Vulnerability of stream biota to climate change in mediterranean climate regions: a synthesis of ecological responses and conservation challenges

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Abstract Freshwater species worldwide are experiencing dramatic declines partly attributable to ongoing climate change. It is expected that the future effects of climate change could be particularly severe in mediterranean climate (med-) regions, which host many endemic species already under great stress from the high level of human development. In this article, we review the climate and climate-induced changes in streams of med-regions and the responses of stream biota, focusing on both observed and anticipated ecological responses. We also discuss current knowledge gaps and conservation challenges. Expected climate alterations have already been observed in the last decades, and include: increased annual average air temperatures; decreased annual average precipitation; hydrologic alterations; and an increase in frequency, intensity and duration of extreme events, such as floods, droughts and fires. Recent observations, which are concordant with forecasts built, show stream biota of med-regions when facing climate changes tend to be displaced towards higher elevations and upper latitudes, communities tend to change their composition and homogenize, while some life-history traits seem to provide biota with resilience and resistance to adapt to the new conditions (as being short-lived, small, and resistant to low streamflow and desiccation). Nevertheless, such responses may be insufficient to cope with current and future environmental changes. Accurate forecasts of biotic changes and possible adaptations are difficult to obtain in med-regions mainly because of the difficulty of distinguishing disturbances due to natural variability from the effects of climate change, particularly regarding hydrology. Long-term studies are needed to disentangle such variability and improve knowledge regarding the ecological responses and the detection of early warning signals to climate change. Investments should focus on taxa beyond fish and macroinvertebrates, and in covering the less studied regions of Chile and South Africa. Scientists, policy makers and water managers must be involved in the climate change dialogue because the freshwater conservation concerns are huge.
Keywords Communities · Ecological responses · Freshwater species · Biodiversity · Mediterranean · Climate · Distribution-range · Life-history · Extinction · Streams

Introduction

The apparent ongoing climate change has been attributed to human-induced alterations, and is now amply considered a major threat to global freshwater biodiversity (Sala et al., 2000; Jenkins, 2003; Thuiller, 2007; Woodward et al., 2010; Maclean & Wilson, 2011). The high rates of freshwater biodiversity decline observed in the past decades, far greater than those measured in terrestrial ecosystems, have been mostly attributed to habitat destruction and non-native species invasions, and are likely to be intensified by the ongoing effects of climate change (Vörösmarty et al., 2010).

Global circulation models project an increase in annual average air temperatures of 1–5°C before the end of this century (IPCC, 2007a; EEA, 2008). Trends of water temperature in streams and rivers will likely be affected, and warming is expected to occur globally, as a result of changes in climate-dependent factors, such as solar radiation and heat fluxes (Caissie, 2006; Nelson & Palmer, 2007; Webb et al., 2008). Alterations in global precipitation patterns, both seasonal and inter-annual, are also expected, as well as increases in the intensity, duration and/or frequency of extreme climate events, which could lead to massive floods, prolonged droughts and intense fires (Arnell, 2004; Milly et al., 2005; Alcamo et al., 2007; EEA, 2008). The global average runoff is expected to increase because of global increase in precipitation (Goudie, 2006). Such alterations will be particularly complex in streams with significant groundwater inputs, high levels of modification, and highly variable climates (Kinouchi et al., 2007; Olden & Naiman, 2010). Overall, climate changes are expected to have a negative impact on water resources, as the benefits of increased annual streamflow in some regions will be overwhelmed by the overall negative effects of shifts in both precipitation and streamflow regimes (IPCC, 2007b).

Both gradual changes and extreme events in climatic patterns described above are likely to greatly affect organisms across the various stages of their life-cycles (e.g. Adrian et al., 2006; Crozier et al., 2008a, b; Blondel et al., 2010). As most aquatic organisms are ectotherms, there are specific ranges of temperatures that they can tolerate for an extended time period, which determines their local and regional distribution (e.g. Burgmer et al., 2007; Haidekker & Hering, 2007; Ohlberger et al., 2011). In addition, most stream biota are spatially restricted to wet habitats in some life stage, and thus have limited abilities to cope with severe environmental changes, such as prolonged droughts (Bèche et al., 2009). Therefore, many stream biota may experience drastic reductions and/or changes in species-distribution ranges, communities and life-histories, and ultimately undergo extinction, and some responses to such climate changes are already apparent (e.g. McCarty, 2001; Walther et al., 2002; Daufresne et al., 2003; Daufresne & Boët, 2007; Heino et al., 2009). Both forecasts of species-distribution ranges using ecological niche modelling and experimental studies are starting to inform climate change science about the key environmental factors and biotic process involved, which will provide necessary knowledge for mitigation and conservation (Pearson & Dawson, 2003). This is of critical importance because, for example, worldwide predictions suggest that up to 75% of freshwater fish biodiversity could disappear by 2070 (Xenopoulos et al., 2005).

The mediterranean climate (hereafter referred to as med-) regions of the world are located in Southwestern Australia, central Chile, coastal California, Western Cape of South Africa, and around the Mediterranean Basin, and these are among the most vulnerable ecosystems to the effects of climate change (IPCC, 2007a). Having warm to hot, dry summers and mild to cool, wet winters driven by large subtropical high pressure ocean cells shifting towards the poles in summer and towards the equator in winter, watercourses located at these regions are characterised by predictable seasonal disturbance events (Gasith & Resh, 1999). However, climate change and consequent changes in hydrology are projected to lead to unpredictable harsh events, exacerbate water stress and desertification, and turn landscapes more desert-like (IPCC, 2007a). Such changes are expected to affect freshwater biota, despite organisms being adapted to withstand the typical natural disturbances (i.e. resistance ability) and to recover rapidly from those disturbances (i.e. resilience ability) (Grubb &
Hopkins, 1986; Lavorel et al., 1999; Bonada et al., 2007a). Simultaneously, temperate regions will become more med-like, with consequences for the inhabiting organisms (Lavorel et al., 1998). Nevertheless there is much current interest in investigating the impacts of climate change on biodiversity (see reviews of Parmesan, 2006 and Bellard et al., 2012), information on past and recent climate change impacts on biota inhabiting med-streams remains scattered, as well as are predictions of the ability of organisms to cope with climate change. This lack of information limits our knowledge to better address conservation and management practices for biodiversity in current freshwater med-ecosystems.

This review explores the observed and expected climate change effects in med-regions on inhabiting biota. We summarize the studies of observed or projected impacts of climate change on such organisms, including examining resilience and resistance of biota to disturbances when facing climate change. Specifically, the aims are to: (1) describe the major environmental trends associated with climate change, (2) summarize observed and projected ecological responses of stream biota (3) examine the particularities of these organisms and the major conservation and management challenges, and (4) point the major key knowledge gaps.

**Climate change in streams of med-regions**

Med-regions are at the epicentre of some of the strongest anticipated global climate change effects (Giorgi, 2006; Baettig et al., 2007; Diffenbaugh et al., 2008). Over the past 50 years, changes in the hydrological cycle and biota in these regions have been attributed to climate change (e.g. Moreno & Oechel, 1995). The Mediterranean Basin is hotter and drier, and is experiencing more extreme climatic events than it did a century ago (EEA, 2008). For example, in the Iberian Peninsula, air temperatures have unequivocally increased (De Castro et al., 2005; Trenberth & Josey, 2007), and aridity is more pronounced as a result of annual precipitation decreases and changes in seasonal precipitation regimes (Costa & Soares, 2009).

Climate change will induce environmental changes that will affect watercourses, including changes in hydrology, wildfire frequency and intensity, and land use. Dramatic shifts in the hydrological patterns of fluvial ecosystems are expected, which will likely be characterized by a continued decrease in the total volume of annual runoff (rather than the increase that is expected in other climate regions) (Boix-Fayos et al., 1998). In addition, because med-region vegetation has relatively high evapotranspiration rates, decreases in streamflow will likely be more related to temperature increases than precipitation decreases (Vicuña et al., 2010). Consequently, streamflow reduction is expected to be higher than if only precipitation is considered (Tague et al., 2009). In the Murray-Darling basin of Australia, for example, a rise of 1°C air temperature results in about a 15% reduction in the climatological annual inflow (Cai & Cowan, 2008). Regarding seasonality, expectations are for higher winter streamflows and lower summer streamflows in all med-regions (Arnell, 2004; Maurer & Duffy, 2005; CSIRO, 2007; Souvignet et al., 2008; Adam et al., 2009; Vicuña et al., 2010). Hydrological connectivity will likely be dramatically disrupted in summer, increasing the occurrence of stream intermittency (Lake, 2003; Merelender & Matella, 2012) and changing water quality of streams and their biota (Lindh, 1992; Avila et al., 1996; Bonada et al., 2007a). Even greater seasonal changes are anticipated for med-regions in snow-dominated basins, including parts of California, Chile and, to a lesser extent, Mediterranean Basin (Arnell, 1999; Adam et al., 2009; Vicuña et al., 2010). Total annual snowfall will likely be reduced and the snowmelt season will likely start earlier each year, which would result in higher winter streamflow than normal (Yarnell et al., 2010).

Along with seasonal changes, climate change is also likely to shift the inter-annual variability in streamflow in med-regions, i.e. the occurrence of years with extreme floods and prolonged droughts could increase, and the magnitude of the effects will also depend on land-use practices. For example, filling of wetlands and channelization of streams can intensify the effects of extreme floods (Giorgi & Lionello, 2008, Opperman et al., 2009). This inter-annual variability is likely to be more important in med-regions that are strongly subjected to ENSO, such as central Chile, where a dramatically higher rainfall period (El Niño) and prolonged dry period (La Niña) are forecasted in some scenarios (Mata et al., 2001).

Wildfire frequency and land uses are also expected to be affected by climate change and to affect streams (IPCC, 2007a). However, those changes are very
difficult to forecast because they are also driven, to a relatively high extent, by social and economic circumstances, such as the availability of fire-fighting services (e.g. Pausas, 2004). Forecasts point to a pronounced increase in frequency and intensity of wildfires because the drought period may be elongated (Moriondo et al., 2006; Anav & Mariotti, 2011). Projected effects of land-use changes on ecosystems are not encouraging, as strong impacts on the biota and on the ecosystem services provisions are expected (Lambin et al., 2003).

Lastly, the described climate or climate-induced changes are expected to shift med-regions towards more desert-like landscapes (Lavorel et al., 1998). Some expansion of med-climate areas is also forecasted, although with regional differences. For example, expansions are expected in the Mediterranean Basin and the Chilean med-regions, whereas contractions are expected in the South African and Australian med-regions (Klausmeyer & Shaw, 2009).

Responses of freshwater biota to climate change in med-regions

Climate and climate-induced changes can alter severely the suitability of med-stream local habitats because of higher temperatures, lack of oxygen, streamflow reduction and/or disruptions in connectivity, and stream biota certainly will be impacted by such changes (e.g. Magoullick & Kobza, 2003; Magalhães et al., 2007; Crozier et al., 2008b; Filipe et al., 2010). Of the studies conducted on climate change and biota reported by the ISI Web of Knowledge from 1899 to 2011, those focusing on freshwaters are scarce (7.7% of all studies) and only 0.4% of all studies focus on med-streams. The number of studies published annually on climate change and biota have been increasing tremendously since 1990 (Fig. 1A), and a similar trend was observed for publications regarding climate change effects on streams (Fig. 1B), and among those the ones focused on med-regions (Fig. 1C). Such increasing interest in stream biodiversity of med-regions allowed us to summarize the observed or predicted stream biota responses to climate and climate-induced changes, namely in shifts in their distribution and communities, adaption through plasticity in phenology, or extinction (Visser, 2008; Table 1; Fig. 2).

Distribution range shifts

Some species may shift their distributional ranges to keep up with climate change based on their dispersal abilities and physiological tolerances to the new and favourable hosting habitats (Hoffman & Parsons,
| Ecological responses | Med-region                          | Time period  | Taxa                                    | Observations or predictions                                                                                                                                  | Correlated drivers                                      | Source                  |
|----------------------|-------------------------------------|--------------|-----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|-------------------------|
| Distribution         | MedBasin (South-western Spain)      | 1980         | *Trithemis annulata* (Odonata)           | Species expanded distribution range to South of Spain from Africa; also previously detected in Italia, Sicilia and Sardinia                                      | Climate (hotter and dryer summers)                       | Romero et al. (1981)   |
|                      | MedBasin (Southern Europe)          | 1980s–1990s  | *Trithemis annulata* (Odonata)           | Species expanded distribution range to Spain, Italy, and Greece from Africa. Also evidences of similar expansion for *Mesogomphus genel*, *Hemiax ephippiger*, and *Diplacodes lefebvrei* | Climate (hotter and dryer summers)                       | Betoret (2000)          |
|                      | MedBasin (South-western Spain)      | 2010–2011    | *Trithemis kirbyi* (Odonata)             | Species expanded distribution range to South of Spain from Africa                                                                                           | Climate (hotter and dryer summers)                       | Rodríguez et al. (2011) |
|                      | MedBasin (Northeastern Spain)       | 1991–2010s   | *Salmo trutta* (fish)                    | Species in future decades will disappear in lowland habitats, and occupy upstream reaches at higher altitudes                                           | Warming and change in precipitation regime               | Filipe et al. (unpublished data) |
|                      | MedBasin (South-eastern France)     | 2051–2080s   | Fishes                                  | Species-distributional ranges in future decades will diminish for cold-water species (located in headwaters), while cool- and warm-water species will expand to suitable habitats upstream | Warming and change in precipitation regime               | Buisson et al. (2008, 2010) |
|                      | MedBasin (Europe, North Africa and the Middle East) | 2070–2080s   | Fishes (diadromous)                     | Species-distribution ranges across large river basins in future decades will contract (14 species will lose suitable basins), have little or no changes (five species), or expand (three species colonizing northward) | Climate                                                  | Lassalle & Rochard (2009) |
|                      | MedBasin (Northeastern Spain)       | 1978–2008    | Macroinvertebrates, fishes, mammals      | Disappearance of white-clawed crayfish (*Austropotamobius pallipes*), Mediterranean barbell (*Barbus meridionalis*), chub (*Squalius cephalus*), European eel (*Anguilla anguilla*), and water vole (*Arvicola sapidus*) | Warming, decrease run-off-rainfall ratio (15% lower than 30 years ago) | Otero et al. (2011)    |
| Community            | California (Northern)               | 1984–2002    | Invertebrates, fishes                    | Organisms impacted negatively and had no resilience during drought. Assemblage composition of invertebrates did not recover while richness and abundance recovered quickly. Native fish abundance was lowest during drought and invasive fish species established and was resilient to subsequent large flow events | 5-y prolonged drought                                    | Bêche et al. (2009)    |
| Ecological responses | Med-region          | Time period | Taxa               | Observations or predictions                                                                 | Correlated drivers                                  | Source                                      |
|----------------------|---------------------|-------------|--------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------|---------------------------------------------|
| California (Northern)| 1984–2003           | Macroinvertebrates | Indexes of biotic integrity (IBI) changed across time; several IBI metrics were related to the El Nino Southern Oscillation Index | Climate variability                                 | Mazor et al. (2009)                            |
| MedBasin (South-eastern France) | 2051–2080s          | Fishes      | Richness in future decades will increase and composition will change considerably            | Warming and change in precipitation regime          | Buisson et al. (2008, 2010)                     |
| MedBasin (South-eastern France) | 2051–2080s          | Fishes      | Communities in future decades will be more homogenous downstream and more diverse upstream. Species and traits diversity will increase upstream and composition will change | Warming and change in precipitation regime          | Buisson & Grenouillet (2009)                    |
| MedBasin (Southern Portugal) | 1993–2008            | Macroinvertebrates | Richness and evenness of assemblages changed at disturbed sites. Changes in composition during extreme events (low precipitation and/or temperature), with shift in equity occurred before elimination | Climate change: 1°C temperature increase and 1.5 mm/d precipitation decrease, and extreme events | Feio et al. (2010)                             |
| MedBasin (Southern Portugal) | 1991–1998            | Fishes      | Species affected differently by droughts and floods: some declined or increased after dry years while others declined after rainy springs. Species recovered quickly but might depend of intensity and duration of droughts and floods | Droughts and floods                                 | Magalhães et al. (2007)                        |
| MedBasin (Southern Portugal) | Summer 2005          | Fishes      | Assemblages shaped by drought refuges characteristics: richness was lower at smaller pools while abundance was higher, and cooler pools (shaded) had highest richness | Reduced water flow, drought                          | Pires et al. (2010)                            |
| MedBasin (North-eastern Spain) | 1992–1998            | Salmo trutta (fish) | Survival of the youngest depended of the low flows during summer droughts | Flow regime variability, droughts                  | Nicola et al. (2009)                            |
| Life-history          | California (Northern) | 1984–2003   | Benthic macroinvertebrates | The longer-lived, larger organisms were less abundant in years with extreme climate conditions; however, common indices and metrics used in biological monitoring were not influenced by climate extremes | Climate (temperature and precipitation extremes) | Lawrence et al. (2010)                       |
| MedBasin (North-eastern Spain) | 1987, 2005            | Ephoron virgo (mayfly) | Changes on secondary production, sex ratio and larvae early development and adult emergence | Water and air temperature warming                  | Cid et al. (2008)                              |
| Ecological responses | Med-region | Time period       | Taxa                        | Observations or predictions                                                                 | Correlated drivers                  | Source                        |
|----------------------|------------|-------------------|-----------------------------|---------------------------------------------------------------------------------------------|-------------------------------------|-------------------------------|
|                      | MedBasin (Southern Europe) | Not applicable (autoecological data) | Plecoptera                  | The species with wide tolerance ranges (namely thermic) and high drought resistance are less vulnerable to climate change | Climate                             | Tierno de Figueroa et al. (2010) |
|                      | MedBasin (Southern Spain)   | 2006–2007         | Serratella ignita (mayfly)  | Nymphal growth was shorter and scraper behaviour was more common in populations of more temporary streams | Reduced flow (intermittency), drought | López Rodriguez et al. (2009)   |
|                      | MedBasin (North-eastern Spain) | Spring 2007      | Macroinvertebrates, fishes  | Feeding habits of fish changed: lower abundance and biomasses in gut contents and negative food electivity. Also lower body condition and gonadal weight due to reduced resource availability in more intermittent streams | Reduced flow (intermittency), drought | Mas-Martí et al. (2010)         |
|                      | Med-regions and semi-arid climate regions | Not applicable (autoecological data) | Macroinvertebrates          | Organisms with desiccation-resistant eggs and/or dispersal by flight and stream drift are less dependent of drought refuges (e.g. blackflies) and thus resistant and resilient to prolonged droughts | Reduced flow (intermittency), drought | Robson et al. (2011)            |
|                      | Australia (South-eastern)   | March–April 2004  | Benthic algae               | Organisms were able to recolonize and regrow if drought refuges were available. Recolonization was made by stream drift, dry biofilm, or both | Reduced flow (water extraction and climate) | Robson et al. (2008)            |

Studies were listed according to a literature search at Web of Science. MedBasin refers to Mediterranean Basin region.
Observations as well as predictions point to distributional shifts for biota as a response to climate change (Parmesan, 2006). Such predictions, available for some common species, have been obtained primarily from ecological niche modelling (SDMs; Pearson & Dawson, 2003), using temperature and precipitation future scenarios (McCarty, 2001).

For example, a few African Odonata species have been recently recorded in the southern Europe, which has been attributed to climate change (Romero, 1981; Betoret, 2000, Rodríguez, 2011). Forecasts indicate cold-water fish species with physiological optima \( <20^\circ C \) (e.g. *Salmo trutta*) will probably face habitat losses leading to strong reductions in their range (Filipe et al., unpublished data). In contrast, cool-water species with physiological optima 20–28°C and warm-water species with physiological optima >28°C (e.g. genera *Barbus* and *Leuciscus*) are predicted to colonize newly suitable areas in higher-elevation reaches or extend their range poleward (Buisson & Grenouillet, 2009; Buisson et al., 2010; Lassalle & Rochard, 2009). A similar pattern is expected for Plecoptera species based on known autoecological data, and only a few species with wider thermal tolerance ranges and drought resistance ability are expected to expand their distribution ranges and population sizes (Tierno de Figueroa et al., 2010).

Scientists face a great opportunity to further improve forecasts regarding distributional shifts of biota. Most studies are probably overpredicting biota occurrence in the future because dispersal abilities and hindrance to pathways of dispersion, such as anthropogenic barriers (e.g. dams, culverts and weirs) and orographic barriers (e.g. river basin limits) are not usually considered (Magalhães et al., 2002; Filipe et al., 2009). Forecasts can be improved by also considering the abilities and barriers for displacement of non-native organisms, which are a great concern in freshwaters (Rahel & Olden, 2008), and ecological niche modelling addressed in a few med-regions (e.g. Gritti et al., 2006 for plants; Vila-Gispert et al., 2005 for fish). In addition, the detailed knowledge of the relationship between species and environmental variability obtained from observations collected in either nature or in the laboratory can provide more realistic results (e.g. Yates et al., 2010). For example, water temperature can have different effects on the overwinter survival of aquatic organisms of distinct age-classes, and such differences can be incorporated in biota predictions (e.g. McCarthy et al., 1999). Finally, the inclusion of multiple environmental drivers of change into forecasts can enhance the reliability of...
their predictions, namely hydrological and land-use factors (Sala et al., 2000).

Community changes

Species range shifts can lead to changes in species richness, turnover and community reassembly (i.e. changes in taxonomic composition of assemblages). Assessments of community changes attributed to climate change have been often based on long-term observations, whereas forecasts are, to date, less common (Parmesan & Yohe, 2003).

Regarding med-streams, Feio et al. (2010) observed in a 15-year study of macroinvertebrate assemblages that climate variability and associated hydrological variation can lead to great changes in taxonomic composition. Also, in California, Bêche & Resh (2007a, b) showed that temporal variability of taxonomic composition tends to be greater than trait-composition variability. Prolonged droughts may have greater effects on biota than short droughts, including the provision of favourable conditions for invasion or biotic exchange (Table 1). In particular, Bêche et al. (2009) observed lack of resilience and resistance during a 5-year, prolonged drought in California med-streams. Authors observed changes in the composition of macroinvertebrate assemblages, and an invasive fish species (*Lepomis cyanellus*) became established. Moreover native fish abundance tends to be lowest during drought years and highest during wet years (Magalhães et al., 2007), which can be further accentuated by human water demands (Slaughter & Wiener, 2007).

Forecasts built for freshwater fish assemblages suggest future communities will depend on position along the upstream–downstream gradient. For example, midstream assemblages located mostly at medium elevations are likely to undergo major shifts, including increases in species richness and species reassembly resulting from both the arrival of non-native species and local extinctions (Buisson et al., 2008, 2010). However, predictive studies focused on assemblages are still very few for biota inhabiting med-streams.

Life-history traits

Changes of life-history traits in organisms, including phenological changes (i.e. shifts of seasonal activity driven by environmental factors) have been observed as ecological effects of recent climate change, with similar trends for terrestrial, marine and freshwater groups (Parmesan, 2006). Regarding streams and rivers in med-regions, recent long-term data attributed the changes in life-history traits of benthic algae, macroinvertebrates and fish to climate and climate-induced changes, as reduced streamflow and droughts (Table 1). Only a few studies exist, however, and they are restricted to three of the five med-regions (i.e. California, Mediterranean Basin and Australia).

The advance of spring reproduction events, which is one of the most documented effects of climate change on terrestrial fauna, has been observed for some aquatic macroinvertebrate taxa. For example, incremental changes in temperature were identified as the main cause of changes observed in the life-cycle of a mayfly (*Ephoron virgo*) in the Iberian Peninsula, including shifts in secondary production, sex ratio, larval development and adult emergence (Cid et al., 2008). Large and long-lived organisms with high food electivity tend to decrease in abundance as a result of hydrology changes related to dryness, while organisms with desiccation-resistant eggs and strong dispersal abilities (as by flight or stream drift) tend to be more abundant because they resist and recover better from extreme droughts and are less dependent on drought refuges, such as deep pools (e.g., Magalhães et al., 2007; Table 1). In fact, macroinvertebrates of med-streams tend to have shorter generation times (less than a year to complete their life-cycle), which facilitates survival and the overcoming of local extinctions (Bonada et al., 2007a), and small, short-lived organisms may benefit from higher temperatures because of their fast metabolism (Daufresne et al., 2009, Lawrence et al., 2010).

Other evidence come from studies on how species react to thermal and hydrological variability (Power et al., 2008). Temperature variability can affect blooms of phytoplankton and zooplankton (e.g. Winder & Schindler, 2004), the growth, timing of development and emergence of macroinvertebrates (e.g. Bayoh & Lindsay, 2003), and migration of fish in freshwaters (e.g. Matthews, 1998). Also, high mobility and small body size facilitates organisms’ rapid response and recovery from large variations in streamflow (Bonada et al., 2007b; Pires et al., 2010; Chester & Robson, 2011).

Opportunities exist for future research at the intersection of environmental variability associated with climate change.
with climate change and life-history characteristics, including whether: (1) a threshold in trait responses can result from genetic-variance constraints; (2) contrasting effects of environmental changes, such as extreme hydrological events, enhance biota matches or mismatches with the environment; and (3) there are consequences on population dynamics (Stenseth & Mysterud, 2002; Stenseth et al., 2002). For example, for brown trout (*Salmo trutta*), which is a cold-water fish, local adaptations to a range of temperatures have been observed, and some populations may have the potential to adapt to changing temperature regimes because of their genetic variance and phenotypic plasticity (Jensen et al., 2008).

**Extinctions**

To our knowledge, no record of extinction of species in med-stream inhabitants has been attributed entirely to climate change. However, several species that were widespread in the past are now very rare and are thus more vulnerable to extinction (e.g. the caddisflies *Chimarra marginata*: Bonada et al., 2007a; *Iberochondrostoma lusitanicum*: Rogado et al., 2005; or *Annitella* sp. C. Zamora-Muñoz, pers. com.). Most likely, we are not aware of the existing species risk in med-regions, mainly because not all risks are known, and the taxonomy of most freshwater groups is far from complete (Bonada et al., 2008a; Davies & Stewart, 2012; De Moor & Day, 2012; Tierno de Figueroa et al., 2012).

The expected rapid loss of suitable habitats makes it probable that next extinctions will occur for geographically restricted species common in the highly endemic med-regions. High, mountain streams are and will be especially vulnerable to biotic extinctions (Zamora-Muñoz et al., 2008; Tierno de Figueroa et al., 2010; Filipe et al., unpublished data). Headwaters tend to have a high β-diversity accounting for a large degree of regional biodiversity at both population, genetic and community levels, which reinforces the importance of these habitats (Finn et al., 2011). In fact, the first record of a species extinction attributed to climate change was a highly restricted freshwater species, the golden toad (*Bufo periglenes*) inhabiting the tropical forest mountains in Costa Rica (Pounds & Crump, 1994; Pounds et al., 1999, 2005).

**Conservation concerns related to climate change in med-regions**

**Unique and highly threatened biota**

Some observations suggest that biota inhabiting med-streams might be more vulnerable to taxonomic extinction triggered by climate change and climate-induced changes than biota inhabiting streams in more stable climate regions.

First, med-regions typically have a high level of endemism and freshwater taxonomic diversity relative to other climate regions (Gasith & Resh, 1999; Bonada et al., 2007a). For example, the Mediterranean Basin hosts many endemic species and is considered one of the most important hotspots of freshwater biodiversity (Bianco, 1995; Filipe et al., 2009; Hermoso et al., 2009; Hermoso et al., 2011; Tierno de Figueroa et al., 2012). The med-region of California is also considered a biodiversity hotspot and the amount of recent urbanization in this region is a serious conservation concern (Davis et al., 2007). Med-regions in South Africa, South America and Australia are also recognized as global centres of endemism and taxonomic diversity, and are home to many rare and endangered fish and amphibian species (Van Rensburg et al., 1999; Fitzpatrick et al., 2008; Heads, 2009). In the Chilean med-region, 81% of the known fish species are endemic and 40% are endangered (Habit et al., 2006). In addition, the regional taxa richness of macroinvertebrates tends to be higher in med-streams than in streams of temperate climate regions while local taxa richness may not differ significantly between both climate regions (Bonada et al., 2007a), and med-streams tend to have lower local abundances than streams in temperate regions (e.g. Magalhães et al., 2002; Statzner et al., 2007a; Bonada et al., 2007a). Altogether these biodiversity patterns of med-streams may lead to a high biodiversity loss driven environmental changes. Second, in spite of being highly resistant and resilient to natural harsh environments, these biota will likely be vulnerable to the projected hydrological extreme events that will severely alter habitats (though less vulnerable to temperature increases because the resident biota are mostly eurithermic). Throughout evolutionary history organismal resistance and resilience abilities to relatively predictable extreme events that occurred in the past in a very heterogeneous environment allowed the
persistence of med-stream biota. But organism’s responses to the already ongoing climate change will depend on the intensity, frequency and duration of future extreme events, which are expected to be considerably distinct from current events, and such responses will likely vary from the individual to the community level (Rundel, 1998). Third, the empty species niches that will be opened through extinction and displacement of species most likely will be occupied by non-native species (Smith & Darwall, 2006; Statzner et al., 2007b; Rahel & Olden, 2008). The establishment of non-native species is already considered a primary driver of change in biota of med-regions (e.g., Clavero & García-Berthou, 2006), together with climate change having (Parmesan, 2006; see also Ficke et al., 2007). Finally, med-streams are already under a great deal of human stress with many species threatened, and climate change effects in these landscapes could be exacerbated in the future as water demands increase (IPCC, 2007b). Such demands could impact ecosystems and biodiversity in such a magnitude that surpasses the intrinsic resistance and resilience capabilities of such threatened and endemic biota.

Conservation investments

In med-streams, the taxonomic and functional biodiversity of aquatic biota is declining rapidly despite legal tools in place for their protection, leading to an increase of species endangerment (Table 2). As climate change might favour species that are more tolerant to higher water temperatures and pollution, or to water withdrawals (Gasith, 1991; Davies et al., 1993; Sabater et al., 1995; Gasith & Resh, 1999; Lawrence et al., 2011), biological invasions of non-native species are expected to occur more frequently, and biotic communities will tend to be more homogenised and with fewer endemic species (Clavero & García-Berthou, 2006). Such alterations in communities will lead to poorer stream ‘ecological status’, as defined in current management programs worldwide, such as the Water Framework Directive or the Clean Water Act (Moyle, 1995; Munné & Prat, 2011; see Table 2 for details).

The described ongoing environmental problems in med-streams are expected to be exacerbated by the human responses to climate change, including increased surface-water withdrawals, inter-basin diversions, and groundwater abstractions for agricultural, industrial and municipal uses (Gleick & Palaniappan, 2010). As a consequence, fisheries in particular will probably continue to suffer diminishing returns, which compromise the capacities of developed countries to maintain strong economies and of developing countries to meet food demands (Worm et al., 2009). Proactive management strategies that reduce environmental stressors beyond climate change, including pollution, overharvesting, water withdrawals, water diversions, habitat destruction, and introductions of non-native species, are necessary to sustain freshwater ecosystems in the future (Ficke et al., 2007).

It is apparent that legal policies in the med-regions are not providing or ensuring adequate conservation of freshwater biodiversity (Johnson et al., 2001). In California, for example, legal frameworks completely ignore climate change impacts, and none adequately addresses freshwaters (Viers & Rheinheimer, 2011). However, one of the methods already being implemented that addresses, at least partially, freshwater conservation aims is the establishment of regional environmental streamflow standards. Such methods allocate water of appropriate quality to ecosystems with a magnitude, frequency, duration, timing and rate of change that is as similar as possible to the natural flow regime, while simultaneously meeting the water needs for the various human uses of water (Acreman & Dunbar, 2004; Arthington et al., 2006; Poff et al., 2010). Nevertheless, the implementation of freshwater-protected areas is still far from assuring the maintenance of freshwater biodiversity (Saunders et al., 2002; Filipe et al., 2004; Hermoso et al., 2009). Societal changes focused on good practices of water-use could also benefit protection and management of freshwater biodiversity in med-regions (Wolff et al., 1989; Gasith & Resh, 1999; Fleckenstein et al., 2004).

Many developed countries already included in their budgets a specific allocation for climate change mitigation. For example, the 2011 budget of the United States of America included US $171.3 million (€128.3 million) for the Climate Change Adaptation Initiative, an increase of almost five times higher than the 2010 budget (Department of the Interior, 2011). For the European Union, estimations of climate change total costs was around €60 billion (US $81 billion) per year, reaching three times more for the high-cost scenarios (Behrens et al., 2008). Particularly in Europe, efforts are underway and funds are
| Med-region | Primary legal tools for protection (date of first implementation) | Taxa | Description of decline | Correlated drivers | Source |
|------------|---------------------------------------------------------------|------|------------------------|-------------------|--------|
| California | Clean Water Act (1972), Endangered Species Act (1972), National Environmental Policy Act (1969), Wild and Scenic Rivers Act (1968) | Fish | 63% of native taxa extinct or in danger of extinction | Hydrologic alteration, land-use, drought | Moyle (1995) |
|           |                                                               | Amphibians and reptiles | Of 20 native aquatic taxa examined, 13 were endangered | Hydrologic alteration and landuse | Jennings & Hayes (1994) |
|           |                                                               | Amphibians | The endemic mountain yellow-legged frog is absent from 50% of its historic range | Introduction of non-native fish | Knapp & Matthews (2000) |
| MedBasin  | Water Framework Directive (2000)                              | Fish | 78% of native species in a south-eastern Pyrenees watershed showed decline | Pollution, habitat modification | Aparicio et al. (2000) |
|           |                                                               | Fish | Of 11 native taxa examined, 4 were endangered and 3 were nearly extinct | Introduction of non-native species | Bianco (1995) |
|           |                                                               | Fish | 64% of native species in the Guadiana basin are threatened | Habitat degradation and invasive species | Hermoso et al. (2011) |
|           |                                                               | Fish | 56% of endemic freshwater fish species threatened and 18% endangered | Pollution, water extraction, restricted range, limited dispersal, drought, invasive species, dam construction | Smith & Darwall (2006) |
| Australia | Australian Water Act (2007), Convention on Biological Diversity (1993), Ramsar Convention on Wetlands (1971) | Fish | 3 of 10 species in south-west Australia are listed as rare or critically endangered | River regulation, loss of riparian vegetation, salinization and sedimentation, eutrophication, and introduction of exotic animals and plants | Lymbery et al. (2010) |
| Chile     | Convention on Biological Diversity (1993)                     | Fish | 40% of 105 streams sampled had no natives | Introduction of exotic species | Soto et al. (2006) |
|           |                                                               | Fish | 81% of species are endemic, 40% are endangered | Introduction of exotic species | Habitat et al. (2006) |
| South Africa | IUCN Red List (1963)                                        | Fish | 47% of endemic species are threatened | Anthropogenic impacts | Skelton et al. (1995) |
|           |                                                               | Fish | 15 of 36 native species examined are endemic, 1/3 of which are threatened | Farming and other forms of land use, exotics, mining, industrial development, human settlement, and construction of dams | Gaigher et al. (1980) |

MedBasin refers to Mediterranean Basin region
allocated to address the effects of climate change in streams, including med-streams (see WISER project <http://www.wiser.eu> and EURO-LIMPACS <http://www.refresh.ucl.ac.uk/eurolimpacs>), and a particular concern has been how to evaluate and forecast future water quality under the aims of the EU Water Framework Directive. However, calculating costs and benefits of climate change policies involves immense complexity and uncertainty, and probably not enough efforts are being made to address such unique and threatened biodiversity inhabiting med-streams (Behrens et al., 2008).

Research needs related to climate change in med-regions

Long-term data collection

Most of the studies described herein were conducted in med-streams of California, Mediterranean Basin and Australia, in restricted local areas, focusing on fish and/or macroinvertebrates, and using data collections from relatively short time-series (Maximum 30-y; Otero et al., 2011, though most were much shorter). Therefore, to our knowledge, there are few species records available that can be used to explicitly determine the effects of climate change (Table 1). To address this data shortage, the collection of long-term ecological data should be made both a national and an international funding priority among med-regions and across various taxa so that ecological responses can be measured in such high-risk regions (Resh et al., 2012). Studies using long-term data to assess spatial and temporal variability of stream communities, and the resilience and resistance of the members of these communities to natural and anthropogenic disturbances, will allow biotic responses to climate change to be examined at different scales. Forecasts from habitat-niche models (SDMs) can also be improved using long-term data.

Ecological response to disturbance

Organisms might not be able to adapt and respond by their resilience and resistance abilities to the new disturbance regimes resulting from climate change that surpass the intensity, frequency, or duration thresholds of natural disturbances (Lytle, 2007; Lytle et al., 2008). The ability of biota to cope with these disturbances is very poorly understood, which weakens the predictive accuracy regarding ecological responses. In addition, the difficulty of disentangling ecological responses resulting from either anthropogenic or natural disturbances characterized by predictable inter- and intra-annual climatic and hydrologic oscillations also weakens advances in knowledge (Gasith & Resh, 1999; Lake, 2000; Humphries & Baldwin, 2003). For example, studies focused on the effects of droughts on biota in med-streams often fail to classify the drying period as a seasonal highly predictive event or climate change induced event because long-term data is rarely available (but see references in Table 1).

Scenarios of future extreme events are just in the early stage of development (Tebaldi et al., 2006) and will be critical to assessing the potential impacts of climate change in med-streams, as well as including other anthropogenic disturbances (e.g. evaluating effects of climate change in disturbed sites).

Genetic diversity

Genetic diversity, which is frequently not considered in studies of climate change effects, is of major relevance when examining the potential ecological impacts of climate change. Often cryptic, the intra-specific patterns of genetic diversity recorded for med-streams (e.g. Lopes-Cunha et al., 2012) should be considered when quantifying climate change effects because forecasts based on taxonomy only might be omitting an important component of biodiversity taking the risk of being lost as a result of range contractions ( Bálint et al., 2011), and because genetic diversity can potentiate the ability of species to adapt to new environments (Visser, 2008). In particular, phylogenetic constraints and conservation of ancient life-history traits might potentiate, limit or impede ecological responses.

Some recent work conducted outside of the med-regions (i.e. in England) examined microevolution using field experiments to simulate conditions of altered climate (Van Doorslaer et al., 2010). These authors examined the genetic adaptations to increasing temperature in life-history traits of the water flea (Daphnia), and found changes in size at maturity. If sufficient genetic variation was present, such adaptations occurred within a single growing season. However, to our knowledge, such microevolutionary
responses have not been examined for biota inhabiting med-streams. Microevolution rates can clearly be determinant for ecological responses to environmental changes, together with species interactions across tropic levels (Van der Putten et al., 2010; Jenouvrier & Visser, 2011).

Conclusions

Climate change effects in med-regions have already been reported (e.g. Pausas, 2004; EEA, 2008), while clear documented responses of organisms to climate change in med-streams are still scarce, notwithstanding these regions are considered an important biodiversity hotspot worldwide (Myers et al., 2000; Malcolm et al., 2006; IUCN, 2008). Here, we conclude that responses of organisms inhabiting med-streams to climate change are/or will be mostly driven by changes in hydrology, including changes in the intensity, duration and frequency of disturbance events (Table 1). Land-use future changes probably will not be such a strong driver as for terrestrial organisms, and will be probably surpassed by climate and biotic changes (Sala et al., 2000).

Responses observed or predicted for freshwater organisms to climate and climate-induced changes span an array of organizational hierarchy, from species to communities, similar to terrestrial and marine organisms (Parmesan, 2006). Where favourable and accessible habitats exist, cool- and warm-water species in med-streams will likely colonize new habitats at higher altitudes or latitudes and become established, whereas cold-water species will probably undergo local extinctions and reductions in their range as a result of habitat loss (Table 1). However, geographic displacements to more favourable habitats may be compromised if suitable habitats are nonexistent nearby (e.g. in South Africa, Chile and Australia) or are inaccessible because oceanic barriers, distinct environments (e.g. deserts), configuration of the stream network, or anthropogenic barriers common across med-regions (e.g. dams and reservoirs; Lehner et al., 2011). In addition, some taxa inhabiting med-streams may be able to cope with local environmental changes because of their life-history traits, such as short generation times, and small body size, or to colonize new habitats because of their high dispersal ability (Bonada et al., 2007a; Daufresne et al., 2009; Lawrence et al., 2010). In fact, life-history traits may allow med-stream biota to adapt to the natural patterns of hydrological extreme events typical of these regions and, under certain thresholds of disturbance, may even confer resistance and resilience that would allow them to survive under climate change. Finally, rapid genetic adaptations of traits may occur under selection pressures (Van Doorslaer et al., 2010), but the role of such adaptations for biota inhabiting med-streams is not well known.

Despite the array of likely responses of stream biota to climate changes in med-regions, arguments support that such biota are more prone to extinction triggered by the climate change than biota inhabiting streams at more stable climate regions. Although med-stream biota have traits acquired through evolution in a predictable climate regarding droughts and floods frequency, the high endemism, species rarity, and low local abundance, together with the already and growing biotic homogenisation and other strong drivers of change, make this biodiversity at high risk under climate change. Ecological effects of climate change rest on the question of whether species and communities inhabiting med-streams will be able to adapt fast enough to keep up with their changing environment or whether the rapidity and severity of climate change will exceed their ability to respond (Parmesan, 2006).

We are only at an early stage in projecting accurately future trends of biota, and the current strong bias on taxonomic group examined and geographic regions covered delays advances of such predictions. Very few studies focus on Chile and South Africa med-regions or in other taxa beyond fish and macroinvertebrates, leaving a large component of freshwater biodiversity of med-streams unrepresented. Also, when compared with streams in more stable climate regions, inter- and intra-annual natural variability in med-streams is a relatively large confounding factor regarding climate change impacts (Gasith & Resh, 1999). It is thus imperative to collect and manage long-term data for distinct med-regions and across taxonomic groups to provide confidence in the accuracy and extrapolation of climate change predictions. Also, although faunal convergence was reported for med-regions (e.g. Bonada et al., 2008b; Blondel et al., 2010), there are distinct evolutionary histories that cannot be disregarded when inferring likely ecological responses to climate change among analogous med-regions (Bonada et al., 2008b).
New challenges are evident concerning management and conservation of med-regions because organisms will respond to the interaction of all future changes that come on top of the unique environmental and socioeconomic problems already present, such as desertification, water scarcity, pollution and food-production limitations (Balanza et al., 2007; Iglesias et al., 2007; Hill et al., 2008; Underwood et al., 2009). The urgency of planning and acting is intensified by the anticipated rates of warming greater than the global average (Cayan et al., 2006; Christensen et al., 2007; IPCC, 2007a; Giorgi & Lionello, 2008; Giannakopoulos et al., 2009). Integration of ecological predictions in an economic context will support conservation and management options and prioritizing investments, as it is vital to determine where to invest and what actions to take (e.g. Wintle et al., 2011).

In conclusion, a better knowledge of how freshwater biota will respond to climate change requires increased investments in data gathering, monitoring, and model-building forecasts. At this point, few data exist for most taxa present in med-streams, and many of them are already considered endangered. Such advances in biodiversity knowledge and projections of future trends, together with changes in management and societal attitudes will be the best way to deal with the growing challenges of freshwater conservation in med-regions. Conservation and management challenges will require huge efforts by multiple stakeholders to advance scientific knowledge and implement new practices.

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