Internat. Rev. Hydrobiol.	**97**	2012	3	200–214

DOI: 10.1002/iroh.201111489

Fengqing Li, Qinghua Cai[1*], Wanxiang Jiang, Xiaodong Qu

State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, Hubei Province 430072, People's Republic of China
e-mail: qhcai@ihb.ac.cn

Research Paper

The response of benthic macroinvertebrate communities to climate change: evidence from subtropical mountain streams in Central China

key words: climate change, north subtropical monsoon, ENSO, water temperature, water flow, benthic macroinvertebrate, biodiversity

Abstract

Ecological effects of climate change on terrestrial and marine ecosystems are increasingly apparent but evidence from freshwater is scarce, particularly in Asia. Using data from two subtropical Central China streams, we predicted the changes of some benthic macroinvertebrate communities under various climatic scenarios. Our results show that the average annual air temperature, in the study watershed, increased significantly ($P < 0.05$) by 0.6 °C over the last 30 years (1978–2007), whereas the average annual water flow declined by 30.9 m^3 s^{-1}. Based on the winter sampling of benthic macroinvertebrates at four stream locations over last six years, we observed that macroinvertebrate abundance and Margalef diversity dropped with increasing water temperatures or decreasing smoothed sea surface temperatures (SSST). The winter macroinvertebrate abundance and biodiversity declined by 11.1% and 6.8% for every 1 °C water temperature rise. In contrast, increases in future SSST by one unit would increase winter macroinvertebrate abundance and biodiversity by 38.2% and 16.0%, respectively. Although many dominant taxa were predicted to persist when water temperatures increase by 1 °C, several scarce taxa, *e.g.*, *Orthocladius clarkei* and *Hippeutis umbilicalis*, could be at a level of potential local extinction. Our identification of these links, between climate change and stream macroinvertebrate communities, has wide implications for the conservation of mountain stream ecosystems in the upper Yangtze River under scenarios of climate change.

1. Introduction

Climate change poses a considerable threat to biodiversity all over the world, especially at high latitudes and altitudes (Brown *et al.*, 2007). Early research on climate change focused on alterations in temperature, rainfall, and the extent of glaciers or snowpacks (Barnett *et al.*, 2005; Brown *et al.*, 2007; Durance and Ormerod, 2007). Since the 1990s, the relationship between climate change and biodiversity conservation has attracted increasing attention because of the potential influence of climatic fluctuations on global ecosystems and regional

* Corresponding author

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 1434-2944/12/306-0200

biodiversity (DAUFRESNE *et al.*, 2004; HARTE *et al.*, 2004; THOMAS *et al.*, 2004). Streams play an important role in the hydrological cycle and the biogeochemistry of nutrients, linking terrestrial to aquatic ecosystems, and provide many resources for human use (VANNOTE *et al.*, 1980; NAIMAN and BILBY, 2001). However, we cannot develop an effective conservation strategy if we do not have the knowledge about the impacts of climate warming on stream organisms. Therefore, we need to assess the influence of climate warming on stream ecosystems.

The two main aspects of climatic impacts on streams are water temperature and water flow (DURANCE and ORMEROD, 2007). The importance of water temperature has long been recognized as a major factor determining the distribution and richness of stream organisms along gradients of latitude and altitude (VANNOTE *et al.*, 1980; QUINN and HICKEY, 1990; REYJOL *et al.*, 2001). Water temperature has large effects on the embryonic development, larval growth, emergence, metabolism and survivorship of stream taxa (MARCHANT and HEHIR, 1999; HAIDEKKER and HERING, 2008). Temperature can also influence production, consumption, and decomposition in stream ecosystems with consequences for ecological energy (RICHARDSON, 1992). Furthermore, global warming can have large effects on regional rainfall patterns by disturbing the current atmospheric circulation patterns, altering the global and regional hydrothermal conditions, and ultimately increasing the frequency and intensity of droughts and floods (STEWART *et al.*, 2004; MOTE *et al.*, 2005). Changes of water flow can influence water quality, stream channel morphology and stability, and indirectly the composition and dynamics of freshwater communities (LAKE, 2000; MILNER *et al.*, 2001; LYTLE and POFF, 2004). In our study we also consider the El Niño Southern Oscillation (ENSO) as a kind of climatic variable because, although ENSO occurs only in the equatorial Pacific region, it could affect over more than 75% of the earth (JONES, 1988; JIANG *et al.*, 2006). Many researchers have indicated that ENSO anomalies, in the equatorial eastern Pacific region, also have tremendous impacts on climatic patterns in China (DONG and LIU, 2000; JIANG *et al.*, 2006). These include the effects on runoff in the upper reaches of the Yellow River (LAN *et al.*, 2002). Generally low river flows are usually associated with El Niño events and floods usually accompany La Niña events in the Yellow River. By affecting such important abiotic variables, such as temperature, precipitation, and water quality, the ENSO phenomena can influence the growth, phenology and persistence of stream organisms on the Asian Continent (VASS *et al.*, 2009).

Ecological effects of climate change on terrestrial and marine ecosystems have been studied extensively (ROOT *et al.*, 2003; ROLIM *et al.*, 2005; SELLANES *et al.*, 2007; HEINRICH *et al.*, 2009). Several studies report on aspects of meteorological and hydrological fluctuations in freshwater ecosystems (ZHANG *et al.*, 2005; JIANG *et al.*, 2006; KEIL *et al.*, 2008), but few have explicitly linked them to biological changes. However, in Europe, America, and Oceania, several studies have ascribed long-term shifts in freshwater communities to directional climatic changes (DAUFRESNE *et al.*, 2004; Harper and PECKARSKY, 2006; Durance and ORMEROD, 2007; Haidekker and HERING, 2008; CHESSMAN, 2009). However, very little information is available on the effects of climate changes on freshwater macroinvertebrate communities in Asia (DUDGEON, 2007; VASS *et al.*, 2009). Thus, a case was quantitatively studied in the Xiangxi River watershed, within the East Asian monsoon region, to reveal the influence of climate change on macroinvertebrate communities in this region.

We believe that uninterrupted ecosystem monitoring of the Xiangxi River system is a good strategy for assessing climatic effects. There exist many published studies in this area that have focused on environmental variables and macroinvertebrates (QU *et al.*, 2005; JIANG *et al.*, 2008; LI *et al.*, 2009a, b). Our present study examines relationships between macroinvertebrate communities and climatic variables in the upper Xiangxi River, Central China, during winter. Our aims were: (i) to test the hypotheses that air temperatures increased, and water flows decreased, in response to global climate change; (ii) to test the hypotheses that there have been significant reductions in macroinvertebrate abundance and diversity related to climatic change and, (iii) to use regression and ordination models to predict future potential effects of shifting climate on metrics and species of stream macroinvertebrates.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

2. Materials and Methods

2.1. Study area and sites setting

The present study was conducted in the Xiangxi River, the largest tributary flowing into the Three Gorges Reservoir (TGR) in Hubei province. This river is a 6th-order stream originating in the mountains of the Shennongjia Forest. The river flows 94 km and descends 1540 m before converging with the Yangtze River. This river drains a catchment covering 3099 km^2 with average annual precipitation of 900–1200 mm. The Gufu, Gaolan, and Jiuchong streams are the three main tributaries in the Xiangxi River watershed (Fig. 1) (LI *et al.*, 2009b; YE *et al.*, 2009). The Jiuchong and the upper Xiangxi watersheds are covered with forests, whereas the Gufu and Gaolan watersheds are mainly dominated by farmlands. Four sites were used in this study, including Sites A and B on the Jiuchong stream and Sites C and D on the upper main stem of the Xiangxi River. All sites had similar altitudes (634–802 m), stream orders (2nd or 3rd), and relatively low anthropogenic disturbance. The adjacent sites were < 10 km apart. pHs (8.29 ± 0.37), conductivities (245.86 ± 34.39 $\mu S\ cm^{-1}$), and concentrations of total dissolved solids (TDS) (149.83 ± 28.01 mg L^{-1}), total nitrogen (TN) (0.85 ± 0.35 mg L^{-1}) and, total phosphorus (TP) (0.03 ± 0.01 mg L^{-1}) in the study area were somewhat lower than at downstream sites.

2.2. Benthic macroinvertebrate sampling

Benthic macroinvertebrate sampling was carried out monthly in winter, from December to February, through six continuous years (2001–2007). However, owing to landslides, no samples were taken in February 2002 and January 2003. We sampled during winter for two main reasons: (1) winter conditions were predicted to be more sensitive to climate change (THOMAS *et al.*, 2004), and (2) macroinvertebrate assemblages were thought to show the maximum stability at this time after recovering from the preceding summer floods (COLLIER and QUINN, 2003).

A 0.42 mm mesh Surber sampler (sampling area = 900 cm^2) was used to take samples for three times at different habitat types (i.e., riffle, run and pool) from a 100 m reach at each sampling site. All stones within the sampler frame were scrubbed with a soft brush to remove attached organisms. Unconsolidated

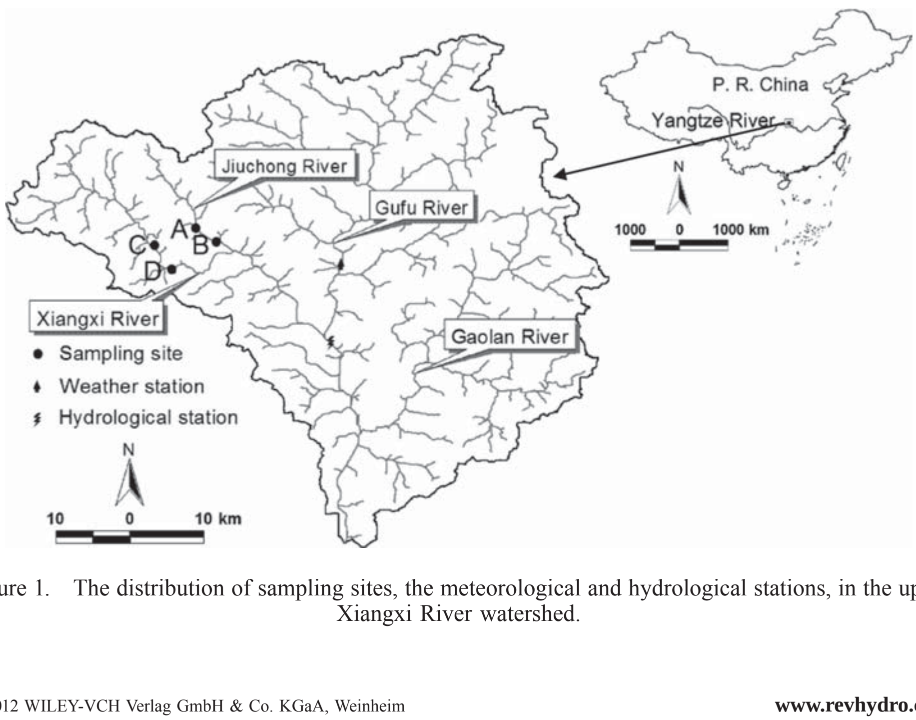

Figure 1. The distribution of sampling sites, the meteorological and hydrological stations, in the upper Xiangxi River watershed.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

substrates were disturbed to a depth of about 10 cm and dislodged organisms were swept into the net by currents. Samples were then preserved in 10% formalin (HUANG *et al.*, 2000), and all collected macroinvertebrates were identified to genus or species levels following KAWAI (1985) and MORSE *et al.* (1994).

2.3. Climatic data collection

Although measured water temperature data are available for each sampling time, we calculated water temperature from a regression model between water and air temperatures at site A. The air temperature data were from an automatic, continuous meteorological station at the town of Gufu (see Fig. 1). The air temperatures were more consecutive and comparable than the measured water temperatures. We used linear regression and calibrated the relationship between water and air temperatures by using data for more than seven years ($R^2 = 0.853$; $n = 349$). These included monthly data from July 2001 to October 2008 ($n = 88$) and daily data of 18th August 2008, 20th September 2008, and 28th October 2008 (the measuring interval is 15 minutes, $n = 261$). Regressive water temperatures were then used to assess the influence of temperature variation on macroinvertebrate assemblages.

Because there is only one hydrological station (Fig. 1), these data cannot be used for the sub-watersheds. Instead, watershed areas of the sampling sites, and the hydrological station site, were calculated using ArcGIS (version 9.2). Therefore, based on the area data, and the multi-year (1959–2007) average daily flow data, from the hydrological station, the water flow of each sub-watershed was calculated with the conversion method according to linear equation between the area and flow data (HÖRMANN *et al.*, 2009). The regressive water flow was then used to assess the influence of flow variation on macroinvertebrate assemblages.

The sea surface temperature (SST), which reflected ENSO events, was obtained from the Climatic Research Unit at the University of East Anglia (UK) (http://www.cru.uea.ac.uk). This index is calculated from the difference of SST for the eastern Pacific region (90–180° W, 0–10° S) (JONES, 1988; JIANG *et al.*, 2006). We parameterized the SST using the preceding 3-month running mean. This resulted in a smoothed sea surface temperature (SSST).

Average annual air temperature, average annual water flow and average annual SSST were then used to clarify the climatic trends from 1978 to 2007.

2.4. Data analysis

One-Way ANOVA did not significantly differ for temperature ($P > 0.5$), pH ($P > 0.5$), conductivity ($P > 0.5$), TDS ($P > 0.5$), TN ($P > 0.5$), abundance ($P > 0.5$), richness ($P > 0.5$), or the Margalef index ($P > 0.5$), between these four sites. Only the TP was an exception in this regard ($P < 0.05$). Thus, environmental variables, including water temperature (Fig. 2), and macroinvertebrate metrics (Fig. 3) of

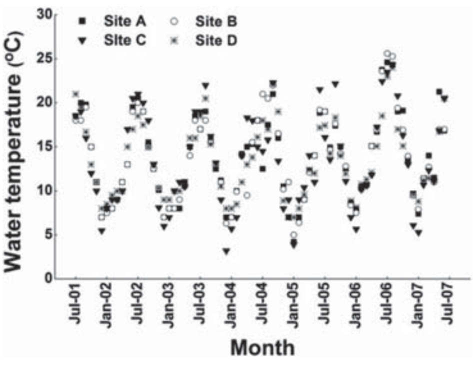

Figure 2. Variations of the water temperature at four sites in the upper Xiangxi River from July 2001 to June 2007.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

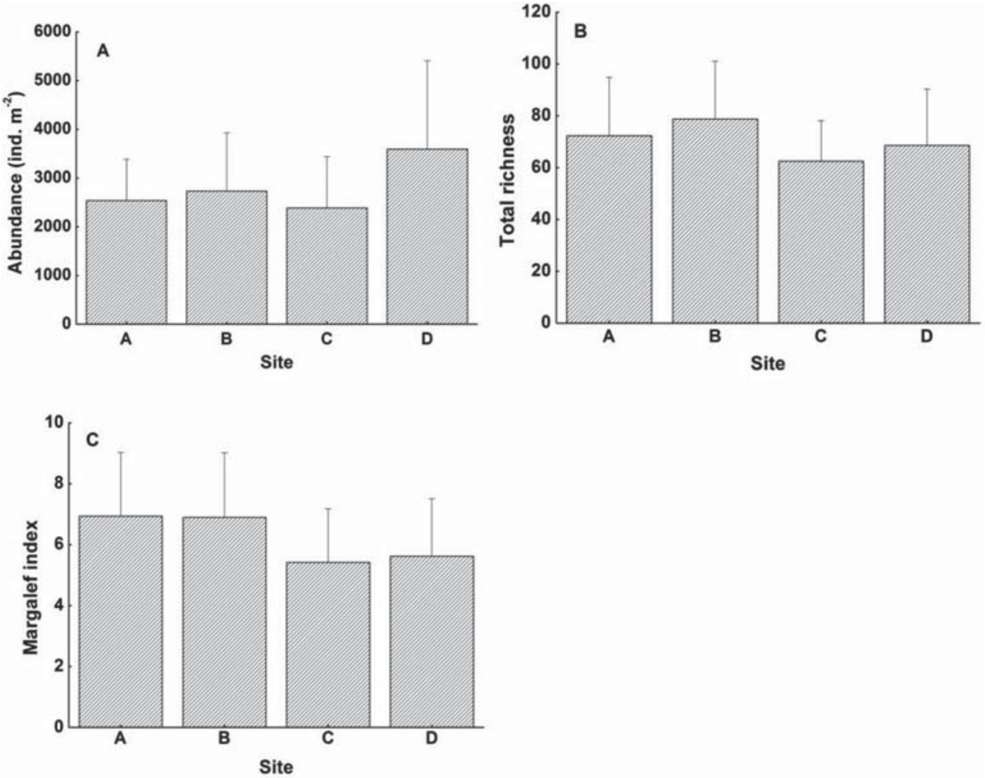

Figure 3. Annual means of the benthic macroinvertebrate metrics at four sites in the upper Xiangxi River from July 2001 to June 2007: (A) abundance, (B) richness and (C) Margalef index.

these four sites were expected to be similar, and we could pool the temperature data at these four sites. Mean values were then calculated for these four sites to reduce the monthly variations. A total of 16 samples (n = 3 winter months × 6 years – 2 months with no samples) were defined for subsequent analysis.

Linear regression was applied to examine the trends of water temperature, water flow, and SSST over the last 30 years. Regression analyses were used to predict the relationships between climatic variables and macroinvertebrate metrics.

Testing hypothesis 2 required data on macroinvertebrate metrics from December 2001 to February 2007. This was normalized for total abundances (numbers of individuals per 1 m^2) and richness (numbers of species per 1 m^2), while diversity was assessed using the Margalef index, which was calculated as:

$$\frac{S-1}{\log_2 N}$$

where S is the number of species in the sample, N is the total abundance in the sample.

We investigated patterns in multivariate benthic macroinvertebrate data using detrended correspondence analysis (DCA), a simple and flexible method of indirect ordination, and then related the scores of DCA to climatic variables. Regression equations relating DCA scores to climatic variables were used to predict the effects of climate change on macroinvertebrate communities. The optimum and tolerance of each species, to certain climatic variables, obtained from the DCA results, were used to indicate the sensitive or potential risk species to climatic variables. We assumed that species, with low optimal tem-

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

peratures, may be more endangered under global warming scenarios, because global warming reduced the available optimal habitats for this species. The above analysis was performed by CANOCO for Windows 4.5 (LEPS and SMILAUER, 2003), with rare species down-weighted and relative abundances of the component taxa transformed before analysis.

Using regression analysis, we predicted the potential effects on macroinvertebrate metrics when the water temperature increased by 1 °C, the water flow decreased by 10%, and the SSST value increased by one unit over the current means in winter (DURANCE and ORMEROD, 2007).

Table 1 Regression relationships ($y = a + bx$) between annual air temperature or water flow and study year in the upper Xiangxi River over the period 1978–2007.

Dependent variable	Independent variables	*a* (SE)	*b* (SE)	*F*	R^2	*df*	*P*
Air temperature	Year	16.57 (0.17)	0.02 (0.01)	4.57	0.14	1,28	0.04
Water flow	Year	77.24 (6.35)	–1.03 (0.35)	8.16	0.23	1,28	0.01
SSST	Year	–6.14 (3.01)	0.11 (0.17)	0.39	0.02	1,28	0.54

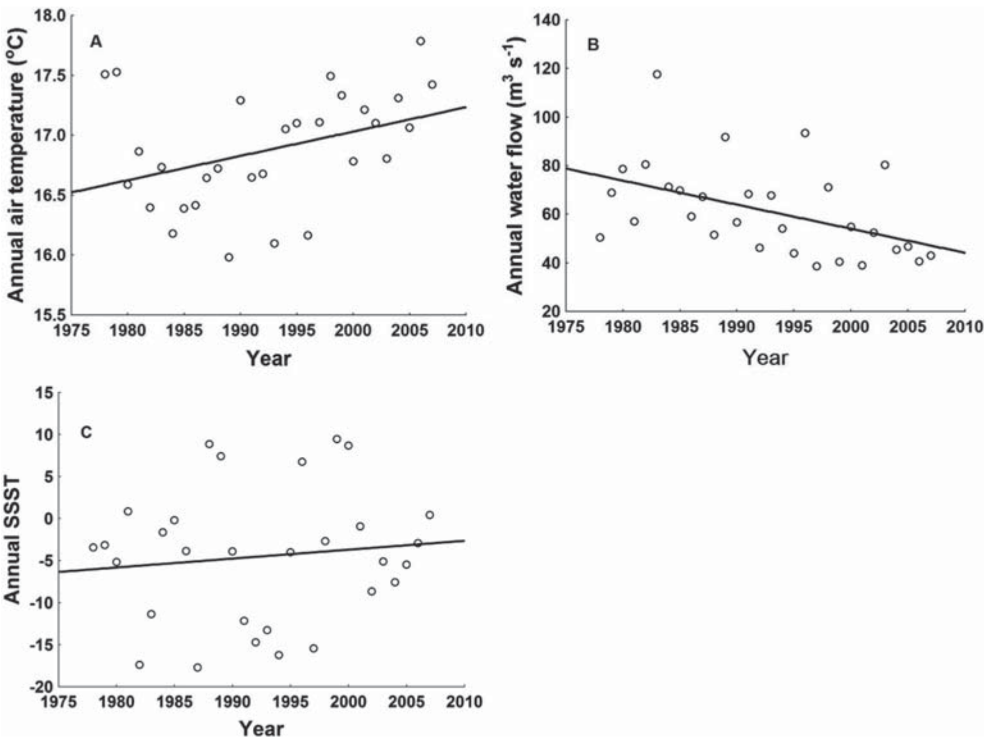

Figure 4. Variations of the annual air temperature (A), annual water flow (B) and annual SSST (C) in the upper Xiangxi River from 1978 to 2007. Fitted (least squares) linear regression lines are shown and regression equations can be found in Table 1.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

3. Results

3.1. Climatic variations in the Xiangxi River watershed

Average annual air temperatures in the study watershed ranged from 16.0 to 17.8 °C from 1978 to 2007, increasing significantly ($P < 0.05$) by 0.2 °C/decade on average (Table 1, Fig. 4A). In contrast, average annual water flows ranged from 38.5 to 117.6 $m^3 s^{-1}$ during this period, decreasing significantly ($P < 0.05$) by 30.9 $m^3 s^{-1}$ on average (Table 1, Fig. 4B). There were no significant long-term temporal trends in the SSST (Table 1, Fig. 4C).

3.2. Relation between benthic macroinvertebrate assemblages and climatic variables

Benthic macroinvertebrate abundance, total richness, EPT richness, and Margalef index all had decreasing trends with increasing water temperature, in winter, over the last six years. The macroinvertebrate metrics increased with increasing SSST (Fig. 5). However, no relationships were found between the macroinvertebrate metrics and the water flow.

The winter macroinvertebrate abundance and the Margalef index fell by 11.1% and 6.8% for each 1 °C rise in water temperature. The relationships between climatic variables and biotic metrics were described in detail in Table 2. A direct relationship was shown between the scores of DCA axis 1 and the water temperature, and 28.3% of the variations in the composition of the community were explained by axis 1. Taxa characteristic of cooler phases included: *Cricotopus* sp., *Potthastia gaedii*, *Orthocladius clarkei*, *Dicranota* sp., *Hippeutis umbilicalis* and *Sinopsephenus* sp., whereas *Polypedilum* sp., Oligochaeta spp., *Rheopelopia* sp., *Bezzia* sp. and *Lithax* sp. were typical of warmer phases (Fig. 6A).

The SSST could explain 32%–54% of the variations in macroinvertebrate metrics across years (Table 2). A projected SSST shift of +1 unit is predicted to increase the abundance of winter macroinvertebrates, and the Margalef diversity index, by up to 38.2% and 16.0% of the current mean values (Table 2, Fig. 5B, H). The total richness will increase by 0.4 taxa as the SSST shifts from –1 to +1 (Table 2, Fig. 5D). Axis 4 of the DCA was positively related to the SSST, and 4.4% of the variations in the community composition, were explained by axis 4. The taxa associated with positive SSST years included: *Aethaloptera* sp., *Lype* sp., *Parapsyche* sp. and *Chaetocladius* sp., whereas *Potthastia gaedii*, *Cricotopus* sp., *Orthocladius luteipes*, *Brachycentrus* sp. and Oligochaeta spp. were characterized by negative SSST phases (Fig. 6B).

3.3. Future effects of climate on benthic macroinvertebrates

Using the regression equations we developed above, we determined the magnitude of change predicted to occur in different macroinvertebrate metrics with climate change. A future increase of 1 °C in water temperature is predicted to increase the scores of DCA axis 1 by 0.6 units (Table 2). This may lead to the potential local extinction of two taxa, *Orthocladius clarkei* and *Hippeutis umbilicalis*, because they tend to occur at narrow ranges of low temperatures (Fig. 6A).

A rise of one SSST unit could reduce the scores of DCA axis 4 by 0.3 units (Table 2). This could lead to the potential local extinction of four other taxa, *Potthastia gaedii*, *Cricotopus* sp., *Orthocladius luteipes* and *Brachycentrus* sp., which occur at narrower ranges of low SSST values. A reduction of one SSST unit could potentially result in the projected loss of other four taxa, *Aethaloptera* sp., *Lype* sp., *Parapsyche* sp. and *Chaetocladius* sp. (Fig. 6B).

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

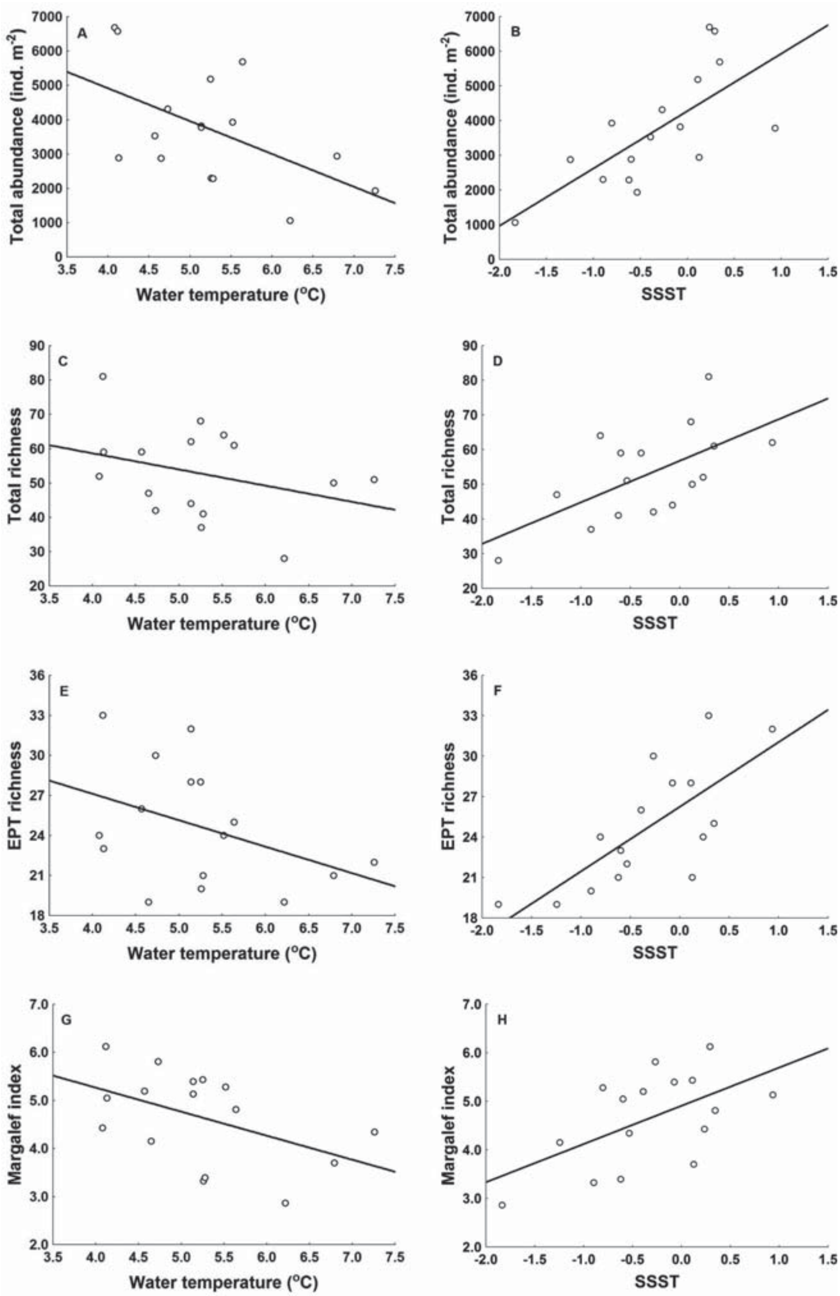

Figure 5. Relationships between benthic macroinvertebrate metrics and water temperature (left) or SSST (right) in the upper Xiangxi River during the winters of 2001 to 2006: (A) water temperature – abundance, (B) SSST – abundance, (C) water temperature – total richness, (D) SSST – total richness, (E) water temperature – EPT richness, (F) SSST – EPT richness, (G) water temperature – Margalef index and (H) SSST – Margalef index. Fitted (least squares) linear regression lines are shown and regression equations can be found in Table 2.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

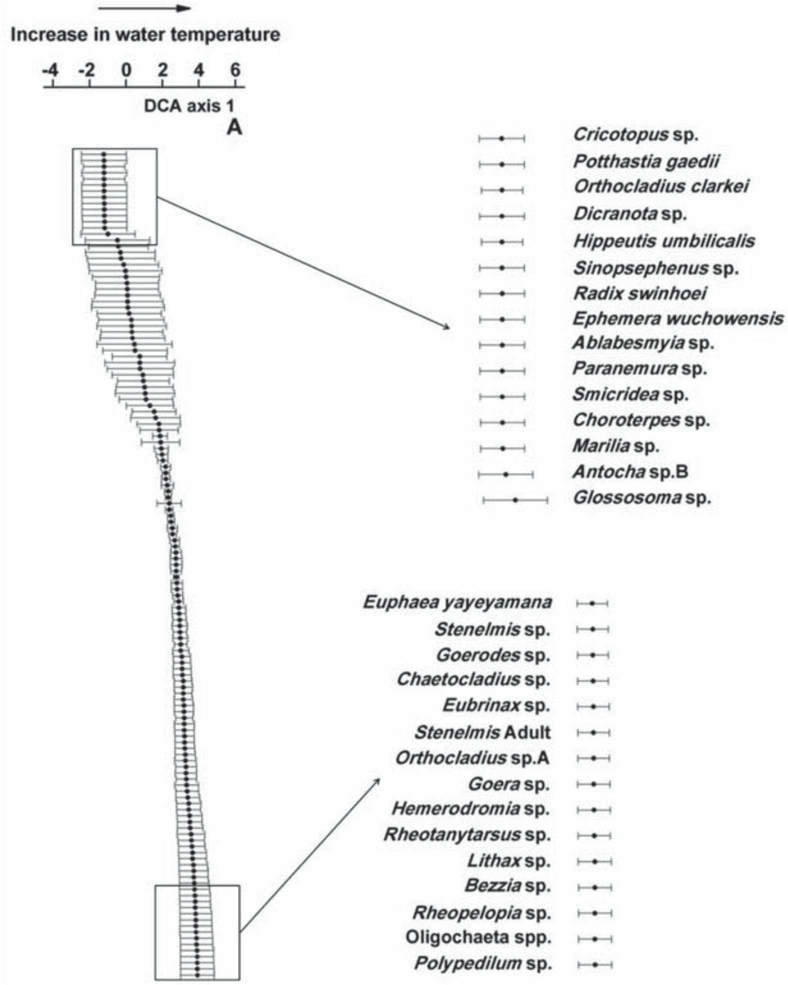

Table 2 Regression relationships ($y = a + bx$) between scores of DCA axis and water temperature or SSST in the upper Xiangxi River during the winters of 2001 to 2006.

Dependent variable	Independent variables	*a* (SE)	*b* (SE)	*F*	R^2	*df*	*P*
Abundance	Water temperature	8736 (2684)	–965 (501)	5.71	0.29	1,14	0.03
Richness	Water temperature	77.27 (19.28)	–4.66 (3.63)	1.75	0.11	1,14	0.22
EPT richness	Water temperature	34.94 (6.30)	–1.96 (1.19)	2.48	0.15	1,14	0.12
Margalef index	Water temperature	7.24 (1.29)	–0.49 (0.24)	4.67	0.25	1,14	0.05
Abundance	SSST	4287 (489)	1639 (818)	13.45	0.49	1,14	0.00
Richness	SSST	58.87 (3.87)	16.42 (7.02)	8.99	0.39	1,14	0.01
EPT richness	SSST	27.20 (1.16)	6.87 (2.11)	16.41	0.54	1,14	0.00
Margalef index	SSST	5.10 (0.27)	1.24 (0.50)	6.59	0.32	1,14	0.02
DCA 1 scores	Water temperature	–0.52 (0.47)	0.55 (0.28)	4.67	0.25	1,14	0.05
DCA 4 scores	SSST	0.43 (0.08)	–0.29 (0.10)	8.42	0.38	1,14	0.01

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

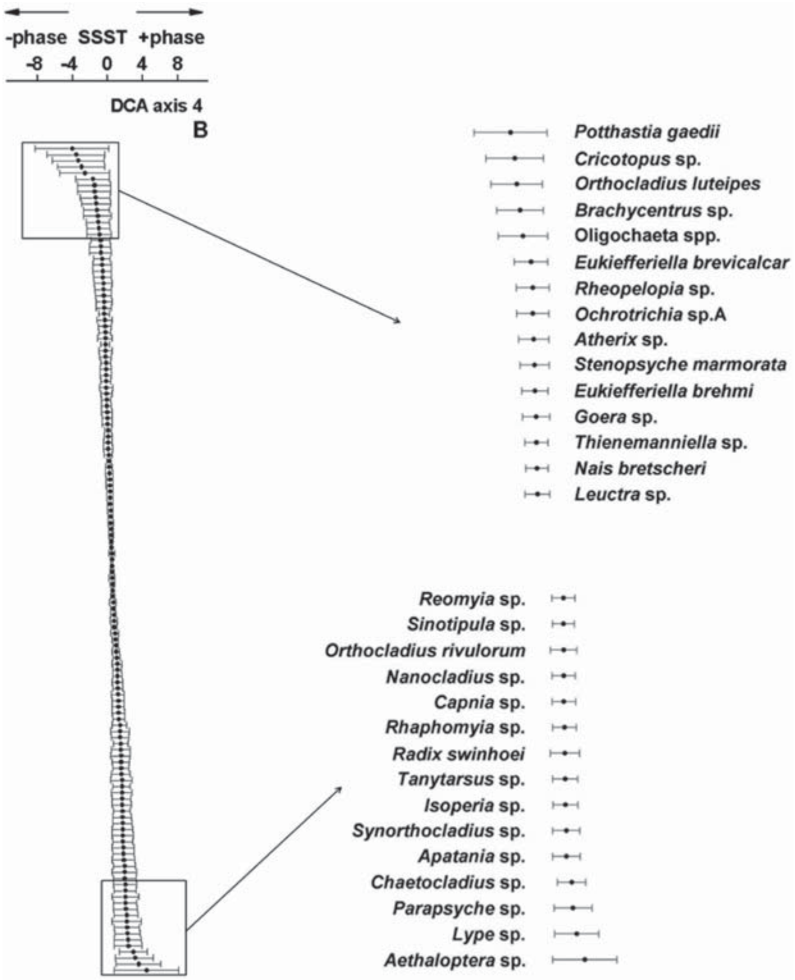

Figure 6. Average scores (+ SD) of DCA 1 or DCA 4 for taxa showing clear relationships with these axes versus changes of (A) water temperature or (B) SSST in the upper Xiangxi River.

4. Discussion

Effects of directional climate change on stream macroinvertebrates, at this subtropical stream, have been studied. Results suggest that there were increases in air temperature and decreases in water flow in the upper Xiangxi River watershed from 1978 to 2007. The winter community abundance and diversity of macroinvertebrates dropped in association with increasing temperature over the last six years. This is in agreement with KLANDERUD and TOTLAND (2005) and DURANCE and ORMEROD (2007). However, except for some rare metrics, the links between metrics of macroinvertebrate assemblages and climatic variables are not so strong. If future effects were found to be consistent with the trends observed, a

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

continued global warming could lead to the disappearance of some taxa from the investigated area. Thus, depending on its strengths, the SSST can influence the compositions of stream organisms that are far away.

4.1. Water temperature and benthic macroinvertebrates

There were long-term increases in air temperature in the Xiangxi River watershed over the last 30 years (confirming our first study objective). This is in agreement with the results found the upper Yangtze basin from 1950 to 2002 (Zhang *et al.*, 2005). The reduction in the community composition in relation to temperature increase is real (confirming our second study objective), because the effects of temperature on stream macroinvertebrate metrics will depend on complex interactions among thermal effects (Elliott *et al.*, 1988; Caissie, 2006). Rising water temperatures may increase the macroinvertebrate predation (Kishi *et al.*, 2005), alter decomposition rates of leaf litter (Lepori *et al.*, 2005), and change algal production. Winter macroinvertebrate abundance might decline by 11.1% for every 1 °C water temperature rise in the study streams, while higher losses (21%) may be expected from stream macroinvertebrates in the British Llyn Brianne River (Durance and Ormerod, 2007). The Margalef biodiversity in winter might be reduced by 6.8% for every 1 °C water temperature rise in the study streams, while an approximate 30% loss, in the diversity of macroinvertebrates, may be associated with the global warming. This has been observed in Canadian Jackfish and Murray lakes from 1930 to 2004 (Sereda *et al.*, 2011). Thus, compared with other studies, the effects of climate change on stream ecosystems are low in this area.

According to the DCA ordinations, several taxa were likely at the risk of extinction in the Xiangxi River watershed. This supports our third study objective. Taxa correlated to high temperature, including some dipterans and oligochaetes, might benefit from global warming, and increase their abundance and range of distribution. The number of individuals might decrease with global warming for some taxa belonging to dipterans and basommatophorans. We believe that macroinvertebrate taxa in the study streams may not be able to fly or drift to other close watersheds. This reflects the biogeographical isolation and habitat loss and fragmentation observed in this and other mountain ranges (Monaghan *et al.*, 2005; Li *et al.*, 2009a). Thus, although temperature increases in the study streams may allow some taxa to shift from lower to higher elevations, it is probable that some cold stenothermic macroinvertebrate taxa, such as *Orthocladius clarkei* and *Hippeutis umbilicalis,* may become locally extinct. Several other taxa have already been reported as locally extinct by Milner *et al.* (2001) and Rossaro *et al.* (2006).

4.2. Water flow and benthic macroinvertebrates

There were long-term reductions in water flow in the upper Xiangxi River over the last 30 years (confirming our first study objective), associated with decreases in precipitation and increases in temperature recorded in the upper Yangtze basin (Zhang *et al.*, 2005). However, no effects of water flow on benthic macroinvertebrate metrics were observed. This may be because: (1) benthic macroinvertebrates in these stony streams can get refuges during catastrophic flood events to decrease the lost influences (Morse *et al.*, 1994); (2) the effects of water flow were masked by water temperature or other variables; or (3) the water flow had a minimal effect on macroinvertebrate communities during some winter periods. However, if the water flow declines with the observed trend, some streams in the Xiangxi River watershed may stop flowing in a low flow period, and undoubtedly leading to marked impacts on stream communities (Li *et al.*, 2009b). A significant increase in biotic variables, associated with the reduction of water flow, has already been observed in French Taillon-

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

Gabiétous River (Brown *et al.*, 2007). Additionally similar, but less pronounced, effects were also observed in the Llyn Brianne River in Britain (Durance and Ormerod, 2007).

4.3. Future effects of climate change on benthic macroinvertebrates

In projecting climate change effects on the biota in the Xiangxi River watershed, the relationships between SSST and biotic metrics, reached 32%–54%. This was more tightly related to biotic metrics than to water temperature (11%–29%), and perhaps is because the SSST effects on temperature and flow were more evident in summer. With the residual the long-term effects on the winter biota, this may reflect the preceding 3-month running mean. If so, the short-term relationships, between macroinvertebrate metrics and temperature or flow regimes in winter (Jiang *et al.*, 2008), may be obscured.

Temperature and flow regions are related to large-scale atmospheric-oceanic oscillations, including ENSO, NAO (North Atlantic Oscillation), NPDO (North Pacific Decadal Oscillation), and AO (Antarctic Oscillation). The frequency and magnitude of these mid-term climate changes may be altered by global warming (Dong and Liu, 2000; Hurrell and Van Loon, 1997; Heinrich *et al.*, 2009). Thus, these periodic climatic changes must be also considered in future studies, and their influences factored out, to examine the effects of long-term directional climate change on stream ecosystems (Dong and Liu, 2000; Jiang *et al.*, 2006; Hurrell and Van Loon, 1997).

Diversities of animals and plants are extraordinarily high in tropical areas, especially in tropical rain forests. However, the reduction of biodiversity, from the equator to the poles, is one of the most pervasive features of nature (Wang *et al.*, 2009). With the trends of global warming, the conditions and dynamics of temperature in subtropical regions will reach those in current tropical regions. This is expected to lead to the movement of species from tropical regions to subtropical regions or from lower mountains to higher elevations. A variety of studies have suggested this (Castella *et al.*, 2001; Jablonski *et al.*, 2006). Currently, stream macroinvertebrates occupy more isolated habitats, owing to natural or artificial barriers which block their migrations. Thus, stream communities in mountain areas are particularly vulnerable to losses in key taxa and biodiversity under the global warming (Brown *et al.*, 2007; Durance and Ormerod, 2007). Long-term changes, in these ecosystems, may be related to the migration or expansion of stream organisms from tropical to subtropical regions or from lower to higher mountains. The immigration of warm-adapted species may increase the biodiversity.

In the early studies, metrics of benthic macroinvertebrates have been widely used as effective indicators for predicting hydrological or anthropological effects in stream ecosystems (Milner *et al.*, 2001). The approach in our study is a novel indication of how stream macroinvertebrate communities could be used as indicators to study the effects of climate change. The optimal and amplitude temperatures, of benthic macroinvertebrates, provide the foundation for a novel biomonitoring approach to assess the extent of temperature increase in other close streams. However, our macroinvertebrate data are based on sampling in six continuous winters. It is possible that we have not encountered extreme flood or drought effects, so our extrapolations to future scenarios must be treated with caution.

We recognize that this 6-year study in the Xiangxi River provides only an initial evaluation of the vulnerability of subtropical stream benthic macroinvertebrates in mountain areas to climate change. However, it does illustrate the potential for using stream macroinvertebrates to help monitor the responses of ecological communities to climate change. Further detailed assessments of subtropical stream macroinvertebrate populations, and their relationships with climatic variables, are required to identify the risk species and to guide conservation and management strategies. In addition to broadening the spatial dimension, studies are required over longer time-scales to assess the effects of changes in climatic timing, as

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

well as their magnitudes discussed herein. Clearly, an extinction scenario for stream macroinvertebrates is undesirable in terms of biodiversity conservation. Hence, we represent the aquatic organisms and lend further weight to call for minimizing greenhouse gas emissions to reduce global biodiversity loss driven by climate change.

5. Acknowledgements

The study was supported by the National Natural Science Foundation of China (No. 40911130508). We would like to thank many colleagues for their assistance in the field and laboratory, especially Tao Tang, Lin Ye, Daofeng Li, Ruiqiu Liu, Ming Cao, Shuchan Zhou, Meiling Shao, Naicheng Wu, Xiaocheng Fu, Yaoyang Xu, Xinghuan Jia, and Shugui Duan. We are particularly grateful to Stanley I. Dodson and Henri Dumont for their helpful contributions to earlier drafts of this paper. We dedicate this paper to the memory of Dr. Stanley I. Dodson.

6. References

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

Brown, L. E., D. M. Hannah and A. M. Milner, 2007: Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. – Global Change Biol. **13**: 958–966.

Caissie, D., 2006: The thermal regime of rivers: a review. – Freshw. Biol. **51**: 1389–1406.

Castella, E., H. Adalsteinsson, J. E. Brittain, G. M. Gislason, A. Lehmann, V. Lencioni, B. Lods-Crozet, B. Maiolini, A. M. Milner, J. S. Olafsson, S. J. Saltveit and D. L. Snook, 2001: Macrobenthic invertebrate richness and composition along a latitudinal gradient of European glacier-fed streams. – Freshw. Biol. **46**: 1811–1831.

Chessman, B. C., 2009: Climate Changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. – Global Change Biol. **15**: 2791–2802.

Collier, K. J. and J. M. Quinn, 2003: Land-use influences macroinvertebrate community response following a pulse disturbance. – Freshw. Biol. **48**: 1462–1481.

Daufresne, M., M. C. Roger, H. Capra and N. Lamouroux, 2004: Longterm changes within the invertebrate and fish communities of the Upper Rhone River: effect of climatic factors. – Global Change Biol. **10**: 124–140.

Dong, J. and L. Liu, 2000: Relationship between SST of the equatorial eastern Pacific and the temperature and precipitation in China. – Meteorology **26**: 25–28.

Dudgeon, D., 2007: Going with the flow: global warming and the challenge of sustaining river ecosystems in monsoonal Asia. – Water Sci. Technol. (Water Supply) **7**: 69–80.

Durance, I. and S. J. Ormerod, 2007: Climate change effects on upland stream macroinvertebrates over a 25-year period. – Global Change Biol. **13**: 942–957.

Elliott, J. M., U. H. Humpesch and T. T. Macan, 1988: Larvae of the British Ephemeroptera: a key with ecological notes. Scientific Publications of the Freshwater Biological Association No 49. Freshwater Biological Association, Ambleside.

Haidekker, A. and D. Hering, 2008: Relationship between benthic insects (Ephemeroptera, Plecoptera, Coleoptera, Trichoptera) and temperature in small and medium-sized streams in Germany: A multivariate study. – Aquat. Ecol. **42**: 463–481.

Harper, M. P. and B. L. Peckarsky, 2006: Emergence cues of a mayfly in a high-altitude stream ecosystem: Potential response to climate change. – Ecol Appl **16**: 612–621.

Harte, J., A. Ostling, J. L. Green and A. Kinzig, 2004: Climate change and extinction risk. Nature **427**: 145–148.

Heinrich, I., K. Weidner, G. Helle, H. Vos, J. Lindesay and J. C. G. Banks, 2009: Interdecadal modulation of the relationship between ENSO, IPO and precipitation: insights from tree rings in Australia. – Clim. Dyn. **33**: 63–73.

Hörmann, G., N. Köplin, Q. Cai and N. Fohrer, 2009: Using a simple model as a tool to parametrize the SWAT model of the Xiangxi river in China. – Quat. Int. **208**: 116–120.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

HUANG, X., W. CHEN and Q. CAI, 2000: Survey, Observation and Analysis of lake ecology. Standards Press of China, Beijing.

HURRELL, J. W. and H. VAN LOON, 1997: Decadal variations in climate association with the North Atlantic Oscillation. – Clim. Change **36**: 301–326.

JABLONSKI D., K. ROY and J. W. VALENTINE, 2006: Out of the tropics: evolutionary dynamics of the latitudinal diversity gradient. – Science **314**: 102–106.

JIANG, T., Q. ZHANG, D. ZHU and Y. WU, 2006: Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). – Quat. Int. **144**: 29–37.

JIANG, W., Q. CAI, T. TANG, N. WU, X. FU, F. LI and R. LIU, 2008: Spatial distribution of macroinvertebrates in Xiangxi River. – Chinese J. Appl. Ecol. **19**: 2443–2448.

JONES, P. D., 1988: The influence of ENSO on global temperatures. – Climate Monitor **17**: 80–89.

KAWAI, T., 1985: An Illustrated Book of Aquatic Insects of Japan. Tokai University Press, Tokyo.

KEIL, A., M. ZELLER, A. WIDA, B. SANIM and R. BIRNER, 2008: What determines farmers' resilience towards ENSO-related drought? An empirical assessment in central Sulawesi, Indonesia. – Clim. Change **86**: 291–307.

KISHI, D., M. MURAKAMI, S. NAKANO and K. MAEKAWA, 2005: Water temperature determines strength of top-down control in a stream food web. – Freshw. Biol. **50**: 1315–1322.

KLANDERUD, K. and O. TOTLAND, 2005: Simulated climate change altered dominance hierarchies and diversity of an alpine biodiversity hotspot. – Ecology **86**: 2047–2054.

LAKE, P. S., 2000: Disturbance, patchiness, and diversity in streams. – J. N. Am. Benthol. Soc. **19**: 573–592.

LAN, Y., Q. MA, E. KANG, J. ZHANG and Z. ZHANG, 2002: Relationship between ENSO cycle and abundant or low runoff in the upper Yellow River (China). – J. Desert Res. **22**: 262–266.

LEPORI, F., D. PALM and B. MALMQVIST, 2005: Effects of stream restoration on ecosystem functioning: detritus retentiveness and decomposition. – J. Appl. Ecol. **42**: 228–238

LEPS, J. and P. SMILAUER, 2003: Multivariate Analysis of Ecological Data using CANOCO. Cambridge University, Cambridge.

LI, F., Q. CAI and J. LIU, 2009a: Temperature-dependent growth and life cycle of *Nemoura sichuanensis* (Plecoptera: Nemouridae) in a Chinese mountain stream. – Int. Rev. Hydrobiol. **94**: 595–608.

LI, F., Q. CAI, X. FU and J. LIU, 2009b: Construction of habitat suitability models (HSMs) for benthic macroinvertebrate and their applications to instream environmental flows – a case study in Xiangxi River of Three Gorges Reservior region, China. – Prog. Nat. Sci. **18**: 1417–1424.

LYTLE, D. A. and N. L. POFF, 2004: Adaptation to natural flow regimes. – Trends Ecol. Evol. **19**: 94–100.

MARCHANT, R. and G. HEHIR, 1999: Growth, production, and mortality of two species of *Agapetus* (Trichoptera: Glossosomatidae) in the Acheron River, southeast Australia. – Freshw. Biol. **41**: 655–671.

MILNER, A. M., J. E. BRITTAIN, E. CASTELLA and G. E. PETTS, 2001: Trends of macroinvertebrate community structure in glacier-fed New Zealand rivers. – Freshw. Biol. **46**: 1833–1848.

MONAGHAN, M. T., C. T. ROBINSON, P. T. SPAAK and J. V. WARD, 2005: Macroinvertebrate diversity in fragmented Alpine streams: implications for freshwater conservation. – Aquat. Sci. **67**: 454–464.

MORSE, J. C., L. YANG and L. TIAN, 1994: Aquatic Insects of China Useful for Monitoring Water Quality. Hohai University Press, Nanjing.

MOTE, P. W., A. F. HAMLET, M. P. CLARK and D. P. LETTENMAIER, 2005: Declining mountain snow pack in western North America. – B. Am. Meteorol. Soc. **86**: 39–49.

NAIMAN, R. J. and R. E. BILBY, 2001: River Ecology and Management. Springer, New York.

QU, X., T. TANG, Z. XIE, L. YE, D. LI and Q. CAI, 2005: Distribution of the macroinvertebrate communities in the Xiangxi River system and their relationship with environmental factors. – J. Freshw. Ecol. **20**: 233–238.

QUINN, J. M. and C. W. HICKEY, 1990: Characterization and classification of benthic invertebrate communities in 88 New Zealand rivers in relation to environmental factors. – N. Z. J. Mar. Freshw. Res. **24**: 387–409.

REYJOL, Y., P. LIM, F. DAUBA, P. BARAN and A. BELAUD, 2001: Role of temperature and flow regulation on the Salmoniform-Cypriniform transition. – Arch. Hydrobiol. **152**: 567–582.

RICHARDSON, J. S., 1992: Coarse particulate detritus dynamics in small montane streams of the southwestern British Columbia. – Can. J. Fish. Aquat. Sci. **49**: 337–346.

ROLIM, S. G., R. M. JESUS, H. E. M. NASCIMENTO, H. T. Z. DO COUTO and J. Q. CHAMBERS, 2005: Biomass change in an Atlantic tropical moist forest: the ENSO effect in permanent sample plots over a 22-year period. – Oecologia **142**: 238–246.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig and J. A. Pounds, 2003: Fingerprints of global warming on wild animals and plants. – Nature **421**: 57–60.
Rossaro, B., V. Lencioni, A. Boggero and L. Marziali, 2006: Chironomids from southern Alpine running waters: ecology, biogeography. – Hydrobiologia **562**: 231–246.
Sellanes, J., E. Quiroga, C. Neira and D. Gutiérrez, 2007: Changes of macrobenthos composition under different ENSO cycle conditions on the continental shelf off central Chile. – Cont. Shelf Res. **27**: 1002–1016.
Sereda, J., M. Bogard, J. Hudson, D. Helps and T. Dessouki, 2011: Climate warming and the onset of salinization: rapid changes in the limnology of two northern plains lakes. – Limnologica **41**: 1–9.
Stewart, I., D. C. Cayan and M. D. Dettinger, 2004: Changes in snowmelt runoff timing in Western North America under a "business as usual" climate change scenario. – Clim. Change **62**: 217–232.
Thomas, C. D., A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. Erasmus, M. F. De Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. Van Jaarsveld, G. F. Midgley, L. Miles, M. A. Ortega-Huerta, A. T. Peterson, O. L. Phillips and S. E. Williams, 2004: Extinction risk from climate change. – Nature **427**: 145–148.
Vannote, R. L., G. L. Minshall, K. W. Cummins, J. R. Sedell and E. Gushing, 1980: The river continuum concept. – Can. J. Fish. Aquat. Sci. **37**: 130–137.
Vass, K. K., M. K. Das, P. K. Srivastava and S. Dey, 2009: Assessing the impact of climate change on inland fisheries in River Ganga and its plains in India. – Aquat. Ecosyst. Health Manage. **12**: 138–151.
Wang, Z.H., J. Brown, Z. Y. Tang and J. Y. Fang, 2009: Temperature dependence, spatial scale, and tree species diversity in eastern Asia and North America. – Proc. Natl. Acad. Sci. U.S.A. **106**: 13388–13392.
Ye, L., Q. Cai, R. Liu and M. Cao, 2009: The influence of topography and land use on water quality of Xiangxi River in Three Gorges Reservoir region. – Environ. Geol. **58**: 937–942.
Zhang, Q., T. Jiang, M. Gemmer and S. Becker, 2005: Precipitation, temperature and runoff analysis from 1950 to 2002 in the Yangtze basin, China. – Hydrol. Sci. J. **50**: 65–80.

Manuscript submitted August 15th, 2011; revised March 16th, 2012; accepted March 31th, 2012

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim