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ORIGINAL PAPER

# Vulnerable taxa of European Plecoptera (Insecta) in the context of climate change

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**Abstract** We evaluated 516 species and/or subspecies of European stoneflies for vulnerability to climate change according to autoecological data. The variables considered were stream zonation preference, altitude preference, current preference, temperature range preference, endemism and rare species. Presence in ecoregions was used to analyse the vulnerability of taxa in relation to their distribution. We selected the variables that provided information on vulnerability to change in climate. Thus, we chose strictly crenal taxa, high-altitude taxa, rheobionts, cold stenotherm taxa, micro-endemic taxa and rare taxa. Our analysis showed that at least 324 taxa (62.79%) can be included in one or more categories of vulnerability to climate change. Of these, 43 taxa would be included in three or more vulnerability categories, representing the most threatened taxa. The most threatened species and the main factors affecting their distribution are discussed. Endangered potamal species, with populations that have decreased mainly as a consequence of habitat alteration, also could suffer from the effects of climate change. Thus, the total number of taxa at risk is particularly high. Not only are a great diversity of European stoneflies concentrated in the Alps, Pyrenees and Iberian Peninsula, but so are the most vulnerable taxa. These places are likely to be greatly affected by climate change according to climate models. In general, an impoverishment of European Plecoptera taxa will probably occur as a consequence of climate change, and only taxa with wide tolerance ranges will increase in abundance, resulting in lower overall faunal diversity.

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## Introduction

European streams and rivers will be affected by climate change, especially increased temperature and changes in precipitation patterns (Allan and Castillo 2008). Since water temperature is mainly determined by heat exchange with the atmosphere, higher air temperatures will lead to higher water temperatures. Environmental impacts of increased water temperatures may include reduced habitats for cold-water aquatic species and oxygen depletion; these changes may have severe consequences for ecosystem structure and function. Most aquatic organisms have a specific range of temperatures that they can tolerate, which determines their local and regional spatial distribution. In recent years some freshwater species have shifted their ranges to higher latitudes and altitudes in response to climate warming and other factors (EEA 2008). For instance, a latitudinal shift of approximately 500 to 600 km for both North American fishes and macroinvertebrates in response to a warming of 3–4°C has been reported (Shuter and Post 1990; Sweeney et al. 1992). On the other hand, annual river flow is projected to decrease in southern and southeastern Europe and to increase in northern and northeastern Europe (EEA 2008; Arnell 2004; Milly et al. 2005; Alcamo et al. 2007). There is growing evidence for changes in the global hydrological cycle in the past 50 years that may be linked to changes in climate, such as increasing continental runoff, a wetter northern Europe and a drier Mediterranean, an increase in the intensity of extreme precipitation events over many regions, and changes in the seasonality of river flows where winter precipitation predominantly falls as snow (EEA 2008). These conditions will adversely affect groups of freshwater invertebrates with aquatic juvenile stages, due to changes in their habitat conditions. Stoneflies (Plecoptera) in general have very narrow environmental tolerances (Zwick 1980; Fochetti and Tierno de Figueroa 2006), and so any change can lead to the local or global extinction of taxa (as has already occurred). Among freshwater macroinvertebrates, stoneflies are the most intolerance of environmental alterations when used as bioindicators (Rosenberg and Resh 1993). Nymphs live mainly in cold, well-oxygenated running waters, and adults are aerial with low dispersal capacity, due to reduced flight ability (Fochetti and Tierno de Figueroa 2008). This makes them especially vulnerable to climate change, while making them a very interesting group to study when assessing biotic responses to predicted global warming.

Within the stoneflies, more vulnerable taxa will be rheobiont, cold stenotherm, at higher altitudes and confined to the upper reaches of streams and rivers, mainly in the crenal zone. Due to restricted distribution or small populations, endemic species and subspecies (and mainly microendemic taxa) and rare taxa will be more threatened. Rare or restricted taxa with the above characteristics will be even more endangered. Of all the European species and subspecies, taxa found in ecoregions that will experience a greater increase in temperature and/or more severe drought episodes (Boulton and Lake 2008) will be more affected by the new conditions.

Within the framework of climate change (Nakicenovic et al. 2000; Gitay et al. 2002), we aim to detect the most vulnerable taxa of European stonefly species to environmental change, using a large autoecological database (Euro-Limpacs consortium 2008; Graf et al. 2009) and to evaluate the global threat for this insect order.

## Materials and methods

We considered all European stonefly taxa at the species and subspecies levels in the 25 European ecoregions defined by Illies (1978) (Fig. 1). We conducted an extensive literature review, including the grey literature and unpublished expert opinions (Graf et al. 2009). We chose variables that indicate which taxa may be endangered by the effects of climate change. Thus, we selected stream zonation preference, altitude preference, current preference, temperature range preference, endemism and rarity (Table 1). Though some of these variables (stream zonation, altitude and temperature) could be partially correlated in some regions of the study area, in many others these are greatly independent. For instance, the same altitude in different ecoregions can have different thermal regimes and correspond to different stream zones. Presence in ecoregions was used afterwards for discussing the vulnerability of taxa. Three different coding systems were used in the database: (1) presence/absence; (2) a 10-point coding system, in which 10 points were distributed among different categories within each variable, with 10 meaning that the taxon fulfils a given category and 0 that the taxon does not belong to the category; (3) one-assignment coding system, in which one category of the variable is chosen (Table 1).

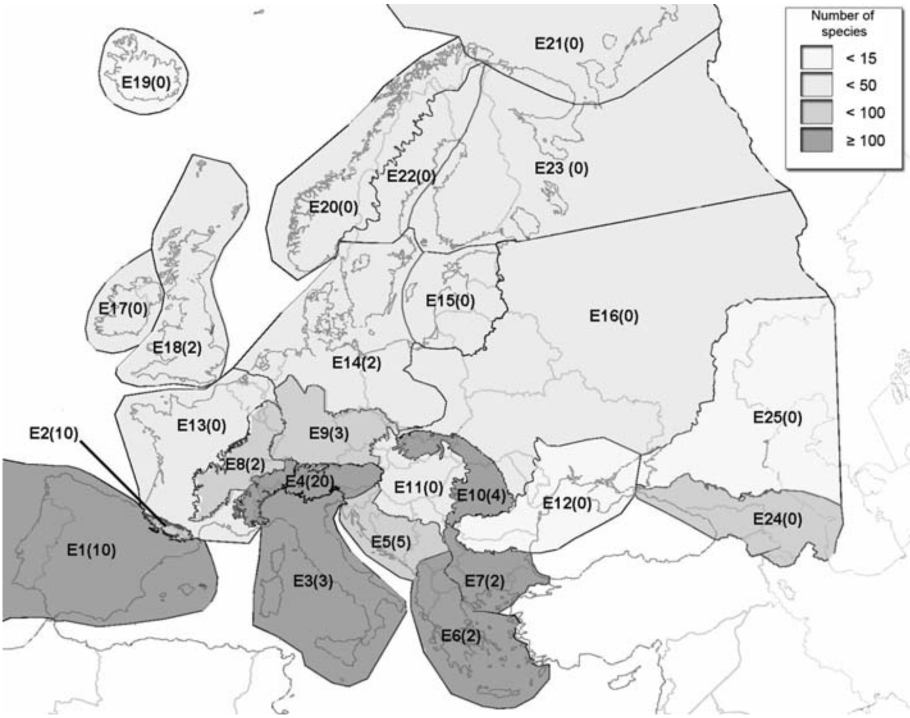


**Fig. 1** Map of the European ecoregions of Illies (1978) showing Plecoptera taxa richness and the number of vulnerable taxa (between parentheses) present in each ecoregion (E). E1: Ibero-Macaronesian region, E2: Pyrenees, E3: Italy, Corsica and Malta, E4: Alps, E5: Dinaric western Balkan, E6: Hellenic western Balkan, E7: Eastern Balkan, E8: Western highlands, E9: Central highlands, E10: The Carpathiens, E11: Hungarian lowlands, E12: Pontic province, E13: Western plains, E14: Central plains, E15: Baltic province, E16: Eastern plains, E17: Ireland and Northern Ireland, E18: Great Britain, E19: Iceland, E20: Borealic uplands, E21: Tundra, E22: Fenno-scandian shield, E23: Taiga, E24: The Caucasus, E25: Caspic depression

**Table 1** Variables used for the data analysis, categories within them and coding system

| Variables | Categories | Information |
|---|---|---|
| Presence in ecoregions | 27 ecoregions according to Illies (1978) | Presence/absence |
| Stream zonation preference | Eucrenal (spring region) | 10 points system |
| | Hypocrenal (spring-brook) | |
| | Epirhithral (upper trout region) | |
| | Metarhithral (lower trout region) | |
| | Hyporhithral (grayling region) | |
| | Epipotamal (barbel region) | |
| | Metapotamal (bream region) | |
| | Hypopotamal (brackish water) | |
| | Littoral (lake and stream shorelines, ponds, etc.) | |
| | Profundal (bottom of stratified lakes) | |
| Altitude preference | Nival (>3100 m) | 10 points system |
| | Subnival (2900–3100 m) | |
| | Alpine (2400–2900 m) | |
| | Subalpine (1900–2400 m in high mountain ecoregions; >1500 m in low mountain ecoregions) | |
| | Montane (1000–1900 m in high mountain ecoregions; 450-1500 m in low mountain ecoregions) | |
| | Submontane (800–1000 m in high mountain ecoregions; 300–450 m in low mountain ecoregions) | |
| | Collin (300–800 m in high mountain ecoregions; 150–300 m in low mountain ecoregions) | |
| | Planar (<300 m in high mountain ecoregions; <150 m in low mountain ecoregions) | |
| Current preference | Limnobiont (occurring only in standing waters) | One assignment |
| | Limnophil (preferably occurring in standing waters; avoids current; rarely found in slowly flowing streams) | |
| | Limno to rheophil (preferably occurring in standing waters but regularly occurring in slowly flowing streams) | |
| | Rheo to limnophil (usually found in streams; prefers slowly flowing streams and lentic zones; also found in standing waters) | |
| | Rheophil (occurring in streams; prefers zones with moderate to high current) | |
| | Rheobiont (occurring in streams; bound to zones with high current) | |
| | Indifferent (no preference for a certain current velocity) | |
| Temperature range preference | Cold stenotherm (preference for a small cold temperature range, below 10°C) | One assignment |
| | Warm stenotherm (preference for a small warm temperature range, above 18°C) | |
| | Eurytherm (no specific preference; wide temperature range) | |
| Endemism | Micro-endemism | One assignment |
| | Micro-endemism ecoregion | |
| | Ecoregion-endemism | |
| | Ecoregion number | |
| Rare species | Rare species | One assignment |
| | Ecoregion number | |

We selected categories that provided specific information on taxa vulnerability to predicted future conditions. Thus, we chose strictly crenal taxa (with a total of ten points when summing the categories "eucrenal" and "hypocrenal"), high-altitude taxa (those with five or more points in the categories "alpine" and above), rheobionts, cold stenotherm taxa, micro-endemic taxa and rare taxa. The amount of available information varied slightly among variables. Nevertheless, data for the majority of taxa were available, strengthening the validity of the results.

To evaluate the vulnerability of taxa from different ecoregions, we used predictions of future temperature and precipitation patterns in the A2 scenario of the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000) and the Intergovernmental Panel on Climate Change (Gitay et al. 2002).

## Results

We evaluated the selected autoecological data for 516 species and/or subspecies of European Plecoptera taxa (Fig. 2). Two hundred and fifty-two taxa of 383 for which we had available data, were present in the crenal zone (66%). This supports the preference of stoneflies for this zone (Hynes 1970; Resh and Rosenberg 1984). Of these 252 taxa, 39 were exclusively associated with the crenal zone (10%). Thus, at least 8% of the European stoneflies are vulnerable to changes in longitudinal zonation due to climate change.

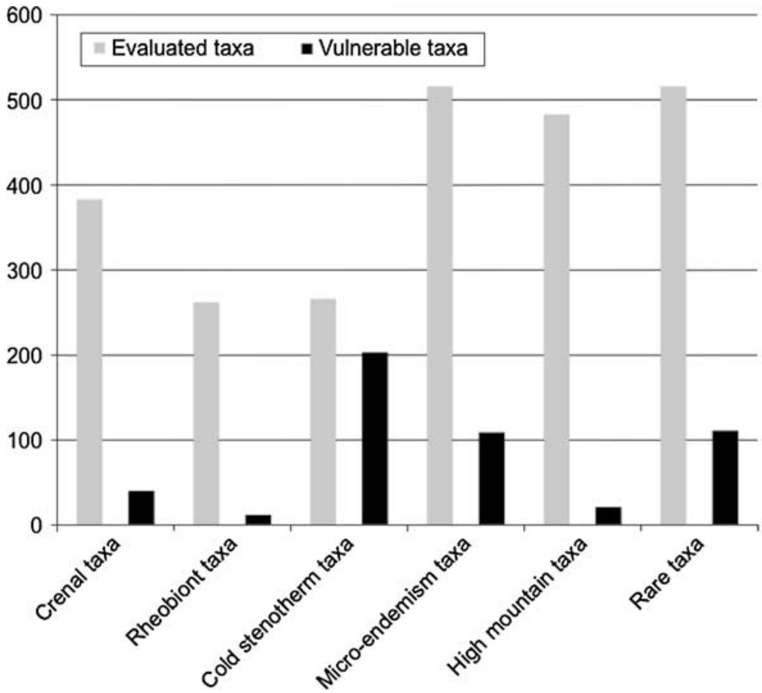


**Fig. 2** Number of vulnerable and evaluated European stonefly taxa according to the chosen variables

Twenty-one species, 4% of taxa with available data, were present mainly at high altitudes. This suggests that the preferred habitats of at least 4% of the European stoneflies are threatened by climate change.

Those species highly dependent on water flow for nymphal development (rheobionts) will be affected by climate change if predicted declines in flow come true. Although 209 taxa (80% of those with available data) are rheophiles, only 12 (5%) are absolute rheobionts, i.e., strictly dependent on flow. Thus, at least 2% of the European stoneflies are threatened because of changes in stream flow.

As is widely known and already mentioned, stoneflies mainly live in cold waters. This is reflected by the high number of cold stenotherm taxa: 201 of 266 with available data for this variable, which means 76% of them. Within the European stoneflies, cold stenotherms represent 39% of the taxa. These taxa may be endangered by rising temperatures.

As a consequence of their usually restricted distribution, endemic and rare taxa are especially vulnerable to changes in environmental conditions. Among these taxa, the most endangered are microendemics, those present in a very limited area (a mountain range, for instance). In the European stonefly fauna, 109 are microendemic (21%). In Europe, rare stoneflies account for a total of 111 taxa (22%).

Some taxa have adaptations that allow them to cope with an increase in temperature and changes in flow. For instance, some species living in the circum-Mediterranean ecoregions, where the greatest shifts from permanent to temporal regimes are predicted to take place, will be able to resist drought. Nonetheless, only 40 European stoneflies exhibit this kind of resistance to environmental change.

Overall, at least 324 taxa (63%) can be included in one or more categories of vulnerability to climate change. This is a conservative estimate given the absence of data for several species. European Plecoptera as a whole are an endangered group. Among them, 43 taxa fall into three or more vulnerability categories and are the most threatened taxa.

## Discussion

Only four of the 43 most threatened European stoneflies [*Leuctra moselyi* Morton, 1929, *Nemoura erratica* Claassen, 1936, *Protonemura hrabei* Raušer, 1956 and *Rhabdiopteryx navicula* Theischinger, 1974] are widespread species in Europe, present in three or more ecoregions. Nevertheless, all of them are considered rare. They are cold stenothermal species and rheobionts.

Twenty-one taxa with reduced distributions in southern Europe are particularly threatened because they inhabit ecoregions 1, 2, 3 and 5, where the average annual temperature is predicted to rise about 4°C and precipitations will decrease up to 0.25 mm/day for the period 2071–2100 (Gitay et al. 2002).

In the Iberian Peninsula (ecoregion 1), 9 endemic taxa can be considered vulnerable according to our analysis. *Amphinemura hibernatarii* Pardo, 1989; *Capnioneura narcea* Vinçon & Sánchez-Ortega, 2002; *Leuctra microstyla microstyla* Vinçon & Ravizza, 2000; *Leuctra microstyla nalon* Vinçon & Ravizza, 2000; *Leuctra microstyla saja* Vinçon & Ravizza, 2000; *Protonemura fusunae* Vinçon & Ravizza, 1998 and *Leuctra willmae* Illies, 1954 are cold stenotherm, crenal and/or high mountain insects. All of them except *Leuctra willmae* are also considered rare. New records of *Leuctra wilmae* have recently shown that this species is not as scarce as previously thought (Tierno de Figueroa et al. 2003). All of these species are microendemic in certain mountain systems: *Amphinemura hibernatarii* in the mountains of Galicia and the remaining species in the Cantabrian Mountains

(Tierno de Figueroa et al. 2003). Only *Protonemura fusunae* can be considered not microendemic, because it is present in both the Northern Galicia and the Western Cantabrian Mountains (Vinçon and Pardo 2004), albeit in limited areas. Two microendemic, cold stenotherm and rare species from the Cantabrian Mountains, *Protonemura brittaini* Vinçon & Ravizza, 1998 and *Rhabdiopteryx antoninoi* Vinçon & Ravizza, 1999, could be added to the endangered list despite not being associated with high mountain areas or crenal sections.

In the Pyrenees (ecoregion 2), the list of cold stenotherm species inhabiting crenal or high mountain streams includes *Leuctra ariega* Pardo & Vinçon, 1995; *Leuctra berthelemy* Zwick & Vinçon, 1993; *Leuctra clerguae* Vinçon & Pardo, 1994; *Leuctra joani* Vinçon & Pardo, 1994; *Leuctra kempnyi* Mosely, 1932 (also present in ecoregion 1); *Pachyleuctra ribauti* Despax, 1930; *Pachyleuctra bertrandi* Aubert, 1952; *Protonemura culmenis* Zwick & Vinçon, 1993; and *Protonemura zhiltzovae* Vinçon & Ravizza, 2005.

The only highly vulnerable species detected exclusively in ecoregion 3 (Italian Peninsula and close islands) is *Taeniopteryx mercuryi* Fochetti & Nicolai, 1996. This rare species has been recorded only in the crenal zone of two springs in the Gran Sasso Mountains (Ravizza and Fochetti 1999).

Two cold stenothermal, microendemic, and rare species from the Dinaric Western Balkan (ecoregion 5), *Leuctra aptera* Kacanski & Zwick, 1970 and *Leuctra jahorensis* (Kacanski, 1972), can be also considered very vulnerable to environmental change.

Another important group of threatened vulnerable taxa is composed of 15 cold stenothermal endemic species from the Alps (ecoregion 4). Only two of them, *Leuctra ameliae* Vinçon & Ravizza, 1996 and *Leuctra sesvenna* Aubert, 1953 are not microendemic but considered rare. The former species inhabits crenal habitat and the latter inhabits high mountains. The remaining 13 taxa are considered microendemic. *Leuctra gardinii* Ravizza, 2005, *Leuctra vesulensis* Ravizza & Ravizza-Dematteis, 1984 (both inhabiting the crenal zone) and *Leuctra queyrassiana queyrassiana* Ravizza & Vinçon, 1991 (a high mountain inhabitant) are microendemic, inhabit the same area of the Monviso massif (Ravizza 2005). *Leuctra astridae* Graf, 2005 and *Leuctra istenicae* Sivec, 1982 are crenal and rare species, the former from Styria (Austria) (Graf 2005) and the latter only known from the type locality (Pohorje, Slovenian Alps) and a few sites in the adjacent Austrian Alps (Koralpe, Graf 1999). The same ecological requirements are seen in *Leuctra vinconi vinconi* Ravizza & Ravizza-Dematteis, 1994 and *Leuctra vinconi aubertorum* Ravizza & Ravizza-Dematteis, 1994, both considered rare taxa from the Western Alps (Ravizza and Vinçon 1998). Also inhabiting the crenal zone is *Leuctra queyrassiana orsera* Ravizza & Vinçon, 2003, but this species does not seem to be as rare as the previous ones. *Leuctra festai* Aubert, 1954 and *Leuctra ravizzai* Ravizza Dematteis & Vinçon, 1994 are two high-mountain species, both rare, from the Western Alps (Ravizza and Vinçon 1998). *Leuctra brevipennis* Ravizza, 1978 and *Leuctra canavensis* Ravizza & Ravizza-Dematteis, 1992 are rare species found in the Italian Alps, particularly in the Pennine Alps (Ravizza and Vinçon 1998). This also occurs with *Nemoura oropensis* Ravizza & Ravizza-Dematteis, 1980. A recently described species, *Siphonoperla ottomoogi* Graf, 2008, a microendemic from the Eastern Alps inhabiting small alpine springs and brooks (crenal), is rare (Graf et al. 2008) and should be added to this group of endemic, vulnerable alpine taxa.

*Nemoura sinuata* Ris, 1902, is found in ecoregions 4 (Alps) and 10 (Carpathians). It is also considered a vulnerable taxon because it is a cold stenothermal, high-mountain species found exclusively in the crenal zone.

Finally, *Perlodes jurassicus* Aubert, 1946, microendemic to the Jura massif (ecoregion 8) is considered a cold stenothermal rare species. Previously considered widely distributed in Europe, its status and distribution drastically changed after the review of Knispel et al. (2002).

Some of the above taxa are micropterous or apterous, including *Leuctra brevipennis*, *Leuctra gardinii*, *Leuctra istenicae,* the three subspecies of *Leuctra microstyla* and *Leuctra aptera*. These taxa all have very restricted ranges, and are even more threatened due to their limited ability to disperse to new regions.

It is likely that the list of vulnerable taxa will expand as new data on particular species are added.

The populations of some endangered species, such as *Marthamea selysii* (Pictet, 1841), *M. vitripennis* (Burmeister, 1839), *Isogenus nubeculum* Newman, 1833, and *Oemopteryx loewii* (Albarda, 1889), have decreased to critical levels from alteration of their potamal zone habitats (Zwick 1992, 2004; Fochetti and Tierno de Figueroa 2006). Although these taxa do not appear on our list of threatened species, higher temperatures in combination with habitat alteration (eutrophication, toxic substances and presence of dams) could also make them vulnerable to climate change. Thus, the total number of taxa at risk is even higher than we have stated.

Regarding European stonefly fauna, the regions that will suffer the greatest effects of climate change according to Nakicenovic et al. (2000) and Gitay et al. (2002) are those with high species diversity (Fig. 1). Moreover, almost all of the most vulnerable taxa are already concentrated in these ecoregions.

In conclusion, a general impoverishment of the European Plecoptera fauna will occur as a consequence of climate change. The great majority of stonefly species and subspecies is threatened, particularly those with the ecological requirements we have discussed.

A few species will likely increase their populations, particularly eurythermic or warm-stenothermic species with a wide stream zonation preference, mainly those found in low and medium altitudes and widely distributed throughout Europe, such as *Leuctra fusca fusca* (Linnaeus, 1758), *Isoperla grammatica* (Poda, 1761) and *Nemoura cinerea cinerea* (Retzius, 1783). Particularly in Southern Europe, changes from permanent to temporary streams could also favour species with drought resistance, but these comprise only a small proportion of Plecoptera species.

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