed, K. I. & Araújo, M. B. (2008). Shifting global invasive potential of European plants with climate change. *PLoS One* **3,** e2441.

Peterson, D. P., Wenger, S. J., Rieman, B. E. & Isaak, D. J. (2013). Linking climate change and fish conservation efforts using spatially explicit decision support tools. *Fisheries* **38,** 112–127.

Petrere, M. (1996). Fisheries in large tropical reservoirs in South America. *Lakes and Reservoirs: Research and Management* **2,** 111–133.

Pianka, E. R. (1994). *Evolutionary Ecology* 5th edn. New York, NY: Harper Collins College Publishers.

Plagányi, É. E., Bell, J. D., Bustamante, R. H., Dambacher, J. M., Dennis, D. M., Dichmont, C. M., Dutra, L. X. C., Fulton, E. A., Hobday, A. J., Ingrid Van Putten, E., Smith, F., Smith, A. D. M. & Zhou, S. (2011). Modelling climate-change effects on Australian and Pacific aquatic ecosystems: A review of analytical tools and management implications. *Marine and Freshwater Research* **62,** 1132–1147.

Planque, B. & Frédou, T. (1999). Temperature and the recruitment of Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Sciences* **56,** 2069–2077.

Poff, N. L. (2002). Ecological response to and management of increased flooding caused by climate change. *Philosophical Transactions of the Royal Society of London A* **360,** 1497–1510.

Pool, T. K. & Olden, J. D. (2012). Taxonomic and functional homogenization of an endemic desert fish fauna. *Diversity and Distributions* **18,** 366–376.

Porcal, P., Koprivnjak, J.-F., Molot, L. & Dillon, P. (2009). Humic substances – Part 7: The biogeochemistry of dissolved organic carbon and its interactions with climate change. *Environmental Science and Pollution Research* **16,** 714–726.

Pörtner, H. O. (2001). Climate change and temperature-dependant biogeography: Oxygen limitation of thermal tolerance in animals. *Naturwissenschaften* **88,** 137–146.

Pörtner, H. O. & Farrell, A. P. (2008). Physiology and climate change. *Science* **322,** 690–692.

Pörtner, H. O. & Peck, M. A. (2010). Climate change effects on fishes and fisheries: Towards a cause-and-effect understanding. *Journal of Fish Biology* **77,** 1745–1779.

Postel, S. L., Daily, G. C. & Ehrlich, P. R. (1996). Human appropriation of renewable fresh water. *Science* **271,** 785–787.

Pratchett, M. S., Bay, L. K., Gehrke, P. C., Koehn, J. D., Osborne, K., Pressey, R. L., Sweatman, H. P. A. & Wachenfeld, D. (2011). Contribution of climate change to degradation and loss of critical fish habitats in Australian marine and freshwater environments. *Marine and Freshwater Research* **62,** 1062–1081.

Prathumratana, L., Sthiannopkao, S. & Kim, K. W. (2008). The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River. *Environment International* **34,** 860–866.

Preston, B. (2006). Risk-based reanalysis of the effects of climate change on U.S. cold-water habitat. *Climatic Change* **76,** 91–119.

Prowse, T. D., Wrona, F. J., Reist, J. D., Gibson, J. J., Hobbie, J. E., Lévesque, L. M. J. & Vincent, W. F. (2006). Climate change effects on hydroecology of Arctic freshwater ecosystems. *Ambio* **35,** 347–358.

Prowse, T. D., Furgal, C., Wrona, F. J. & Reist, J. D. (2009). Implications of climate change for Northern Canada: Freshwater, marine, and terrestrial Ecosystems. *Ambio* **38,** 282–289.

Rahel, F. J. (2002). Homogenization of freshwater faunas. *Annual Review of Ecology and Systematics* **33,** 291–315.

Rahel, F. J. & Nutzman, J. W. (1994). Foraging in a lethal environment: Fish predation in hypoxic waters of a stratified lake. *Ecology* **75,** 1426–1253.

Rahel, F. J. & Olden, J. D. (2008). Assessing the effects of climate change on aquatic invasive species. *Conservation Biology* **22,** 521–533.

Rahel, F. J., Keleher, C. J. & Anderson, J. L. (1996). Potential habitat loss and population fragmentation for cold water fish in the North Platte

River drainage of the Rocky Mountains: Response to climate warming. *Limnology and Oceanography* **41,** 1116–1123.

Rahel, F. J., Bierwagen, B. & Taniguchi, Y. (2008). Managing aquatic species of conservation concern in the face of climate change and invasive species. *Conservation Biology* **22,** 551–561.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A. & Taylor, K. E. (2007). Climate models and their evaluation. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L., eds), pp. 589–662. Cambridge: Cambridge University Press.

Ravinet, M., Syväranta, J., Jones, R. I. & Grey, J. (2009). A trophic pathway from biogenic methane supports fish biomass in a temperate lake ecosystem. *Oikos* **119,** 409–416.

Regier, H. A., Welcomme, R. L., Steedman, R. J. & Henderson, H. F. (1989). Rehabilitation of degraded river ecosystems. *Canadian Special Publication of Fisheries and Aquatic Sciences* **106,** 86–97.

Regier, H. A., Holmes, J. A. & Pauly, D. (1990). Influence of temperature changes on aquatic ecosystem: An interpretation of empirical data. *Transactions of the American Fisheries Society* **119,** 374–389.

Reid, S. D., McDonald, D. G. & Wood, C. M. (1997). Interactive effects of temperature and pollutant stress. In *Global Warming: Implications for Freshwater and Marine Fish* (Wood, C. M. & McDonald, D. G., eds), 325–350 Cambridge: Cambridge University Press.

Reinthal, P. N. & Kling, G. W. (1994). Exotic species, trophic interactions, and ecosystem dynamics: A case study of Lake Victoria. In *Theory and Application in Fish Feeding Ecology* (Stouder, D. J., Fresh, K. L. & Feller, R. J., eds), pp. 19–43. Columbia, SC: University of South Carolina Press.

Reist, J. D., Wrona, F. J., Prowse, T. D., Power, M., Dempson, J. B., Beamish, R. J., King, J. R., Carmichael, T. J. & Sawatzky, C. D. (2006*a*). General effects of climate change on Arctic fishes and fish populations. *Ambio* **35,** 370–380.

Reist, J. D., Wrona, F. J., Prowse, T. D., Power, M., Dempson, J. B., King, J. R. & Beamish, R. J. (2006*b*). An overview of effects of climate change on selected Arctic freshwater and anadromous fishes. *Ambio* **35,** 381–387.

Reist, J. D., Wrona, F. J., Prowse, T. D., Dempson, J. B., Power, M., Köck, G., Carmichael, T. J., Sawatzky, C. D., Lehtonen, H. & Tallman, R. F. (2006c). Effects of climate change and UV radiation on fisheries for Arctic freshwater and anadromous species. *Ambio* **35,** 402–410.

Reusch, T. B. H. & Wood, T. E. (2007). Molecular ecology of global change. *Molecular Ecology* **16,** 3973–3992.

Reyjol, Y., Léna, J. P., Hervant, F. & Pont, D. (2009). Effects of temperature on biological and biochemical indicators of the life-history strategy of bullhead *Cottus gobio*. *Journal of Fish Biology* **75,** 1427–1445.

Richard, J. C. & Rypel, A. L. (2013). Water body type influences climate–growth relationships of freshwater drum. *Transactions of the American Fisheries Society* **142,** 1308–1320.

Ricker, W. E. (1979). Growth rates and models. In *Fish Physiology* Vol. VIII (Hoar, W. S., Randall, D. J. & Brett, J. R., eds), pp. 677–743 New York, NY: Academic Press.

Roberts, J. J., Fausch, K. D., Peterson, D. P. & Hooten, M. B. (2013). Fragmentation and thermal risks from climate change interact to affect persistence of native trout in the Colorado River basin. *Global Change Biology* **19,** 1383–1398.

Robinson, B. W. & Parsons, K. J. (2002). Changing times, spaces, and faces: Tests and implications of adaptive morphological plasticity in the fishes of northern postglacial lakes. *Canadian Journal of Fisheries and Aquatic Sciences* **59,** 1819–1833.

Rojas, R., Feyen, L., Bianchi, A. & Dosio, A. (2012). Assessment of future flood hazard in Europe using a large ensemble of bias-corrected regional climate simulations. *Journal of Geophysical Research: Atmospheres* **117,** D17109.

Rombough, P. J. (1997). Effects of temperature on embryonic and larval development. In *Global Warming: Implications for Freshwater and Marine Fish* (Wood, C. M. & McDonald, D. G., eds), pp. 177–223. Cambridge: Cambridge University Press.

Root, T. L., Price, J. T., Hall, K. R., Schneider, S. H., Rosenzweig, C. & Pounds, J. A. (2003). Fingerprints of global warming on animals and plants. *Nature* **421,** 57–60.

Rosenberg, D. M., Berkes, F., Bodaly, R. A., Hecky, R. E., Kelly, C. A. & Rudd, J. W. (1997). Large-scale impacts of hydroelectric development. *Environmental Reviews* **5,** 27–54.

Rosenzweig, C., Casassa, G., Karoly, D. J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T. L., Seguin, B. & Tryjanowski, P. (2007*a*). Supplementary material to Chapter 1: Assessment of observed changes and responses in natural and managed systems. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van Der Linden, P. J. & Hanson, C. E., eds), pp. SM1–SM13. Cambridge: Cambridge University Press.

Rosenzweig, C., Casassa, G., Karoly, D., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T. L., Seguin, B. & Tryjanowski, P. (2007*b*). Assessment of observed changes and responses in natural and managed systems. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., Van der Linden, P. J. & Hanson, C. E., eds), pp. 79–131. Cambridge: Cambridge University Press.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T. L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S. & Imeson, A. (2008). Attributing physical and biological impacts to anthropogenic climate change. *Nature* **453,** 353–357.

Rosgen, D. L. (1994). A classification of natural rivers. *Catena* **22,** 169–199.

Roulet, N. & Moore, T. R. (2006). Environmental chemistry: Browning the waters. *Nature* **444,** 283–284.

Rouse, W. R., Douglas, M. S. V., Hecky, R. E., Hershey, A. E., Kling, G. W., Lesack, L., Marsh, P., McDonald, M., Nicholson, B. J., Roulet, N. T. & Smol, J. P. (1997). Effects of climate change on the freshwaters of Arctic and subarctic North America. *Hydrological Processes* **11,** 873–902.

Ruddiman, W. F. (2001). *Earth's Climate: Past and Future*. New York, NY: W. H. Freeman.

Russell, B. D., Harley, C. D. G., Wernberg, T., Mieszkowska, N., Widdicombe, S., Hall-Spencer, J. M. & Connell, S. D. (2012). Predicting ecosystem shifts requires new approaches that integrate the effects of climate change across entire systems. *Biology Letters* **8,** 164–166.

Rypel, A. L. (2009). Climate–growth relationships for largemouth bass (*Micropterus salmoides*) across three southeastern USA states. *Ecology of Freshwater Fish* **18,** 620–628.

Sacchi, J. (2011). *Analysis of Economic Activities in the Mediterranean: Fishery and Aquaculture Sectors*. Valbonne: Plan Bleu.

Salinas, S. & Munch, S. B. (2012). Thermal legacies: Transgenerational effects of temperature on growth in a vertebrate. *Ecology Letters* **15,** 159–163.

Sandström, O., Neuman, E. & Thoresson, G. (1995). Effects of temperature on life history variables in perch. *Journal of Fish Biology* **47,** 652–670.

Sandström, O., Abrahamsson, I., Andersson, J. & Vetemaa, M. (1997). Temperature effects on spawning and egg development in Eurasian perch. *Journal of Fish Biology* **51,** 1015–1024.

Sarch, M.-T. & Birkett, C. (2000). Fishing and farming at Lake Chad: Responses to lake-level fluctuations. *Geographical Journal* **166,** 156–172.

Sarmento, H., Amado, A. M. & Descy, J.-P. (2013). Climate change in tropical fresh waters (comment on the paper 'Plankton dynamics under different climatic conditions in space and time' by de Senerpont Domis et al. *Freshwater Biology* **58,** 2208–2210.

Scarfe, A. D., Lee, C. S. & O'Bryen, P. J. (Eds) (2006). *Aquaculture Biosecurity: Prevention, Control, and Eradication of Aquatic Animal Disease*. Oxford: Blackwell Publishing.

Schiedek, D., Sundelin, B., Readman, J. W. & Macdonald, R. W. (2007). Interactions between climate change and contaminants. *Marine Pollution Bulletin* **54,** 1845–1856.

Schindler, D. W. (2001). The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. *Canadian Journal of Fisheries and Aquatic Sciences* **58,** 18–29.

Schindler, D. E. & Scheuerell, M. D. (2002). Habitat coupling in lake ecosystems. *Oikos* **98,** 177–189.

Schindler, D. W., Beaty, K. G., Fee, E. J., Cruikshank, D. R., Debruyn, E. R., Findlay, D. L., Linsey, G. A., Shearer, J. A., Stainton, M. P. & Turner, M. A. (1990). Effects of climatic warming on lakes of the central boreal forest. *Science* **250,** 967–970.

Schindler, D. W., Bayley, S. E., Parker, B. R., Beaty, K. G., Cruikshank, D. R., Fee, E. J., Schindler, E. U. & Stainton, M. P. (1996). The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. *Limnology and Oceanography* **41,** 1004–1017.

Schlesinger, D. A. & Regier, H. A. (1982). Climatic and morphoedaphic indices of fish yields from natural lakes. *Transactions of the American Fisheries Society* **111,** 141–150.

Schneider, P. & Hook, S. J. (2010). Space observations of inland water bodies show rapid surface warming since 1985. *Geophysical Research Letters* **37,** L22405.

Schneider, P., Hook, S. J., Radocinski, R. G., Corlett, G. K., Hulley, G. C., Schladow, S. G. & Steissberg, T. E. (2009). Satellite observations indicate rapid warming trend for lakes in California and Nevada. *Geophysical Research Letters* **36,** L22402.

Schultz, E. T. (2002). *The Ecozones of the World: The Ecological Divisions of the Geosphere*. Berlin: Springer-Verlag.

Schwalb, A. (2003). Lacustrine ostracodes as stable isotope recorders of late-glacial and Holocene environmental dynamics and climate. *Journal of Paleolimnology* **V29,** 265–351.

Scott, M. C. & Helfman, G. S. (2001). Native invasions, homogenization, and the mismeasure of integrity of fish assemblages. *Fisheries* **26,** 6–15.

Scrimgeour, G. J., Prowse, T. D., Culp, J. M. & Chambers, P. A. (1994). Ecological effects of river ice break-up: A review and perspective. *Freshwater Biology* **32,** 261–275.

Seitzinger, S. P., Mayorga, E., Bouwman, A. F., Kroeze, C., Beusen, A. H. W., Billen, G., Van Drecht, G., Dumont, E., Fekete, B. M., Garnier, J. & Harrison, J. A. (2010). Global river nutrient export: A scenario analysis of past and future trends. *Global Biogeochemical Cycles* **24,** GB0A08.

de Senerpont Domis L. N., Elser, J. J., Gsell, A. S., Huszar, V. L. M., Ibelings, B. W., Jeppesen, E., Kosten, S., Mooij, W. M., Roland, F., Sommer, U., Van Donk, E., Winder, M. & Lürling, M. (2013). Plankton dynamics under different climatic conditions in space and time. *Freshwater Biology* **58,** 463–482.

Sharma, S., Jackson, D. A., Minns, C. K. & Shuter, B. J. (2007). Will northern fish populations be in hot water because of climate change? *Global Change Biology* **13,** 2052–2064.

Sharp, G. D. (1987). Climate and fisheries: Cause and effect or managing the long and short of it all. *South African Journal of Marine Science* **5,** 811–838.

Sharp, G. D. (2003). *Future Climate Change and Regional Fisheries: A Collaborative Analysis* Rome: Food and Agriculture Organization of the United Nation.

Sheridan, J. A. & Bickford, D. (2011). Shrinking body size as an ecological response to climate change. *Nature Climate Change* **1,** 401–406.

Shuter, B. J. & Meisner, J. D. (1992). Tools for assessing the impact of climate change on freshwater fish populations. *GeoJournal* **28,** 7–20.

Shuter, B. J. & Post, J. R. (1990). Climate, population viability, and the zoogeography of temperate fishes. *Transactions of the American Fisheries Society* **119,** 314–336.

Shuter, B. J., Maclean, J. A., Fry, F. E. J. & Regier, H. A. (1980). Stochastic simulation of temperature effects on first-year survival of smallmouth bass. *Transactions of the American Fisheries Society* **109,** 1–34.

Shuter, B. J., Finstad, A. G., Helland, I. P., Zweimüller, I. & Hölker, F. (2012). The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. *Aquatic Sciences* **74,** 637–657.

Siegenthaler, U., Stocker, T. F., Monnin, E., Luthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fischer, H., Masson-Delmotte, V. & Jouzel, J. (2005). Stable carbon cycle-climate relationship during the late Pleistocene. *Science* **310,** 1313–1317.

Silvano, R. M. & Valbo-Jørgensen, J. (2008). Beyond fishermen's tales: Contributions of fishers' local ecological knowledge to fish ecology and fisheries management. *Environment, Development and Sustainability* **10,** 657–675.

Simberloff, D. & Von Holle, B. (1999). Positive interactions of nonindigenous species: Invasional meltdown? *Biological Invasions* **1,** 21–32.

Skeffington, R. A., Wade, A. J., Whitehead, P. G., Butterfield, D., Kaste, Ø., Andersen, H. E., Rankinen, K. & Grenouillet, G. (2010). Modelling catchment-scale responses to climate change. In *Climate Change Impacts on Freshwater Ecosystems* (Kernan, M., Battarbee, R. W. & Moss, B., eds), pp. 236–261. Oxford: Wiley-Blackwell.

Skov, C. & Koed, A. (2004). Habitat use of 0+ year pike in experimental ponds in relation to cannibalism, zooplankton, water transparency and habitat complexity. *Journal of Fish Biology* **64,** 448–459.

Smith, L. C., Sheng, Y., Macdonald, G. M. & Hinzman, L. D. (2005). Disappearing Arctic lakes. *Science* **308,** 1429.

Smol, J. P. & Douglas, M. S. V. (2007). From controversy to consensus: Making the case for recent climate change in the Arctic using lake sediments. *Frontiers in Ecology and the Environment* **5,** 466–474.

Snieszko, S. F. (1974). The effects of environmental stress on outbreaks of infectious diseases of fishes. *Journal of Fish Biology* **6,** 197–208.

Sogard, S. M. (1997). Size-selective mortality in the juvenile stage of teleost fishes: A review. *Bulletin of Marine Science* **60,** 1129–1157.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L. (Eds) (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Solomon, C. T., Carpenter, S. R., Clayton, M. K., Cole, J. J., Coloso, J. J., Pace, M. L., Vander Zanden, M. J. & Weidel, B. C. (2011). Terrestrial, benthic, and pelagic resource use in lakes: Results from a three-isotope Bayesian mixing model. *Ecology* **92,** 1115–1125.

Somero, G. N. (2010). The physiology of climate change: How potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers'. *The Journal of Experimental Biology* **213,** 912–920.

Soto, D., Jara, F. & Moreno, C. (2001). Escaped salmon in the inner seas, Southern Chile: Facing ecological and social conflicts. *Ecological Applications* **11,** 1750–1762.

Souchon, Y. & Tissot, L. (2012). Synthesis of thermal tolerances of the common freshwater fish species in large Western Europe rivers. *Knowledge and Management of Aquatic Ecosystems* **405,** 03.

Staaks, G. (1996). Experimental studies on temperature preference behaviour of juvenile cyprinids. *Limnologica* **26,** 165–177.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., Van Lanen, H. A. J., Sauquet, E., Demuth, S., Fendekova, M. & Jódar, J. (2010). Streamflow trends in Europe: Evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences* **14,** 2367–2382.

Stearns, S. C. & Koella, J. C. (1986). The evolution of phenotypic plasticity in life-history traits: Predictions of reaction norms for age and size at maturity. *Evolution* **40,** 893–913.

Stefan, H. G. & Fang, X. (1997). Simulated climate change effects on ice and snow covers on lakes in a temperate region. *Cold Regions Science and Technology* **25,** 137–152.

Stefan, H. G., Fang, X. & Eaton, J. G. (2001). Simulated fish habitat changes in North American lakes in response to projected climate warming. *Transactions of the American Fisheries Society* **130,** 459–477.

Stein, B. A., Staudt, A., Cross, M. S., Dubois, N. S., Enquist, C., Griffis, R., Hansen, L. J., Hellmann, J. J., Lawler, J. J., Nelson, E. J. & Pairis, A. (2013). Preparing for and managing change: Climate adaptation for biodiversity and ecosystems. *Frontiers in Ecology and the Environment* **11,** 502–510.

Stenseth, N. C., Ottersen, G., Hurrell, J. W., Mysterud, A., Lima, M., Chan, K. S., Yoccoz, N. G. & Ådlandsvik, B. (2003). Studying climate effects on ecology through the use of climate indices: The North Atlantic Oscillation, El Niño Southern Oscillation and beyond. *Proceedings of the Royal Society B* **270,** 2087–2096.

Stenseth, N. C., Ottersen, G., Hurrell, J. W. & Belgrano, A. (Eds) (2004). *Marine Ecosystems and Climate Variation*. Oxford: Oxford University Press.

Stephenson, S. R., Smith, L. C. & Agnew, J. A. (2011). Divergent long-term trajectories of human access to the Arctic. *Nature Climate Change* **1,** 156–160.

Stigebrandt, A. & Gustafsson, B. G. (2003). Response of the Baltic Sea to climate change—theory and observations. *Journal of Sea Research* **49,** 243–256.

Straile, D., Livingstone, D. M., Weyhenmeyer, G. A. & George, D. G. (2003). The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation. In *The North Atlantic Oscillation. Climate Significance and Environmental Impact* (Hurrell, J. W., Kushnir, Y., Ottersen, G. & Visbeck, M., eds), pp. 263–279. Washington, DC: American Geophysical Union.

Straškraba, M. (2007). Reservoirs and other artificial water bodies. In *The Lakes Handbook* (O'Sullivan, P. E. & Reynolds, C. S., eds), pp. 300–327. Oxford: Blackwell Science Ltd.

Strayer, D. L. (2010). Alien species in fresh waters: Ecological effects, interactions with other stressors, and prospects for the future. *Freshwater Biology* **55,** 152–174.

Strecker, A. L. & Arnott, S. E. (2008). Invasive predator, *Bythotrephes*, has varied effects on ecosystem function in freshwater lakes. *Ecosystems* **11,** 490–503.

Strüssmann, C. A., Conover, D. O., Somoza, G. M. & Miranda, L. A. (2010). Implications of climate change for the reproductive capacity and survival of New World silversides (family Atherinopsidae). *Journal of Fish Biology* **77,** 1818–1834.

Sturmbauer, C., Baric, S., Salzburger, W., Rüber, L. & Verheyen, E. (2001). Lake level fluctuations synchronize genetic divergences of cichlid fishes in African lakes. *Molecular Biology and Evolution* **18,** 144–154.

Subasinghe, R. R. (2005). Epidemiological approach to aquatic animal health management: Opportunities and challenges for developing countries to increase aquatic production through aquaculture. *Preventive Veterinary Medicine* **67,** 117–124.

Svedäng, H., Neumann, E. & Wickström, H. (1996). Maturation patterns in female European eel: Age and size at the silver eel stage. *Journal of Fish Biology* **48,** 342–351.

Swennen, C., Heessen, H. J. L. & Höcker, A. W. M. (1979). Occurrence and biology of the trematodes *Cotylurus (Ichthyocotylurus) erraticus, C.(I.) variegatus and C. (I.) platycephalus* (Digenea: Strigeidae) in the Netherlands. *Netherlands Journal of Sea Research* **13,** 161–191.

Sylvestre, F., Servant, M., Servant-Vildary, S., Causse, C., Fournier, M. & Ybert, J.-P. (1999). Lake-level chronology on the southern Bolivian Altiplano (18°–23°S) during late-glacial time and the early Holocene. *Quaternary Research* **51,** 54–66.

Symon, C., Arris, L. & Heal, B. (Eds) (2005). *Arctic Climate Impact Assessment*. Cambridge: Cambridge University Press.

Tabacchi, E., Correll, D. L., Hauer, R., Pinay, G., Planty-Tabacchi, A.-M. & Wissmar, R. C. (1998). Development, maintenance and role of riparian vegetation in the river landscape. *Freshwater Biology* **40,** 497–516.

Taniguchi, Y., Rahel, F. J., Novinger, D. C. & Gerow, K. G. (1998). Temperature mediation of competitive interactions among three fish species that replace each other along longitudinal stream gradients. *Canadian Journal of Fisheries and Aquatic Sciences* **55,** 1894–1901.

Taylor, E. B. (1991). A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon. *Aquaculture* **98,** 185–207.

Tedesco, P. A., Oberdorff, T., Cornu, J.-F., Beauchard, O., Brosse, S., Dürr, H. H., Grenouillet, G., Leprieur, F., Tisseuil, C., Zaiss, R. & Hugueny, B. (2013). A scenario for impacts of water availability loss due to climate change on riverine fish extinction rates. *Journal of Applied Ecology* **50,** 1105–1115.

Teixeira-De Mello, F., Meerhoff, M., Pekcan-Hekim, Z. & Jeppesen, E. (2009). Substantial differences in littoral fish community structure and dynamics in subtropical and temperate shallow lakes. *Freshwater Biology* **54,** 1202–1215.

Thackeray, S. J., Sparks, T. H., Frederiksen, M., Burthe, S., Bacon, P. J., Bell, J. R., Botham, M. S., Brereton, T. M., Bright, P. W., Carvalho, L., Clutton-Brock, T. I. M., Dawson, A., Edwards, M., Elliott, J. M., Harrington, R., Johns, D., Jones, I. D., Jones, J. T., Leech, D. I., Roy, D. B., Scott, W. A., Smith, M., Smithers, R. J., Winfield, I. J. & Wanless, S. (2010). Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology* **16,** 3304–3313.

Thackeray, S. J., Henrys, P. A., Feuchtmayr, H., Jones, I. D., Maberly, S. C. & Winfield, I. J. (2013). Food web de-synchronisation in England's largest lake: An assessment based upon multiple phenological metrics. *Global Change Biology* **19,** 3568–3580.

Thieme, M. L., Lehner, B., Abell, R. & Matthews, J. (2010). Exposure of Africa's freshwater biodiversity to a changing climate. *Conservation Letters* **3,** 324–331.

Thomson, J. R., Bond, N. R., Cunningham, S. C., Metzeling, L., Reich, P., Thompson, R. M. & Mac Nally, R. (2012). The influences of climatic variation and vegetation on stream biota: Lessons from the Big Dry in southeastern Australia. *Global Change Biology* **18,** 1582–1596.

Tibby, J. & Tiller, D. (2007). Climate–water quality relationships in three Western Victorian (Australia) lakes 1984–2000. *Hydrobiologia* **591,** 219–234.

Tierney, J. E., Mayes, M. T., Meyer, N., Johnson, C., Swarzenski, P. W., Cohen, A. S. & Russell, J. M. (2010). Late-twentieth-century warming in Lake Tanganyika unprecedented since AD 500. *Nature Geoscience* **3,** 422–425.

Tomanek, L. (2010). Variation in the heat shock response and its implication for predicting the effect of global climate change on species' biogeographical distribution ranges and metabolic costs. *The Journal of Experimental Biology* **213,** 971–979.

Tompkins, E. L. & Adger, W. N. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society* **9,** 1–10.

Tonn, W. M. (1990). Climate change and fish communities: A conceptual framework. *Transactions of the American Fisheries Society* **119,** 337–352.

Townsend, S. A., Boland, K. T. & Wrigley, T. J. (1992). Factors contributing to a fish kill in the Australian wet/dry tropics. *Water Research* **26,** 1039–1044.

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., Dillon, P., Finlay, K., Fortino, K., Knoll, L. B., Kortelainen, P. L., Kutser, T., Larsen, S., Laurion, I., Leech, D. M., McCallister, S. L., McKnight, D. M., Melack, J. M., Overholt, E., Porter, J. A., Prairie, Y., Renwick, W. H., Roland, F., Sherman, B. S., Schindler, D. W., Sobek, S., Tremblay, A., Vanni, M. J., Verschoor, A. M., Wachenfeldt, E. V. & Weyhenmeyer, G. A. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology & Oceanography* **56,** 2298–2314.

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J. A., Rusticucci, M., Soden, B. & Zhai, P. (2007). Observations: Surface and atmospheric climate change. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H. L., eds), pp. 235–336. Cambridge: Cambridge University Press.

Turner, M. A., Huebert, D. B., Findlay, D. L., Hendzel, L. L., Jansen, W. A., Bodaly, R. A., Armstrong, L. M. & Kasian, S. E. M. (2005). Divergent impacts of experimental lake-level drawdown on planktonic and benthic plant communities in a boreal forest lake. *Canadian Journal of Fisheries and Aquatic Sciences* **62,** 991–1003.

Underwood, A. J. (1996). Spatial and temporal problems with monitoring. In *River Restoration* (Petts, G. & Calow, P., eds), pp. 182–204. Oxford: Blackwell Science.

Unnevehr, L. J. (2008). Food safety issues and fresh food product exports from LDCs. *Agricultural Economics* **23,** 231–240.

Vadeboncoeur, Y., Vander Zanden, M. J. & Lodge, D. M. (2002). Putting the lake back together: Reintegrating benthic pathways into lake food webs. *BioScience* **52,** 44–54.

Van Vliet, M. T. H., Franssen, W. H. P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P. & Kabat, P. (2013). Global river discharge and water temperature under climate change. *Global Environmental Change* **23,** 450–464.

Vander Zanden, M. J. & Vadeboncoeur, Y. (2002). Fishes as integrators of benthic and pelagic food webs in lakes. *Ecology* **83,** 2152–2161.

Vander Zanden, M. J., Casselman, J. M. & Rasmussen, J. B. (1999). Stable isotope evidence for food web shifts following species invasions of lakes. *Nature* **401,** 464–467.

Vanderwal, J., Murphy, H. T., Kutt, A. S., Perkins, G. C., Bateman, B. L., Perry, J. J. & Reside, A. E. (2012). Focus on poleward shifts in species' distribution underestimates the fingerprint of climate change. *Nature Climate Change* **3**, 239–243.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. & Cushing, C. E. (1980). River continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* **37,** 130–137.

Vass, K. K., Das, M. K., Srivastava, P. K. & Dey, S. (2009). Assessing the impact of climate change on inland fisheries in River Ganga and its plains in India. *Aquatic Ecosystem Health & Management* **12,** 138–151.

Verdonschot, P. F. M., Hering, D., Murphy, J., Jähnig, S. C., Rose, N. L., Graf, W., Brabec, K. & Sandin, L. (2010). Climate change and the hydrology and morphology of freshwater ecosystems. In *Climate Change Impacts on Freshwater Ecosystems* (Kernan, M., Battarbee, R. W. & Moss, B., eds), pp. 65–83. Oxford: Wiley-Blackwell.

Vidic, R. D., Brantley, S. L., Vandenbossche, J. M., Yoxtheimer, D. & Abad, J. D. (2013). Impact of shale gas development on regional water quality. *Science* **340,** 6134. doi: 10.1126/science.1235009

Vigg, S. & Burley, C. C. (1991). Temperature-dependent maximum daily consumption of juvenile salmonids by northern squawfish (*Ptychocheilus oregonensis*) from the Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* **48,** 2491–2498.

Vincent, W. F., Laurion, I., Pienitz, R. & Anthony, K. M. W. (2013). Climate impacts on Arctic Lake ecosystems. In *Climatic Change and Global Warming of Inland Waters: Impacts and Mitigation for Ecosystems and Societies* (Goldman, C. R., Kumagai, M. & Robarts, R. D., eds), pp. 27–42. Chichester: John Wiley & Sons, Ltd.

Vitousek, P. M. (1994). Beyond global warming: Ecology and global change. *Ecology* **75,** 1861–1876.

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H. & Tilman, D. G. (1997). Human alteration of the global nitrogen cycle: Sources and consequences. *Ecological Applications* **7,** 737–750.

Vlaming, V. L. (1972). Environmental control of teleost reproductive cycles: A brief review. *Journal of Fish Biology* **4,** 131–140.

Vollmer, M. K., Bootsma, H., Hecky, R. E., Patterson, G., Halfman, J. D., Edmond, J. M., Eccles, D. H. & Weiss, R. F. (2005). Deep-water warming trend in Lake Malawi, East Africa. *Limnology & Oceanography* **50,** 727–732.

Vondracek, B., Zimmerman, J. K. H. & Westra, J. V. (2003). Setting an effective TMDL: Sediment loading and effects of suspended sediment on fish. *Journal of the American Water Resources Association* **39,** 1005–1015.

Wackernagel, M., Lewan, L. & Hansson, C. B. (1999). Evaluating the use of natural capital with the ecological footprint: Applications in Sweden and subregions. *Ambio* **28,** 604–612.

Walther, G.-R., Hughes, L., Vitousek, P. & Stenseth, N. C. (2005). Consensus on climate change. *Trends in Ecology and Evolution* **20,** 648–649.

Walther, G.-R., Roques, A., Hulme, P. E., Sykes, M. T., Pysek, P., Kühn, I., Zobel, M., Bacher, S., Botta-Dukát, Z., Bugmann, H., Czúcz, B., Dauber, J., Hickler, T., Jarosík, V., Kenis, M., Klotz, S., Minchin, D., Moora, M., Nentwig, W., Ott, J., Panov, V. E., Reineking, B., Robinet, C., Semenchenko, V., Solarz, W., Thuiller, W., Vilà, M., Vohland, K. & Settele, J. (2009). Alien species in a warmer world: Risks and opportunities. *Trends in Ecology & Evolution* **24,** 686–693.

Ward, J. V. (1998). Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation* **83,** 269–278.

Ward, J. V., Tockner, K., Arscott, D. B. & Claret, C. (2002). Riverine landscape diversity. *Freshwater Biology* **47,** 517–539.

Warren, R., Price, J., Fischlin, A., Nava Santos, S. & Midgley, G. (2011). Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. *Climatic Change* **106,** 141–177.

Warren, D. R., Robinson, J. M., Josephson, D. C., Sheldon, D. R. & Kraft, C. E. (2012). Elevated summer temperatures delay spawning and reduce redd construction for resident brook trout (*Salvelinus fontinalis*). *Global Change Biology* **18,** 1804–1811.

Webb, B. W. (1996). Trends in stream and river temperature. *Hydrological Processes* **10,** 205–226.

Wedekind, C. & Kung, C. (2010). Shift of spawning season and effects of climate warming on developmental stages of a grayling (Salmonidae). *Conservation Biology* **24,** 1418–1423.

Wedekind, C., Evanno, G., Székely, T., Pompini, M., Darbellay, O. & Guthruf, J. (2013). Persistent unequal sex ratio in a population of grayling (Salmonidae) and possible role of temperature increase. *Conservation Biology* **27,** 229–234.

Weiss, R. F. (1970). The solubility of nitrogen, oxygen and argon in water and seawater. *Deep-Sea Research* **17,** 721–735.

Welcomme, R. L. (1979). *Fisheries Ecology of Floodplain Rivers*. London: Longman.

Welcomme, R. L. (1985). *River Fisheries*. Rome: FAO.

Welcomme, R. L. (2001). *Inland Fisheries: Ecology and Management*. Oxford: Fishing News Books.

Welcomme, R. L. (2011). An overview of global catch statistics for inland fish. *ICES Journal of Marine Science* **68,** 1751–1756.

Welcomme, R. L., Winemiller, K. O. & Cowx, I. G. (2006). Fish environmental guilds as a tool for assessment of ecological condition of rivers. *River Research and Applications* **22,** 377-396.

Welcomme, R. L., Cowx, I. G., Coates, D., Béné, C., Funge-Smith, S., Halls, A. & Lorenzen, K. (2010). Inland capture fisheries. *Philosophical Transactions of the Royal Society B* **365,** 2881–2896.

Wenger, S. J., Isaak, D. J., Dunham, J. B., Fausch, K. D., Luce, C. H., Neville, H. M., Rieman, B. E., Young, M. K., Nagel, D. E., Horan, D. L. & Chandler, G. L. (2011*a*). Role of climate and invasive species in structuring trout distributions in the interior Columbia River Basin, USA. *Canadian Journal of Fisheries and Aquatic Sciences* **68,** 988–1008.

Wenger, S. J., Isaak, D. J., Luce, C. H., Neville, H. M., Fausch, K. D., Dunham, J. B., Dauwalter, D. C., Young, M. K., Elsner, M. M., Rieman, B. E., Hamlet, A. F. & Williams, J. E. (2011*b*). Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America* **108,** 14175–14180.

Wetzel, R. G. (2001). *Limnology: Lake and River Ecosystems,* 3rd edn. London: Academic Press.

Weyhenmeyer, G. A., Livingstone, D. M., Meili, M., Jensen, O., Benson, B. & Magnuson, J. J. (2011). Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology* **17,** 268–275.

Wheeler, T. & Von Braun, J. (2013). Climate change impacts on global food security. *Science* **341,** 508–513.

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M. & Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* **54,** 101–123.

Whitlock, M. C. (2011). Data archiving in ecology and evolution: Best practices. *Trends in Ecology & Evolution* **26,** 61–65.

Whitney, C. K., Hinch, S. G. & Patterson, D. A. (2013). Provenance matters: Thermal reaction norms for embryo survival among sockeye salmon *Oncorhynchus nerka* populations. *Journal of Fish Biology* **82,** 1159–1176.

Wiedner, C., Rücker, J., Brüggemann, R. & Nixdorf, B. (2007). Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. *Oecologia* **152,** 473–484.

Wilbanks, T. J., Lankao, P. R., Bao, M., Berkhout, F., Cairncross, S., Ceron, J.-P., Kapshe, M., Muir-Wood, R. & Zapata-Marti, R. (2007). Industry, settlement and society. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E., eds), pp. 357–390. Cambridge: Cambridge University Press.

Wilby, R. L., Orr, H., Watts, G., Battarbee, R. W., Berry, P. M., Chadd, R., Dugdale, S. J., Dunbar, M. J., Elliott, J. A., Extence, C., Hannah, D. M., Holmes, N., Johnson, A. C., Knights, B., Milner, N. J., Ormerod, S. J., Solomon, D., Timlett, R., Whitehead, P. J. & Wood, P. J. (2010). Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation principles into practice. *Science of the Total Environment* **408,** 4150–4164.

Wilks, D. S. (2010). Use of stochastic weather generators for precipitation downscaling. *Wiley Interdisciplinary Reviews: Climate Change* **1,** 898–907.

Williams, W. D. (1999). Salinisation: A major threat to water resources in the arid and semi-arid regions of the world. *Lakes & Reservoirs: Research & Management* **4,** 85–91.

Williams, J. W. & Jackson, S. T. (2007). Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* **5,** 475–482.

Williams, J. W., Jackson, S. T. & Kutzbach, J. E. (2007). Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America* **104,** 5738–5742.

Williams, S. E., Shoo, L. P., Isaac, J. L., Hoffmann, A. A. & Langham, G. (2008). Towards an integrated framework for assessing the vulnerability of species to climate change. *PLoS Biol* **6,** e325.

Williamson, C. E., Metgar, S. L., Lovera, P. A. & Moeller, R. E. (1997). Solar ultraviolet radiation and the spawning habitat of yellow perch, *Perca flavescens*. *Ecological Applications* **7,** 1017–1023.

Williamson, C. E., Dodds, W., Kratz, T. K. & Palmer, M. A. (2008). Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes. *Frontiers in Ecology and the Environment* **6,** 247–254.

Willis, K. J. & Bhagwat, S. A. (2009). Biodiversity and climate change. *Science* **326,** 806–807.

Wilsey, C. B., Lawler, J. J., Maurer, E. P., McKenzie, D., Townsend, P. A., Gwozdz, R., Freund, J. A., Hagmann, K. & Hutten, K. M. (2013). Tools for assessing climate impacts on fish and wildlife. *Journal of Fish and Wildlife Management* **4,** 220–241.

Winder, M. & Schindler, D. E. (2004*a*). Climate change uncouples trophic interactions in an aquatic ecosystem. *Ecology* **85,** 2100–2106.

Winder, M. & Schindler, D. E. (2004*b*). Climatic effects on the phenology of lake processes. *Global Change Biology* **10,** 1844–1856.

Winfield, I., Fletcher, J. & James, J. (2008). The Arctic charr (*Salvelinus alpinus*) populations of Windermere, UK: Population trends associated with eutrophication, climate change and increased abundance of roach (*Rutilus rutilus*). *Environmental Biology of Fishes* **83,** 25–35.

Winfield, I. J., Hateley, J., Fletcher, J. M., James, J. B., Bean, C. W. & Clabburn, P. (2010). Population trends of Arctic charr (*Salvelinus alpinus*) in the UK: Assessing the evidence for a widespread decline in response to climate change. *Hydrobiologia* **650,** 55–65.

Wismer, D. A. & Christie, A. E. (1987). *Temperature Relationships of Great Lakes Fishes: A Data Compilation*. Ann Arbor, MI: Great Lakes Fishery Commission.

de Wit, M. & Stankiewicz, J. (2006). Changes in surface water supply across Africa with predicted climate change. *Science* **311,** 1917–1921.

Witte, F., Welten, M., Heemskerk, M., van der Stap, I., Ham, L., Rutjes, H. & Wanink, J. A. N. (2008). Major morphological changes in a Lake Victoria cichlid fish within two decades. *Biological Journal of the Linnean Society* **94,** 41–52.

Witte, F., de Graaf, M., Mkumbo, O. C., El-Moghraby, A. I. & Sibbing, F. A. (2009). Fisheries in the Nile system. In *The Nile* (Dumont, H. J., ed.), pp. 723–747. Dordrecht: Springer.

Wohlschlag, D. E. (1957). Differences in metabolic rates of migratory and resident forms of an arctic whitefish. *Ecology* **38,** 502–510.

Woodward, G., Perkins, D. M. & Brown, L. E. (2010). Climate change and freshwater ecosystems: Impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B* **365,** 2093–2106.

Wrona, F. J., Prowse, T. D., Reist, J. D., Beamish, R., Gibson, J. J., Hobbie, J., Jeppesen, E., King, J., Koeck, G., Korhola, A., Lévesque, L., Macdonald, R., Power, M., Skvortsov, V., Vincent, W., Clark, R., Dempson, B., Lean, D., Lehtonen, H., Perin, S., Pienitz, R., Rautio, M., Smol, J., Tallman, R. & Zhulidov, A. (2005). Freshwater ecosystems and fisheries. In *Arctic Climate Impact Assessment* (Symon, C., Arris, L. & Heal, B., eds), pp. 353–452. Cambridge: ACIA.

Wrona, F. J., Prowse, T. D., Reist, J. D., Hobbie, J. E., Lévesque, L. M. J., Macdonald, R. W. & Vincent, W. F. (2006*a*). Effects of ultraviolet radiation and contaminant-related stressors on Arctic freshwater ecosystems. *Ambio* **35,** 388–401.

Wrona, F. J., Prowse, T. D., Reist, J. D., Hobbie, J. E., Lévesque, L. M. J. & Vincent, W. F. (2006*b*). Climate change effects on aquatic biota, ecosystem structure and function. *AMBIO: A Journal of the Human Environment* **35,** 359–369.

Xenopoulos, M. A., Lodge, D. M., Alcamo, J., Märker, M., Schulze, K. & Van Vuuren, D. P. (2005). Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology* **11,** 1557–1564.

Young, J. A. & Muir, J. F. (2008). Marketing fish. In *Handbook of Fish Biology and Fisheries* (Hart, P. J. B. & Reynolds, J. D., eds), pp. 37–60. Oxford: Blackwell Science Ltd.

Yvon-Durocher, G., Jones, J. I., Trimmer, M., Woodward, G. & Montoya, J. M. (2010). Warming alters the metabolic balance of ecosystems. *Philosophical Transactions of the Royal Society B* **365,** 2117–2126.

Zagarese, H. E. & Williamson, C. E. (2001). The implications of solar UV radiation exposure for fish and fisheries. *Fish and Fisheries* **2,** 250–260.

Zeug, S. C. & Winemiller, K. O. (2008). Evidence supporting the importance of terrestrial carbon in a large-river food web. *Ecology* **89,** 1733–1743.

Zhang, X., Harvey, K. D., Hogg, W. D. & Yuzyk, T. R. (2001). Trends in Canadian streamflow. *Water Resources Research* **37,** 987–998.

Zhang, Y., Gao, F., He, D. & Li, S. (2007). Comparison of spatial-temporal distribution characteristics of water temperatures between Lancang River and Mekong River. *Chinese Science Bulletin* **52,** 141–147.

Zholdasova, I. (1997). Sturgeons and the Aral Sea ecological catastrophe. *Environmental Biology of Fishes* **48,** 373–380.

Electronic References

Capdevila-Arguelles, L. & Zilletti, B. (2008). Convention on the Conservation of European Wildlife and Natural Habitats Standing Committee. 2nd Meeting of the Group of Experts on Biodiversity and Climate Change: A perspective on climate change and invasive alien species. *T-PVS/Inf (2008) 5*. Council of Europe, Strasbourg, 16 June 2008. Available at http://www.nonnativespecies.org/downloadDocument.cfm?id=397

Povlsen, A. F. (1993). Observations on the biology and ecology of rainbow trout, *Oncorhynchus mykiss*, and its implications for fisheries in the highlands of Papua New Guinea. A report prepared for the Sepik River Fish stock Enhancement Project. *FI:PNG/85/001. Field Doc. 21.* Rome: FAO. Available at http://www.fao.org/docrep/field/003/AC084E/AC084E00.htm (last accessed 6 January 2015).