REVIEW

Effects of global climate change on freshwater biota: A review with special emphasis on the Italian situation

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Abstract
There is much evidence that climate is rapidly changing at a global scale, especially regarding mean annual temperatures, precipitations and evaporation. The consequences of this rapid environmental change on freshwater biota are still not clear, but undoubtedly they could be severe. Among the main effects of climate change, we can individuate the enhancement of water temperatures, particularly important for poikilothermic organisms, with the consequent diminution of dissolved oxygen, and the reduction of available habitats for most stenothermal organisms. Another consequence of climate change is the alteration of hydrologic cycles, with increasing intensity and frequency of extreme events such as droughts, especially in Southern Europe. This scenario could severely affect freshwater biota, especially in mid-latitude regions, such as the Italian peninsula: shifts in phenology, life cycles and distribution ranges are likely to be expected for many organisms, with the extinction of many sensitive species. In particular, species adapted to perennial and cold waters are likely to suffer reductions in their distribution range and also local extinctions, while more tolerant organisms may enlarge their distribution ranges. Global climate change may also promote and enhance invasions of alien species. In this work, concepts and hypotheses about the presumable impacts of climate change upon freshwater biota are reported, with examples and predictions related to the Italian situation.

Keywords: Climate change, global warming, freshwaters, biodiversity, Italy

Introduction
Observational records and projections provide an increasing amount of evidence that at global scale climate is rapidly changing (IPCC 2007). Although the climate of our planet varies naturally in response to differences in solar radiation, volcanic eruptions and aerosol concentrations, our climate is also subject to forcing from anthropic pressures, such as the emission of greenhouse gases and the alteration of land cover (Mann et al. 1998). It is demonstrated that mean global temperatures have risen during the last century by about 0.7°C (IPCC 2007; Mann et al. 2008). Further warming is predicted to continue for the next 100 years: in particular, the Earth’s mean surface temperature is projected to increase from 1.8 to 4.0°C by the end of the twenty-first century (IPCC 2007). This observed warming is coupled with changes in the hydrological cycle at a large scale: for example, climate model simulations predict in the future a precipitation increase in high latitudes and part of the tropics and a decrease in sub-tropical and mid-latitude regions (from 10°S to 30°N). Furthermore, many areas will be subjected to the increase of drought and flooding events.

This rapid climate change is projected to affect the biodiversity of large regions dramatically, with changes in the presence and distribution of many species, the decrease of the taxonomic richness, and
the disappearance of entire ecosystems (Svenning et al. 2009). There is much evidence that global warming is already threatening the biological diversity of our planet (Kühn et al. 2008): for example, recent studies have found correspondences between temperature increase and changes in the fish community of the Atlantic Ocean (Quero 1998), Australian and Caribbean coral reefs senescence and death (Munday et al. 2008), changes in the life cycles of some insects (Gomi et al. 2007; Balletto et al. 2008). Extinction risk has grown for many species, and almost one case of extinction, the disappearance of the Costa Rican Golden Toad (Bufo periglenes Savage, 1967) has been associated with climate change (Pounds et al. 1999).

In this scenario, freshwater ecosystems are particularly vulnerable and freshwater biota could experience dramatic impacts. Some recent studies underlined that freshwater biodiversity has declined faster than either marine or terrestrial ones over the past three decades (Jenkins 2003). For this reason, there is increasing attention on the possible influences of climate change upon inland water systems and biota (Figure 1). The purpose of this review is to provide information about different aspects of the potential effects of climate change upon freshwater biota, with particular reference to the Italian situation.

Impacts of global climate change on freshwater biota

It is well known that inland water conditions are intimately coupled with weather and atmospheric temperature variations, so that climate change may have strong direct and indirect effects on freshwater biota (Bates et al. 2008). Among the direct effects we can consider the raising of inland water temperatures, the disruption of hydrologic cycles, the alteration of rainfall and snow cover in different regions, and the increase of extreme precipitation events. In parallel, the general alteration of climate conditions could lead to some indirect effects, such as landscape transformation, increase in river morphology alteration, enhancement of agricultural irrigation needs, increase in the construction of dams with the consequent river fragmentation, worsening water quality, and invasion of allochthonous species (Figure 2). In this review, we will focus on some of the main effects of climate change, such as temperature increase, hydrologic cycles change and invasions of exotic species, reporting some of the most important cases of study in Table I.

Temperature increase

Stream temperature is strictly dependent on air temperature, but is also influenced by some other factors,
such as shading from riparian vegetation, watershed storage in wetlands, land cover, and groundwater connections (Mohseni et al. 1999). Water temperature has important effects on freshwater organism life, both directly and indirectly (for example, because the solubility of oxygen in water decreases as temperature increases). Most freshwater animals are poikilothermic, with an internal temperature that varies with that of their surroundings: thus, water temperature influences their main physiological processes and metabolic activity, and has a strong effect on the survival, longevity and reproductive success of freshwater animals (Giller & Malmqvist 1998). In particular, growth of aquatic organisms is often temperature-dependent, since higher temperatures are known to enhance feeding activity and digestion rate (Allan 1995). For example, recent studies in North Italian rivers revealed that populations of the mayflies Oligoneuriella rhenana (Imhoff, 1852) (Ephemeroptera: Oligoneuriidae) and Pothamantus luteus (Linnaeus, 1767) (Ephemeroptera: Pothamantiidae) have a faster development in warmer environments (Fenoglio et al. 2005, 2008). Moreover, Erba et al. (2003) recently demonstrated that thermal characteristics seem to be the major factor responsible for the observed differences in life cycle patterns of different species of Baetidae (Ephemeroptera) in the Italian Alps. We can hypothesize that, with the projected increase of water temperatures, the life cycles and phenotype of many aquatic organisms will change, with shifts in ontogeny and breeding time, decrease of mean body size, the alteration of sex ratios, and the reduction of fecundity (Hogg & Williams 1996).

Furthermore, some aquatic organisms in inland waters are stenothermal, occupying narrow temperature ranges. In lotic environments, the longitudinal distribution of the species is strictly related to water temperature, with some groups (such as Salmonidae among vertebrates and Blephariceridae among invertebrates) having low lethal thermal thresholds (about 24–28°C for Brown Trout; Elliott 1994). Climatic warming has been correlated with poleward and upward distributional shifts of terrestrial animals (Levinsky et al. 2007), but evidence from lotic systems is very scarce at the moment. For example, analysing the Perlid stonyfly (Plecoptera) populations of 35 sites in the Rocky Mountains, Sheldon (2007) reported that median elevations of some species, such as Acroneuria abnormis (Newman, 1838) and Ecroptura xanthenes (Newman, 1838), shifted uphill ~65 m in the last three decades. It is to be expected that, with the progressive thermal increase, the area occupied by many species may
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restrict or even disappear: in fact, while terrestrial or marine migratory species can respond rapidly to yearly climate variation by altering the timing or destination of migration (Parmesan et al. 1999), most freshwater animals are sedentary and live in confined environments, and are therefore incapable of rapid responses to environmental variations. In this context, for example, fish distribution may be dramatically altered by climate warming, because these organisms have no physiological ability to regulate their body temperature and their dispersal ability is constrained by the network structure of drainage basins (Grant et al. 2007). In a recent study, Buisson et al. (2008) hypothesized that stream fish assemblages will change in the future throughout Europe, with warm-water species, such as Barbus meridionalis Risso, 1826, Gobio gobio (Linnaeus, 1758) and Leuciscus cephalus (Linnaeus, 1758), possibly experiencing an increase in their distribution, while cold-water ones, such as Salmo trutta fario (Linnaeus, 1758) and Cottus gobio (Linnaeus, 1758), are expected to lose many previously suitable habitats. It is likely that, in the future, these impacts could be enhanced because of the increase of water withdrawal. Furthermore, this situation could be worsened in Italy by the high presence of dams and barriers that disrupt the longitudinal connectivity of lotic systems, inhibiting fish migration (Fiorese et al. 2005). In a recent paper, Xenopoulos et al. (2005) predicted a model of freshwater fish extinction on the basis of two scenarios (A2 and B2) of climate change provided by the International Panel of Climate Change (IPCC 2001). Both scenarios predicted an evident reduction in the fish species richness in two Italian lotic environments. In the Po River, the most severe scenario (A2) could determine a loss of fish species ranging from 7 to 13%, while the other (B2) could range from 3 to 6%. In the Ombrone River, the expected losses would be more impressive, with the extinction of 10–15% (A2) or 5% (B2) of the total fish species number in the future.

Table I. Effects of global change on some freshwater organisms.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Effect of global change</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Mollusca</td>
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<tr>
<td>Dreissena polymorpha (Pallas, 1771)</td>
<td>+ Population increase&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Pisidium ammonium (Müller, 1774)</td>
<td>– Population collapse&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Pisidium casertanum (Pol, 1791)</td>
<td>– Population collapse&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Pisidium henslowanum (Sheppard, 1823)</td>
<td>– Population collapse&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Pisidium montesierianum (Paladilhe, 1866)</td>
<td>– Population collapse&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Pisidium nitidum Jenyns, 1832</td>
<td>– Population collapse&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Pisidium subtruncatum Malm, 1855</td>
<td>– Population collapse&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Crustacea</td>
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<td>Thermocyclops oithonoide (Sars 1863)</td>
<td>+ Change in phenology and abundance increase&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Hesperodiaptomus arcticus (Marsh, 1920)</td>
<td>– Population reduction&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>Eudiaptomus intermedius (Steuer, 1897)</td>
<td>– Modification of life history strategies&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>Insecta</td>
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<tr>
<td>Gomphus vulgatissimus (L.)</td>
<td>– Change in phenology and emergence&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>Chloroperla sp.</td>
<td>– Habitat reduction&lt;sup&gt;f&lt;/sup&gt;</td>
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<td>Protonemura sp.</td>
<td>– Habitat reduction&lt;sup&gt;f&lt;/sup&gt;</td>
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<td>Nemoura sp.</td>
<td>– Habitat reduction&lt;sup&gt;f&lt;/sup&gt;</td>
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<tr>
<td>Ecdyonurus sp.</td>
<td>– Habitat reduction&lt;sup&gt;f&lt;/sup&gt;</td>
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<tr>
<td>Serratella ignita (Poda 1761)</td>
<td>+ Habitat expansion&lt;sup&gt;g&lt;/sup&gt;</td>
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<tr>
<td>Dinocras cephalotes (Curtis, 1827)</td>
<td>– Habitat reduction&lt;sup&gt;f&lt;/sup&gt;</td>
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<tr>
<td>Cloeon dipterum L.</td>
<td>No direct, immediate effects&lt;sup&gt;i&lt;/sup&gt;</td>
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<td>Vertebrata</td>
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<td>Salmo trutta fario (Linnaeus 1758)</td>
<td>– Habitat reduction&lt;sup&gt;l,m&lt;/sup&gt;</td>
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<td>Cottus gobio Linnaeus, 1758</td>
<td>– Habitat reduction&lt;sup&gt;i&lt;/sup&gt;</td>
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<td>Lampetra planeri (Bloch 1784)</td>
<td>– Habitat reduction&lt;sup&gt;i&lt;/sup&gt;</td>
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<td>Gobio gobio (Goc)</td>
<td>+ Habitat expansion&lt;sup&gt;i&lt;/sup&gt;</td>
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<td>Leuciscus cephalus (Lec)</td>
<td>+ Habitat expansion&lt;sup&gt;i&lt;/sup&gt;</td>
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<sup>a</sup> Mouthon & Daufresne 2006; <sup>b</sup> Adrian et al. 2006; <sup>c</sup> Holzapfel & Vinebrooke 2005; <sup>d</sup> Primicerio et al. 2007; <sup>e</sup> Richter et al. 2008; <sup>f</sup> Daufresne et al. 2003; <sup>g</sup> López–Rodríguez et al. 2009; <sup>h</sup> Fenoglio et al. 2007a; <sup>i</sup> McKee & Atkinson 2000; <sup>j</sup> Buisson et al. 2008; <sup>m</sup> Hari et al. 2006.
Evident changes are also expected in lentic environments, because most mountain lakes, for example, are characterized by long periods of cold water and low primary and secondary production. The thermal increase will result in stronger thermal stratification, enhanced nutrient resuspension, and increased lake production (Rouse et al. 1997); consequently, the productivity of the system will move from benthic to pelagic compartments and the taxonomic composition could be strongly altered (Primicerio et al. 2007). Finally, water temperature increases may have unexpected consequences, because different taxa show different responses to warming. Winder and Schindler (2004) noticed that the long-term decline in Daphnia populations in a large temperate lake was coupled with the disruption of trophic linkages: because of temperature rise, phytoplankton bloom advanced by almost a month in the study period, creating a temporal mismatch with the presence of zooplankton consumers.

**Hydrologic cycle change**

One of the most significant consequences resulting from climate change may be the alteration of regional hydrologic cycles and subsequent changes in stream flow regimes (Trenberth 1999; Huntington 2006). It is well known that climate is the most important element influencing the quantity and timing of river flow which are essential elements for the biota of river systems (Poff et al. 1997). In recent years, precipitation and hydrologic regimes have been changing on a large scale (Mauget 2003); because of global warming, snowmelt and ice cover are expected to reduce considerably, while atmospheric water vapour and precipitation are expected to increase globally. Much of this precipitation increase may be localized in some regions, such as high latitudes of the Northern Hemisphere, African tropics, Southern and Eastern Asia (Nijssen et al. 2001), while other areas, such as the Mediterranean basin, may become drier (Palmer & Räisänen 2002). In addition, there is much evidence that future regimes will be characterized by the enhancement of frequency and intensity of ‘extreme’ events (Folland et al. 2001). In particular, climatic scenarios predict more frequent and extended droughts, especially in mid latitudes (Boulton & Lake 2008), and so a progressive shift from permanent to temporary water bodies may occur. In this context, the Deutscher Verband für Wasserwirtschaft und Kulturbau (DVWK 1998) provided evidence that droughts have increased in frequency, duration and severity over the last few decades throughout Europe, probably in relation to two phenomena: the alteration of seasonal meteorological conditions and the increase of artificial influences in catchments (Hisdal et al. 2001). Furthermore, Zanchettin et al. (2008), analysing a 200-year time series of discharges of the Po River, observed an increase in both peak flow and low discharge events, with an evident sharpening of extremes in recent decades (particularly prolonged drought periods). This hydrologic change is expected to strongly affect the freshwater biota. The impact of droughts on aquatic biota can be direct, due to decreased water level, disruption of the hydrological connectivity, and habitat reduction (Stanley et al. 1994), or indirect, due to increase of competition and predation, and change in the nature of food resources (Miller & Golladay 1996). Considering flow conditions, we can differentiate between temporary streams, in which flow occurs either seasonally (intermittent streams) or in response to irregular rain (episodic streams), and permanent streams with perennial flow (Hose et al. 2005). Temporary streams, characterized by a natural dry period (Williams 1996), can be found in coastal and Southern regions of Italy with Mediterranean-type climates, while Apenninic and Northern Italian lotic environments are considered perennial (Gasith & Resh 1999). The freshwater biota of intermittent environments show adaptations and strategies to survive dry periods (e.g. desiccation-resistant stages or colonization of hyporheic environment; Boulton & Lake 1992), but less is known about the biological impact of droughts in perennial rivers. In a recent experiment, Fenoglio et al. (2007a) analysed the impact of the duration of drought periods on macroinvertebrate assemblages in the upper Po River, a lotic system in which droughts are a recent and human-induced phenomenon. Macroinvertebrate samplings were performed in four reaches of the Po River, characterized by different periods of absence of surface water, and sub-substratum traps were also placed to assess hyporheic colonization during dry periods. The abundance of macroinvertebrates and taxonomic richness were found to be inversely related to the length of the dry period, and functional organization of the benthic community was also affected by the lack of flow permanence. Moreover, areas with a discontinuous presence of water were mainly colonized by small, fast-growing, plurivoltine organisms. The sub-substratum traps showed a low taxa richness, demonstrating that only few taxa could survive drought periods by colonizing interstitial and hyporheic habitats (Fenoglio et al. 2006). This study demonstrated that in naturally perennial prealpine rivers, the recent increase in droughts will likely cause a general depletion of biological diversity. Finally, we must consider that this
predicted hydrological transformation is not likely to affect all organisms in the same way. In a recent study on the life history of *Serratella ignita* (Poda, 1761) (Ephemeroptera: Ephemerellidae) in two Mediterranean streams, one permanent and one seasonal, López-Rodríguez et al. (2009) discovered a great plasticity in the life cycle, secondary production and feeding behaviour of this mayfly. Thanks to this ecological flexibility, *S. ignita* shows a high fitness in both perennial and intermittent habitats; therefore, this study supports the hypothesis that such species will cope with the presumable future global climate change scenario maintaining, or even increasing, their populations at the expense of more stenoecic species.

Considering the other hydrological extreme, floods are usually predictable events, occurring in the same season year after year, for example following snowmelt in Alpine regions. There is evidence that these phenomena are also likely to increase in frequency and strength, because of the increasing number of precipitation events belonging to the highest intensity class (Brunetti et al. 2004). Severe floods can represent ‘pulse disturbances’ (sensu Lake 2000), affecting aquatic organisms by a combination of increased water velocity, habitat alteration, and physical scouring (Suren & Jowett 2006). Generally, river communities react to floods with a reduction in density and taxonomic richness (e.g. in Piemonte after the catastrophic 1994 and 2000 floods; Fenoglio et al. 2003) and evident shifts in community composition, mainly because floods can affect differently taxa characterized by different morphological and ecological characteristics. For example, Hendricks et al. (1995) reported that an important flood event can halve the density of three *Hydropsyche* species (Trichoptera: Hydropsychidae), with no apparent effects on the abundance of *Ephorhynchus leucon* Williamson, 1802 (Ephemeroptera: Polymitarcidae).

**Allochthonous species invasion**

There is ample evidence that climatic warming influences the distribution of organisms (Southward et al. 1995; Sagarin et al. 1999; Stachowicz et al. 2002), and many studies assume the existence of a direct relationship between climate change and biological invasions (Dukes & Mooney 1999; Thomas & Lennon 1999). Global warming enables some species to expand their distribution, moving poleward and upward; in particular, climate change leads to the survival and dispersal of tropical and sub-tropical species, mainly those able to modify their seasonal cycles (Turchetto & Vanin 2004). Furthermore, global climate change disrupts community structure and increases native species loss and extinction. Recent studies evidenced that many invasive species share traits that allow them to capitalize on the various elements of global change; for example, invasive species are more likely to be generalists than specialists, and thus might be more able to adapt to new climates (Dukes & Mooney 1999). Biological invasions are among the main causes of biodiversity loss, and currently represent the second cause of animal extinctions (Millennium Ecosystem Assessment 2005). In fact, long-distance human-mediated dispersal of organisms has, in recent times, allowed an impressive change in local faunas throughout the world (Corriero et al. 2007).

There are many examples of successful invasions in inland waters, mostly because in freshwater environments many human activities, such as sport and commercial fishing, aquaculture practices, pet trade, and fur farming, have lead to allochthonous species import. Furthermore, eradication of aliens can be very difficult. Recently, Gherardi et al. (2007) published a list of alien animal species that are nowadays present in Italian inland waters. A total of 112 non-indigenous species (64 invertebrates and 48 vertebrates) was found, contributing about 2% of the freshwater fauna in Italy. Among vertebrates, the fish fauna of the Italian peninsula is characterized by the presence of 29 alien species, which mostly arrived through direct import, such as the Pumpkinseed *Lepomis gibbosus* (Linnaeus, 1758) first introduced in the Varano Lake in 1900, and the Wels Catfish (*Silurus glanis* Linnaeus, 1758) which appeared in 1957 and that in recent years experienced a noticeable increase in distribution (Zerunian 2002). Among invertebrates, alien species can be found in many taxonomic groups, such as Crustacea Copepoda (Ferrari & Rossetti 2006), Gastropoda Prosobranchia (Modena & Turin 1991) and Hirudinea (Genoni & Fazzone 2008). Two impressive examples of successful aquatic invaders in Italian freshwaters are represented by the Zebra mussel and the Red swamp crayfish. Native of Caspian Sea region, the Zebra mussel *Dreissena polymorpha* (Pallas, 1771) has progressively invaded many freshwater ecosystems in Europe and North America, because of the high fecundity, high mobility and dispersal rates of its veliger and postveliger, the adults’ adherence on boats and other objects, and high adaptability to colonize almost any solid substratum (Lancioni & Gaino 2006; Casagrandi et al. 2007). The crayfish *Procambarus clarkii* Girard, 1859 native of the southeastern US, nowadays dominates many waterbodies of southern Europe, including Italy (Delmastro 1999; Fea et al. 2006; Gherardi 2006).
Italian Alpine and Mediterranean areas

There is no doubt that Italy’s climate is changing rapidly (Figure 3). Recent studies confirmed a temperature increase of about 1°C per century in the last 150 years, with an increase generally higher for minimum temperatures than for maximum ones (Brunetti et al. 2006; Bartolini et al. 2008). Furthermore, analysing 45 daily precipitation series covering quite uniformly the Italian territory for the period 1880–2002, Brunetti et al. (2004) evidenced that the number of wet days per year has a clear and highly significant negative trend all over the peninsula, but, besides this reduction, there is a tendency toward an increase in the intensity of precipitation. Unfortunately, evaluations of possible impacts of recent climate change on Italian inland water fauna must rely on scarce and indirect evidences. Nevertheless, we can hypothesize that in the future climate change could affect Italian inland fauna, especially in some areas such as the Alps, Southern regions, Sardinia and Sicily.

Alpine aquatic environments are considered especially sensitive to climate change, as warming events reduce snowpack and ice cover. In this context, Alpine lakes and ponds could suffer because of decreased albedo and increased heat absorption (Strecker et al. 2004), with, as a consequence, the enhancement of water temperature. Primicerio et al. (2007) predicted that climate change may represent a major driver of future biodiversity loss in Alpine lentic habitats, because these environments are mostly inhabited by cold stenothermal organisms. The foreseen global warming may enhance extinction rates of native species, because of cold water habitat reduction, dissolved oxygen depletion, changes in the ecological functioning, and introduction of allochthonous invaders (Holzapfel & Vinebrooke 2005). Considering that many Alpine organisms are relictual endemisms, and that most of them are zooplanktonic, lacking aerial life stages and with scarce or no possibilities to migrate, we can predict a severe biodiversity loss in lentic Alpine fauna in the future. Also, the fauna of Alpine lotic systems may be strongly altered by the direct and indirect effects of global warming: headwaters, and especially glacial streams, are highly sensitive to climate changes that may lead to important thermal and hydrological modifications (McGregor et al. 1995). Alpine stream faunal communities are mostly composed of coldwater stenotherm organisms, such as Plecoptera, Ephemeroptera, Trichoptera and some specialized Diptera (Maiolini & Lencioni 2001): some organisms, such as Dyctiogenus fontium (Riss, 1896) (Plecoptera: Perlodidae), which are orophilous species endemic to the Alps with a discontinuous and fragmented distribution (Fenoglio et al. 2007b), may promptly reduce their distribution or even disappear.

Another subject of great interest is represented by Mediterranean climate regions (particularly Sardinia, Sicily and Southern Italy). It is well known that inland waters in these environments are physically, chemically, and biologically shaped by predictable and seasonal events of flooding and drying over an annual cycle (Gasith & Resh 1999). Simulations predict that the frequency of summers as hot as that of 2003 will progressively increase to become the norm in the second half of the twenty-first century (Schär et al. 2004). In this context, the predicted increase of warm and dry periods, and the related water withdrawal for agricultural uses, may lead to the general alteration of hydrologic regimes, and to the disappearance of many temporary freshwater systems and their fauna.

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