Ecography

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Supplementary material

Appendix 1

Box A1. Definition of the invertebrate traits.

Each taxon was characterised using 13 autecological traits and 70 categories (Table A1) from Tachet et al. (2010). These traits were selected to describe the potential adaptations of taxa to the environmental characteristics of their habitat (e.g. life-cycle duration) as well as their potential spatial niche (e.g. longitudinal distribution), food requirements and sensitivity to specific stressors (e.g. temperature). Preferences of taxa for each trait category were fuzzy-coded from '0' (i.e. no affinity) to '3' or '5' (i.e. strong affinity) according to the trait complexity and the amount of available autecological information (see Chevenet et al. 1994 and Usseglio-Polatera et al. 2000 for further details). As trait description was mostly available at the species or genus level, we coded the trait preferences of higher-level taxa by calculating mean scores from species/genera already identified in our dataset over the study period (i.e. by averaging the trait category scores over all the species/genera of a given taxon). Finally, preferences of each taxon for each trait were transformed into relative use frequency distributions by dividing the taxon affinity scores for the categories of a fuzzy-coded trait by their sum.

Chevenet, F. et al. 1994. A fuzzy coding approach for the analysis of long-term ecological data. – Freshwater Biology 31: 295–309.

Tachet, H. 2010. Invertébrés d'eau douce: systématique, biologie, écologie. CNRS ed, Paris, France.

Usseglio-Polatera, P. et al. 2000. Biological and ecological traits of benthic freshwater macroinvertebrates: relationships and definition of groups with similar traits. – Freshwater Biology 43: 175–205.

Table A1. Description of the autecological traits and categories used in the study.

Trait	Category
Life-cycle duration	≤ 1 year
	> 1 year
Number of reproductive cycles	< 1 $year^{-1}$
	1 $year^{-1}$
	> 1 $year^{-1}$
Aquatic stages	Egg
	Larva
	Nymph
	Adult
Reproduction	Ovoviviparity
	Isolated eggs, free
	Isolated eggs, cemented
	Clutches, cemented or fixed
	Clutches, free
	Clutches, in vegetation
	Clutches, terrestrial
	Asexual reproduction
Respiration	Tegument
	Gill
	Plastron
	Spiracle (aerial)
	Hydrostatic vesicle (aerial)
Locomotion	Flier
	Surface swimmer
	Full water swimmer
	Crawler
	Burrower (epibenthic)
	Interstitial (endobenthic)
	Temporary attached
	Permanent attached
Transversal distribution	River channel
	Banks, connected side-arms
	Ponds, pools, disconnected side-arms
	Marshes, peat bogs
	Temporary waters
	Lakes
	Groundwaters

Table A1 (continued).

Trait	Category
Longitudinal distribution	Crenon
	Epirithron
	Metarithron
	Hyporithron
	Epipotamon
	Metapotamon
	Estuary
	Outside river system
Altitude	Lowlands (< 1000 m)
	Piedmont level (1000-2000 m)
	Alpine level (> 2000 m)
Current velocity (preferendum)	Null
	Slow (< 25cm/s)
	Medium (25-50 cm/s)
	Fast (> 50 cm/s)
Temperature (preferendum)	Psychrophilic (< 15°C)
	Thermophilic (> 15°C)
	Eurythermic
pH (preferendum)	≤ 4
	> 4-4.5
	> 4.5-5
	> 5-5.5
	> 5.5-6
	> 6
Food	Fine sediment + microorganisms
	Detritus < 1mm
	Dead plant > 1mm
	Living microphytes
	Living macrophytes
	Dead animal > 1mm
	Living microinvertebrates
	Living macroinvertebrates
	Vertebrates

Box A2. Computation of the functional trait-based indices.

On the one hand, following the approach of Hering et al. (2009) and Conti et al. (2014), we selected EPTCO species from the www.freshwaterecology.info database (Schmidt-Kloiber and Hering 2015) which are present in France and potentially endangered by climate change (i.e. according to the criteria defined by the authors). 107 species matched the criteria for which we also extracted trait preferences for all the 13 traits except 'food' at www.freshwaterecology.info (Schmidt-Kloiber and Hering 2015). We merged trait preferences of the 278 taxa and the 107 endangered species and performed a fuzzy correspondence analysis (FCA; Chevenet et al. 1994) on the resulting 12-trait array. As already highlighted by Conti et al. (2014), the FCA approach was able to detect the potential vulnerability of EPTCO taxa since the endangered species were clustered in a narrow range of the first axis (Fig. A1). Thus, we used the values on this axis as a synthetic index of the potential climate vulnerability of the 278 taxa. As a result, they were distributed along a vulnerability gradient with, in average, *Coleoptera* being the most tolerant and *Plecoptera* being the most vulnerable (Fig. A2a).

On the other hand, we estimated the degree of feeding specialisation of the 278 taxa based on their relative affinities for 9 types of food resources described in the trait 'Food' (not used in the climate vulnerability computation; Table A1). Individual scores of specialisation were computed using the following equation:

$$S_t = \sum^{k} c_{tk}^2$$

with S_t the specialisation score of taxon t, and c_{tk} the relative use of category k of trait 'Food' by taxon t (e.g. Mondy and Usseglio-Polatera 2014). As such, a truly specialist taxon using only one type of food (i.e. one trait category) was characterised by a maximal specialisation score (i.e. 1.00; Fig. A2b), whereas a truly generalist taxon evenly using the 9 types of foods (i.e. all the trait categories) was characterised by a low specialisation score (Fig. A2c).

Box A2 (continued).

To obtain comparable gradients of climate vulnerability and feeding specialisation, i.e. both bounded between 0 (for tolerant taxa and generalists, respectively) and 1 (for vulnerable taxa and specialists, respectively), we defined adjusted individual scores as follow:

$$aFI_t = (FI_t - min_{FI})/(max_{FI} - min_{FI})$$

with FI one of the two functional indices, FI_t the individual score of taxon t for this index and aFI_t its adjusted individual score. First, we verified that the adjusted individual scores from the two indices were only weakly correlated (r = -0.16). Then, we calculated the community weighted means of climate vulnerability and feeding specialisation for each of the 4734 site-by-date samples by averaging the adjusted individual scores of occurring taxa.

Chevenet, F. et al. 1994. A fuzzy coding approach for the analysis of long-term ecological data. – Freshwater Biology 31: 295–309.

Conti, L. et al. 2014. A trait-based approach to assess the vulnerability of European aquatic insects to climate change. – Hydrobiologia 721: 297–315.

Hering, D. et al. 2009. Potential impact of climate change on aquatic insects: a sensitivity analysis of European caddisflies (Trichoptera) based on distribution patterns and ecological preferences. – Aquatic Science 71: 3–14.

Mondy, C. P. and Usseglio-Polatera, P. 2014. Using fuzzy-coded traits to elucidate the non-random role of anthropogenic stress in the functional homogenisation of invertebrate assemblages. – Freshwater Biology 59: 584–600.

Schmidt-Kloiber, A. and Hering, D. 2015. www.freshwaterecology.info - An online tool that unifies, standardises and codifies more than 20,000 European freshwater organisms and their ecological preferences. – Ecological Indicators 53: 271–282.

Figure A1. Fuzzy Correspondence Analysis (FCA) performed on the 12-trait array describing the 278 taxa from our dataset along with 107 species which are present in France and are potentially endangered by climate change. Eigenvalues of the different axes of the FCA (bottom left bar plot) and ordination of the 278 taxa (black circles) and the 107 endangered species (green diamonds) on the first factorial plan (F1-F2).

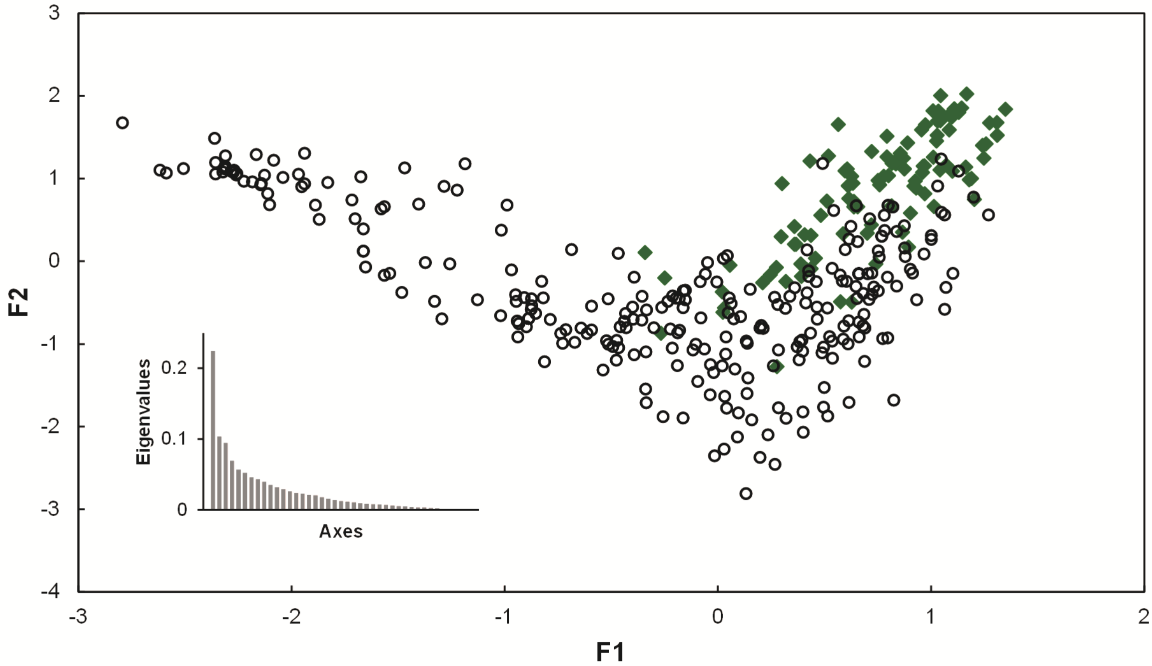
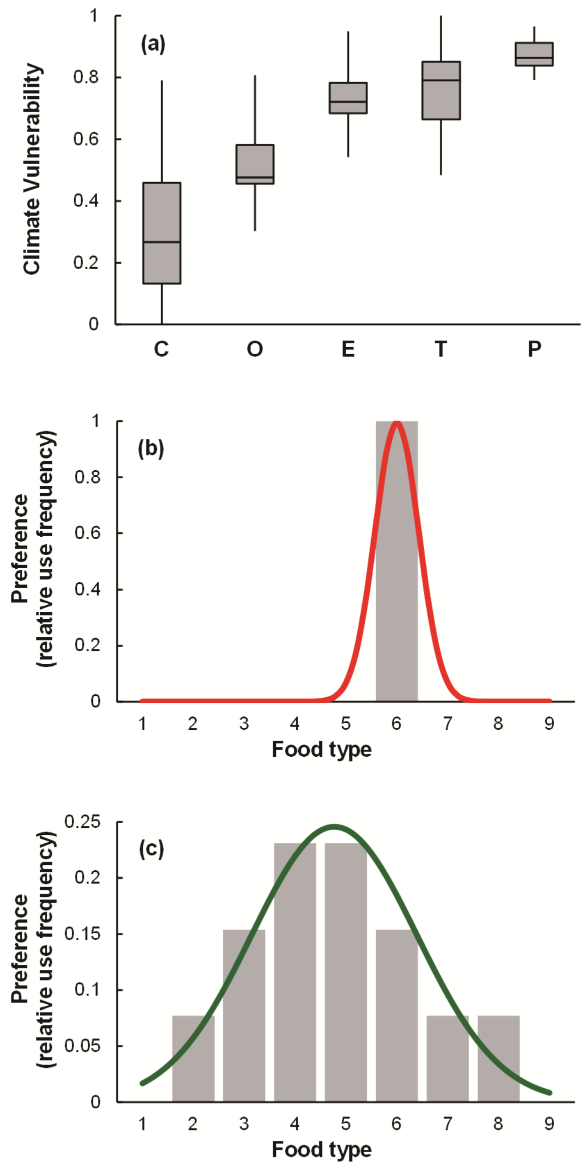


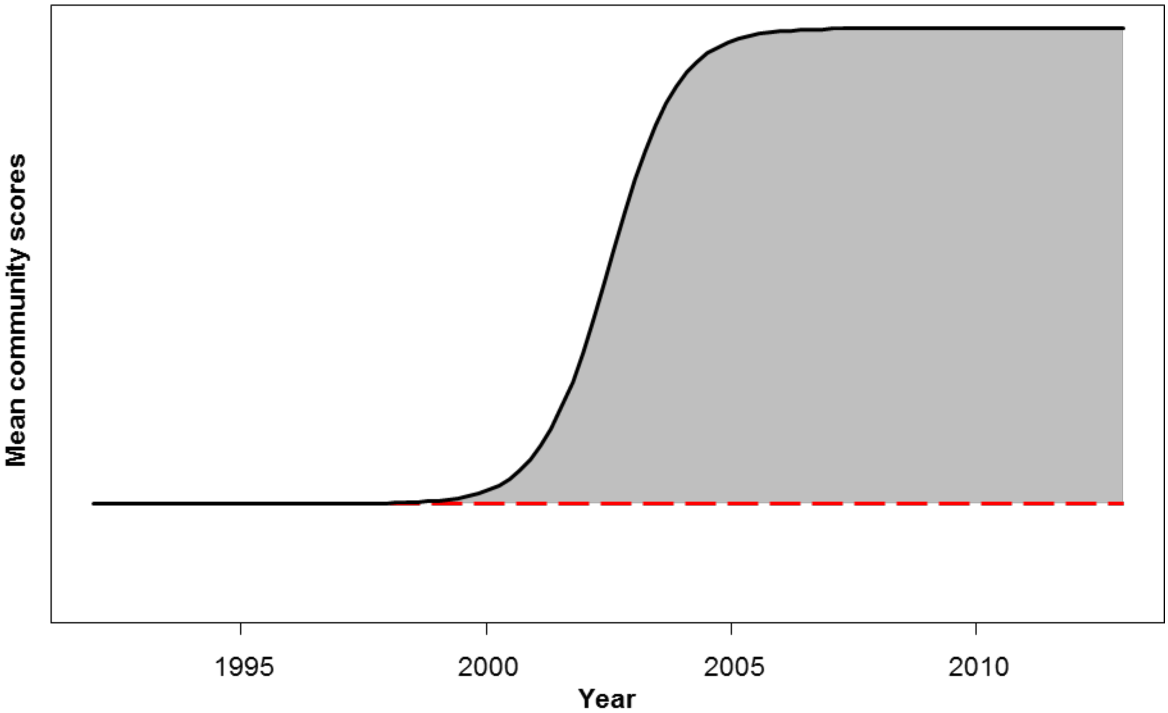
Figure A2. Illustration of the two trait-based indices. (a) Distribution of the adjusted individual scores of climate vulnerability of the 278 taxa according to their order: C = *Coleoptera*, O = *Odonata*, E = *Ephemeroptera*, T = *Trichoptera* and P = *Plecoptera*. Examples of distribution of the relative use frequencies of the nine categories from the trait ‘Food’ associated with (b) a truly specialist taxon (*Calopteryx, Odonata*), characterised by a feeding specialisation score of 1, and (c) a generalist taxon (*Siphlonurus, Ephemeroptera*), characterised by a feeding specialisation score of 0. The coloured curves depict the respective feeding niches.



Box A3. Estimation of the long-term changes in the functional indices.

We aimed at defining adequate estimators of the long-term changes in climate vulnerability, feeding specialisation and functional diversity of communities, since the main objective of the study was to assess the relative influence of the two former on the latter. The long-term trend in functional diversity averaged over the 305 sites exhibited an increasing S-shaped curve with a lower threshold ranging approximatively from 1992 to 2001. Therefore, we proposed to quantitatively estimate the long-term changes in the functional indices as areas between long-term series and initial basal values (Fig. A3). To this end, for each functional index at each sampling site, (i) we defined the initial baseline by averaging the index values over the first ten years (i.e. 1992-2001), (ii) we modelled the long-term time series as a function of year using cubic regression splines (with a degree of smoothness fixed around 0.2 of the time series length) in generalised additive models (GAMs), and (iii) we estimated the area between the smoothed time series and the baseline using an integral calculation. 'CV', 'FS' and 'FD' indices refer to these values of long-term changes in climate vulnerability, feeding specialisation and functional diversity, respectively.

Figure A3. Schematic description of the approach used to estimate the long-term changes in the functional indices. The black solid curve represents the long-term changes in the mean scores of a theoretical community for one of the three functional metrics: functional diversity (FD), climate vulnerability (CV) or feeding specialisation (FS). The red dashed line represents the baseline score of this community for the functional metric averaged over the 1992-2001 period. The grey area represents the estimation (using an integral calculation) of the long-term changes defining the functional indices FD, CV and FS.



Appendix 2

Table A2. Summary statistics calculated from the local regression coefficients estimated at the 305 sites using geographically weighted regression (GWR) models: sd = standard deviation, min = minimum value, max = maximum value, %neg = percentage of negative values, %pos = percentage of positive values.

	Intercept	CV	FS	γ_0
mean	-0.15	-0.40	0.20	-0.33
sd	0.34	0.21	0.19	0.28
min	-0.92	-1.09	-0.33	-1.47
max	0.61	0.07	0.62	0.52
%neg	69.5	98.7	13.4	91.5
%pos	30.5	1.3	86.6	8.5