# Introduction: Biodiversity in freshwater systems, and the key roles played by crayfish

More than 20 years ago, the term 'biodiversity' was coined, deriving its name from the concept of 'biological diversity', at a time when the ecological importance of the various components in communities was becoming generally evident (Wilson, 1988). Several authors, such as Gaston & Spicer (1998), have since emphasized the multiplicity and range of meanings associated with the term. Biodiversity, the variety of life and its processes, includes not just the panoply of living organisms (species diversity) and the genetic differences between them, but the communities and ecosystems, including landscapes (habitat diversity), in which they occur, and the ecological and evolutionary processes through which they function, change and adapt. The pool of living diversity is dynamic, with changes in genetic variation, structure and function. However, the biodiversity of an area cannot be simply represented as the number of taxa present; thus, introducing a species to a community does not necessarily increase its biodiversity, and may in fact deplete it. Nonetheless, as we shall see, focusing on individual species is a valuable means of monitoring and protecting biodiversity.

## Freshwater communities: structure and function

Fresh waters are an essential component of landscapes in most of the world, and are often critically linked to the welfare of terrestrial and marine ecosystems. Freshwater availability or flow is the dominant variable in freshwater ecosystem functioning, so it is vitally important to maintain and secure water supply to streams and wetlands. Indicators of functioning, or their measurable surrogates, have been suggested for some freshwater ecosystems: these include litter breakdown rates, benthic metabolism, and functional feeding groups. Among the most important members of any community are 'keystone species', defined as those that control communities by reason of their size, abundance, feeding patterns or dominance in interactions, and which thereby affect ecosystem functioning. Numerous fish and crayfish species are excellent examples of keystone species in freshwater communities, and the latter are the main focus of this book.

Many ideas current in freshwater ecological thinking have been derived from terrestrial systems. However, participation at multiple trophic levels is common in freshwater organisms, more so than in terrestrial ones. Freshwater systems are often complex, interacting mosaics with important boundary properties, and there is a contemporary focus on habitat spatial heterogeneity and patch connectivity. Functional linkages include exchanges of materials and nutrients between water and landscape, and trophic fluxes, with overall a net transfer of aquatic-derived energy into riparian food webs. How might the diversity of aquatic and terrestrial communities affect the amount and direction of transfer? Aquatic insects may spend only short periods of time in the terrestrial phase, but life history events such as mating and egg-laying may be restricted to the terrestrial 'airscape', leading to system nutrient losses or gains. Some crustaceans – crayfish, crabs and amphipods – are amphibious or will forage on land. However, exclusively aquatic (homotopic) crustaceans or molluscs must chiefly be transferred through the aquatic food web, or to terrestrial systems through amphibious predators such as newts, otters and herons. Detailed measurement is lacking for such land–aquatic interactions.

## Freshwater species richness

At the global level, species richness increases strongly towards the equator. This is true for freshwater fishes in general, although certain well-studied groups such as freshwater crayfish are much less diverse in the tropics than in temperate regions. The overall number of freshwater species (species richness, a major component of biodiversity) is low compared with either marine or terrestrial systems. However, species richness in fresh waters is enormous in relation to the tiny global extent of surface water habitats (0.3% by area). Among the diverse and species-rich animal groups in freshwater habitats are fishes, decapod crustaceans, bivalve molluscs, dragonflies and water beetles; for example, over 40% of the 28 000 known fish species are freshwater forms and, given the distribution of water on the Earth's surface, this is equivalent to one fish species for every 15 $km^3$ of fresh waters, compared to one for every 100 000 $km^3$ of seawater. This richness is often associated with the linear or fragmented, 'island' nature of catchments and waterbodies, with high border to area ratios. While much catchment diversity often resides outside the main channel, in marshes and ditches, individual small lakes and ponds may also develop high biodiversity. Ecological corridors are vital to link such sites both in floodplains and upper catchments, and such ecosystem connectivity enhances biodiversity. Diversity 'hot-spots' for several freshwater groups, including crayfish, occur where there has been a mixture of isolation and climatic stability; particularly rich areas are in the south-eastern USA, Southeast Asia and western Australia.

However, biological diversity is not just concerned with species richness – a list of species observed over several visits and with standardized methodology; it also involves species evenness, dominance, rarity and indicator status, and the recognition of naturally fluctuating species. Susceptibility to invasions of alien species is also important, including the question of whether high biodiversity affords better protection against invasion by an alien species, or whether species richness is irrelevant in this context. Other knowledge gaps include demonstrating a fundamental relationship between biodiversity and the maintenance of important ecosystem processes in fresh

**Table 1.** Comparison of bird and amphibian species in the 2008 IUCN Red List, assessed for climate-change susceptibility. Categories: RED: threatened and climate-change-susceptible; ORANGE: threatened but not climate-change-susceptible; YELLOW: not threatened but climate-change-susceptible; and GREEN: not threatened and not climate-change-susceptible (after Foden *et al.*, 2009).

| | | Birds | | | Amphibians | | |
|---|---|---|---|---|---|---|---|
| Threatened? | | Yes | No | Totals | Yes | No | Totals |
| Climate-change-susceptible? | Yes | 978 (10%) [RED] | 2452 (25%) [YELLOW] | 35% | 1488 (24%) [RED] | 1729 (28%) [YELLOW] | 52% |
| | No | 248 (2%) [ORANGE] | 6172 (67%) [GREEN] | 65% | 503 (8%) [ORANGE] | 2502 (40%) [GREEN] | 48% |
| | Total | 12% | 88% | 9856 | 32% | 68% | 6222 |

waters, and determining whether there are any intrinsic relationships between freshwater biodiversity and the health of humans and wild organisms.

Among freshwater organisms, some crustaceans are characteristic of wetlands and marshes, while others are restricted to rivers, streams and small lakes. Freshwater crayfish living in shallow water are important components of each of these systems, and may be indicators of water quality or habitat. Crayfish ecology is discussed in Chapters 3 and 6. The impacts of invasive non-indigenous crayfish species (NICS) on indigenous crayfish species (ICS) and their habitats are introduced below, further examined in Chapter 4, and their control through management in order to protect ICS discussed in Chapter 8.

## Drivers of freshwater biodiversity

By their nature, freshwater systems are often fragmented (patchy) or linear in structure. Freshwater ecosystems and communities occupy a wide variety of waterbody types both above and below ground, large and small, temporary and permanent, stationary and flowing, intermittent and continuous. They range from springs and headwaters to rivers, lakes and wetlands; they also include transitional systems such as marshes, karstic temporary ponds or turloughs, and estuaries that link freshwater systems with terrestrial and marine environments. Small systems are intrinsically vulnerable to disturbance and stresses. In addition, freshwater systems necessarily lie at the lowest points in the landscape, where they collect and integrate multiple inputs and influences from the entire catchment. These systems are also often highly dynamic, with rapid changes in both space and time in their biological, hydrological, chemical and physical properties. All these features contribute to their vulnerability to disturbance. Table 1 illustrates this, contrasting data for birds and for amphibians (representing wetlands) derived from the 2008 IUCN Red List (after Foden *et al.*, 2009).

In most countries today there are marked gradients in species distribution and richness. Such gradients often indicate a decline in diversity. The situation is most evident in fresh waters, but there may be many different causes. Dudgeon *et al*. (2006) explored the special features of freshwater habitats and the communities they support that make them especially vulnerable to human activities. They documented threats to global freshwater biodiversity under five headings: overexploitation, water pollution, flow modification, destruction or degradation of habitat, and invasion by exotic species. Their combined and interacting influences have resulted in population declines and range reductions of freshwater biodiversity worldwide (Dudgeon *et al*., 2006). The drivers of biodiversity in fresh waters are both natural and anthropogenic and, while the former are fairly well understood, there is immediate need for the latter to be quantified and communicated to decision makers if effective management is envisaged.

Across the globe, natural drivers have produced gradients in species distribution and richness. Natural drivers include evolutionary pressures and hot-spots, affecting biodiversity through habitat restriction, isolation, change over time associated with mountain building, infilling of lakes, and climatic change. However, observed gradients in biodiversity in fresh waters are frequently due to human intervention, where a gradient may indicate a loss of biodiversity. Climate change and anthropogenic drivers are discussed below.

## Climate change

Climate change, by encouraging migrations and leading to extinctions and new evolutionary situations, can influence biodiversity in fresh waters. A drying climate – or its anthropogenic analogue, increased abstraction – will reduce both perennial flows and seasonal supplies to off-river habitats and could depress gene flow. Species characteristics which increase susceptibility to climate change impacts have been described by Foden *et al*. (2009) and are summarized in Table 2. This is further developed with reference to crayfish in Chapter 6.

Recent research has addressed the reductions in freshwater biodiversity under plausible scenarios of climate change and water consumption. About half of the world's investigated rivers may experience reduced water availability due to both global warming and the withdrawal of water for human needs. By 2070, in these drying rivers, the loss of local fish species is suggested to range from less than 4% to more than 22%, with up to 75% loss predicted in the most severely affected rivers.

In 1990, for the first time, a team of international experts responded to this problem, using two climate change scenarios from the Intergovernmental Panel on Climate Change (IPCC) to cover a large range of possible outcomes. They combined these scenarios with a global hydrological model to estimate possible losses in river water availability due to climate change and trends in water consumption. Linking the obtained results to known relationships between fish species and changes in water availability, they investigated future trends in riverine fish richness for over 300 of the world's river basins (Tockner & Stanford, 2002; Xenopoulos *et al*. (2005).

In both scenarios, their calculations showed that, by 2070, water availability would decrease up to 80% in more than 130 investigated rivers with available fish data. About half of these rivers were predicted to lose more than 10% of their fish species when

**Table 2.** Species characteristics which make them susceptible to climate change (after Foden *et al*., 2009). Species phenotypic plasticity and genetic diversity will determine the likelihood of adaptation.

| | |
|---|---|
| **A** | Specialized habitat or microhabitat requirements, especially where opportunities for dispersal are restricted. |
| **B** | Narrow environmental tolerances or thresholds, occurring at any stage in the life cycle, likely to be exceeded due to climate change (e.g. temperature, pH, rainfall, flooding). |
| **C** | Dependence on specific environmental triggers likely to be disrupted by climate change; e.g., for migration, onset of breeding, egg-laying, hibernation or emergence; climate change may lead to uncoupling of such activities from necessary resources. |
| **D** | Dependence on interspecific interactions that are likely to be disrupted by climate change (e.g. interactions with prey, competitors or symbionts). |
| **E** | Poor or restricted ability to disperse or colonize a more suitable range as the ‘bioclimatic envelope’ shifts polewards or to higher altitudes. |

climate change and water consumption impacts were considered, and a maximum of 75% of local fish losses was calculated for several rivers. The effect of climate change was by far the most important factor contributing to freshwater fish loss under the scenarios, with anthropogenic water withdrawal contributing much less to species loss (an additional 0–5%). However, in regions where substantial irrigation has occurred in the past and is expected to increase (e.g. southern Asia and the Middle East), water consumption is particularly important for fish biodiversity decline. These forecasts are probably underestimates of fish losses, because many other important drivers (e.g. introduced species, reductions in channel–floodplain connectivity) were not included in the calculations.

Most catchments thus have multiple stressors. In a well-studied example, the North American Great Lakes ecosystem, containing some 18% of the planet’s supply of fresh water, lies in a basin that is home to 25% of Canadian agricultural production and 7% of that of the USA, and that provides drinking water for 40 million people, as well as 210 million $m^3$ daily for municipal, agricultural and industrial use. The implications of climate change (lower lake levels, extreme swings) on major catchments and large lake ecosystems are profound. Point source pollution regulation has dramatically improved water quality since the 1980s (helped by the filtering activities of invasive zebra mussels).

## Anthropogenic drivers

Twenty-five years ago, economists estimated that organic material equivalent to about 40% of the present net primary production (photosynthesis) in terrestrial ecosystems is being co-opted by human beings each year, and concluded that the diversion and destruction of these terrestrial resources clearly contributes to human-caused extinctions of species and to genetically distinct populations (Vitousek *et al*., 1986). Today, the situation is even more extreme, because of rising populations and increasing consumer demands. We now know that the Earth’s hydrological regimes are being fundamentally altered to meet the needs of rapidly expanding societies (Vörösmarty *et al*., 2004), despite our incomplete knowledge and understanding of either the diverse species present or the larger-scale consequences.

Many human activities lead to increases in highly managed, species-poor freshwater habitats (e.g. canalized rivers, drainage ditches, eutrophic ponds, and reservoirs) and promote deterioration and fragmentation, increasing the patchiness of natural and often species-rich habitats such as river floodplains. However, some species can have their movement restricted by something as apparently trivial as a road though otherwise pristine habitat (Trombulak & Frissell, 2000). Short-term monitoring measurements, e.g. of dissolved oxygen, bacteria or water chemistry, may not indicate longer-term impacts, but biological water quality, measured universally by the range of macroinvertebrates present, inevitably falls. Residual small and isolated populations tend to be more sensitive than larger ones to both demographic and environmental factors such as the spread of disease or changes in food supply. To other human impacts are added the effects of many introduced species, and we need a better understanding of how these affect biodiversity.

Rivers, lakes, wetlands and connecting groundwaters are the lowest points, the 'sinks' into which landscapes drain, and freshwater ecosystems are greatly influenced by human modifications of such landscapes as well as to the waters (Baron *et al*., 2003). However, knowledge about the resistance of our biosphere to human-caused changes in biodiversity is still lacking. Monitoring the impact of anthropogenic drivers of biodiversity is often unfeasibly complex. We need a better understanding of the effects of introduced species. More knowledge is also needed about natural ecological processes in the face of increasing use of artificial pesticides, fertilizers, and pharmaceutical and veterinary drugs. Pollution and pesticides can lower habitat quality, reduce species breeding and survival rates, and even cause local species extinction.

Three global anthropogenic drivers of aquatic ecosystems are nutrient enrichment from agriculture and/or organic pollution, physical disturbance (alterations in hydrology), and toxicity (trace metals, pesticides, acidification). Up to half of all nutrient loads in large lowland rivers originate from agriculture, because of inadequate controls – much more than from industry. Agriculture has a major impact on fresh waters through land-use change and increasing production intensity, and through its impacts on stream boundaries. Crops, both edible and for biomass, may require increased water abstraction at sensitive times, while intensive dairying and fish farming may cause other environmental stresses through the concentration of silage and other feedstuffs, and disposal of wastes. There is a continuing need for applied agro-ecological research into the roles of natural communities in recycling nutrients and animal wastes. Other impacts come from soil erosion and the destruction of floodplains. Further research is also needed on the detrimental impacts of land drainage in environmentally fragile landscapes. The Organisation for Economic Cooperation and Development (OECD) in 2001 recommended taking a holistic view of agricultural impacts on biodiversity rather than focusing exclusively on threatened species and habitats (see www.oecd.org) – but this approach has obvious limitations and dangers.

## Invasive species

Biological invasions are considered to be one of the main issues in conservation biology worldwide (e.g. Mack *et al*., 2000; Sala *et al*., 2000), and their success is acknowledged to be supported by climate change processes. The global homogenization of biota is under way, through the worldwide introduction and establishment of non-indigenous (exotic) species (Lodge *et al*., 1998). This is particularly true for freshwater ecosystems because of their greater vulnerability than terrestrial biomes to biological invasions (Rodrigues *et al*., 2006). The rate of colonization has gone up many times in recent years but it is not clear whether these aliens, including crayfish, may find impacted systems easier to infiltrate than intact ones.

Major differences between the impacts of invasive alien species (biological pollution) and of chemical pollution include the fact that ecosystem recovery from chemical pollution typically begins once the stress has been removed, and engineering solutions can often be highly successful. However, invasive species, like extinctions, are typically permanent and their impacts are irreversible. Prevention is thus the preferred option, although this is very difficult.

Invasive alien species are now a global problem, reflecting world trade, and exacerbated by free trade conventions and agreements. Well-known aquatic examples from the last 100 years are the impacts of North American waterweeds (*Elodea* spp.) in Europe, the invasion of lampreys into the North American Great Lakes, the recent spread of Ponto-Caspian amphipods from the Black Sea across Europe, and the worldwide movements of zebra mussels (*Dreissena* spp.). There are at least 162 exotic invasive species that have modified Great Lakes habitats, reduced native biodiversity and altered food webs; they include zebra and quagga mussels, sea lamprey, predatory zooplankton and amphipods. Human translocations of crayfish, an important focus of this book, have been a major problem for over a century.

Invasive species ecology has obvious synergies with anthropogenic threats to aquatic biodiversity and ecosystem functioning. While some positive impacts of species introductions have been mooted (e.g. American crayfish in East Africa and in lagoons of southern Spain, providing a novel food source for declining native predators such as otters and field-feeding storks and cranes), human-mediated invasives usually result in community change; by being dominant competitors or effective predators, they can drive many native species to low densities or extinction, thus reducing biodiversity (Reid & Miller, 1989; Holdich & Pöckl, 2007).

Key principles in the management of aquatic invasive species include detailed risk assessments of known potential invaders to prevent future problems, assessment of the potential impacts of climate change, and studies on distribution, ecology and genetics. Management involves controlling external sources, taking early action on new outbreaks, providing long-term funding, involving stakeholders and invoking their responsibilities, while developing good monitoring systems. In the context of this book, we are primarily concerned about direct invasions by exotic crayfish, and their food, predators and parasites. The invasion of a number of North American crayfish species into other continents is discussed in Chapter 4, and attempts at their management and control in Chapter 8.

## Threats to biodiversity and ecosystem functioning

Worldwide, it is clear that – on average – freshwater biodiversity is more threatened than terrestrial biodiversity (Allan & Flecker, 1993; Williams *et al*., 1993; McAllister *et al*., 1997; Ricciardi & Rasmussen, 1999). Freshwater organisms are severely threatened globally because bodies of fresh water are at the heart of social and economic sustainability, and demands for water are steadily expanding. However, freshwater biodiversity underpins many processes, e.g. self-purification and protein production, and is important for sustaining goods and services for humans. From those species considered in the 1996 IUCN Red List, Abell *et al*. (2002) concluded that some 20% of reptiles, 25% of amphibians, and 34% of fishes (mostly freshwater species) were threatened (crayfish had not then been evaluated). At a regional scale, the projected mean future extinction rate for North American freshwater fauna was considered to be about five times greater than that for terrestrial fauna. There is no evidence that this number is too high for Europe, with its millennia of land development and wetland alteration.

The implications of this worldwide decline in freshwater biodiversity are potentially serious. Baron *et al*. (2003) noted that human societies extract increasingly vast quantities of water to supply their various requirements, while overlooking the equally vital benefits of water remaining instream that provide economically valuable commodities and ecosystem services. These include flood control, fish and other foods, and marketable goods. Intact systems are more likely to sustain production of these goods and services in the face of future environmental disruptions such as climate change.

Ecological services are defined as the conditions and processes through which natural ecosystems, and the species that make them up, sustain human life. They are costly or impossible to replace when systems are degraded. One salient example is flooding, a natural function of every river. Small streams and wetlands normally absorb significant amounts of rainwater, run-off and snowmelt before flooding occurs. They also slow flow rates through irregular beds, trap sediment, and their natural cleansing ability improves water quality and stores nutrients, recycling them instream and sustaining downstream ecosystems. Stream modifications by humans or by landscape changes include more incised channels and a smoother bed that harbours fewer organisms and allows water to run faster, eroding more strongly and flooding earlier. Even if the headwaters maintain the biological diversity that underpins ecosystem services, this biodiversity is easily threatened because of the small size of these habitats.

Decline in freshwater habitat quality and species populations is evident worldwide, and at present poor water quality is increasingly the norm. Many human activities promote the fragmentation of natural and often species-rich habitats (e.g. river floodplains) and the increase in highly managed habitats that may be species-poor. Many freshwater ecosystems are now disconnected from each other, rendering each system more vulnerable to degradation. Small, isolated populations tend to be more sensitive than larger ones, because of demographic factors, random events affecting the survival and reproduction of individuals, or environmental factors such as the spread of pollutants or disease, or a reduction in food supply. Other external pressures such as overexploitation or introduced predators may also threaten the survival of small or isolated populations of a species.

In summary, the chief threats to freshwater biodiversity include biological invasions, organic and chemical pollution, and climate change, arguably all caused by increasing demands from burgeoning human populations. Environmental changes occurring at the global scale, such as nitrogen deposition, warming, and shifts in precipitation and run-off patterns, are superimposed upon all of these threat categories (Dudgeon *et al*., 2006). The biodiversity loss in fresh waters is even greater and more rapid than in terrestrial systems. Freshwater ecosystem functioning is a critical component of almost all human activities, but is also strongly impacted by these activities as they modify water flow or use the systems for waste disposal.

## Key indicators of biodiversity

### Monitoring for management

Biodiversity in fresh waters is thus subject to multiple stressors and drivers. Because of its complexity, a good way to understand and manage biodiversity is by identifying and studying representative key functional species. These indicators of biodiversity can be the focus of local-scale monitoring for biodiversity drivers (Kapoor-Vijay & Usher, 1993). Other types of indicator, e.g. impact indicators for such parameters as the degree of habitat fragmentation, are also important in systems management for conservation. Indicators of habitat quality are different from those that measure biodiversity, but there has been insufficient research into selecting those indicators whose abundance and distribution reflect general trends in biodiversity, disagreement as to which bioindicators are best (Andersen, 1999), and indeed, whether there are useful synergies between bioindicators of species richness or biodiversity, and other social or economic indicators.

Conventions on biological diversity and landscape strategy all stress the importance of biodiversity indicators, but there have been few attempts to develop technical lists of biodiversity indicators (e.g. Reid *et al*., 1993). However, this has since been streamlined by the International Convention on Biological Diversity (CBD) in 2002 (at COP-VI), which supported the initiative to stop biodiversity loss by 2010 – the International Year of Biodiversity. Some observers feel that indicators should be confined to ecologically important components of a community, but others believe that threatened species can also provide useful indicators for monitoring biodiversity. Biodiversity indicators should be suitable at different scales. Stakeholders and policy makers demand regional and national-scale data, but ecological meaning is first studied and understood at a local scale. If losses in biodiversity are detected, experimentation is needed to see how these trends can be reduced or reversed through sustainable development management. Finally,

**Table 3.** Life history traits of surrogate, umbrella and flagship species (after Caro & O'Doherty, 1999).

| Indicator type | Body size | Generation time | Sensitive to human disturbance |
|---|---|---|---|
| Health indicator | Small | Short | Yes |
| Population indicator | Irrelevant | Short | Yes |
| Biodiversity indicator | Irrelevant | Irrelevant | Irrelevant |
| Umbrella species | Large | Long | Not necessarily |
| Flagship species | Large | Long | Yes |

can threatened indicator species be adequately monitored without risk to their status? All these problems are relevant to freshwater indicator organisms such as crayfish.

The choice of indicators may also have consequences for conservation policy. If indicators focus on habitat quality rather than biodiversity, then legislation will do likewise. Legislation rewards management practices that result in good-quality habitats, including the presence or absence of specific indicator species. This also affects the type and timing of monitoring. If monitoring for habitat quality, indicators can be selected to assess the capacity of ecological corridors. In some cases, a suite of rare species, as developed in the IUCN Red Lists, might provide a better estimate of habitat quality than common species. However, some indicator lists may be politically developed, rather than being a useful monitoring tool. Table 3 (after Caro & O'Doherty, 1999) summarizes the ecological attributes of indicator species.

The 2008 update of the IUCN Red List includes conservation assessments for nearly 45 000 species (Vié *et al*., 2008), dominated by an evaluation of all the described mammals and birds. However, these represent a tiny fraction of the world's known biodiversity (fewer than 300 000 out of 1.8 million species) and many other groups are hardly considered. Again, it appears that freshwater groups are most at risk, including 37% of fishes and 30% of amphibians. There is also recent information for dragonflies and damselflies (Odonata) and for freshwater crabs (16% threatened). For such threatened invertebrates, the species most at risk are those with very restricted ranges. There are centres of threat in Southeast Asia, in Sri Lanka, and in Colombia and Mexico, related directly or indirectly to human population pressures. The level of threat for freshwater crayfish has recently been assessed (Nadia Richman, personal communication, 2010) and the IUCN approval process is now under way (see Chapter 12). However, although human pressures on freshwater resources remain the root cause, the threat pattern for crayfish, as elaborated in this book, appears different from that for other evaluated invertebrates.

## Species indicators for communities and habitats

Heritage or flagship species are iconic species used in conservation to attract the attention of the public; the panda and polar bear are prime examples. In freshwater habitats, iconic species need to be of interest to human observers and also ecologically significant organisms that can carry the flag for other aquatic denizens. However, not all have