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RESEARCH PAPER OPEN ACCESS

The vulnerability of British aquatic insects to climate change

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Abstract – Freshwater ecosystems are particularly at risk from climate change due to the intrinsic link between the physical properties of the water environment and those species that live there. Mayflies, stoneflies and caddisflies are key indicators of the health of freshwater environments and their biological traits and ecological preferences determine their vulnerability to climate change. Traits and preferences for 289 British species were analysed, with voltinism, length of flight period, altitudinal preference and affinity to headwaters being the main factors causing vulnerability. Sixteen species were deemed to be at risk from climate change. These species are distributed across Great Britain, but particular hotspots of vulnerability are present in upland areas. These areas should be targeted with mitigation measures to reduce the impacts of climate change on populations of aquatic insects.

Keywords: Climate / indicators / Ephemeroptera / Plecoptera / Trichoptera

1 Introduction

Climate change is recognised as a major driver of change in nature, globally (Diaz *et al.*, 2019; Hannah, 2014). Freshwater habitats and species are particularly at risk, because of profound effects of physical properties of the water environment and resultant effects on ecosystem functioning (Macan, 1963, Brittain, 2008; Darwall *et al.*, 2018). The impacts of climate change on freshwaters are likely to include increased air and water temperatures, and an increased extent and frequency of flooding and droughts (Watts *et al.*, 2015). All these potential changes have been documented to affect invertebrate communities *e.g.* temperature (Durance and Ormerod, 2007; Taubmann *et al.*, 2011), flooding (Scrimgeour and Winterbourn, 1989; Death, 2008) and drought (Stubbington *et al.*, 2016; Chadd *et al.*, 2017).

The predicted changes to freshwater invertebrates from rising temperatures and flow regime alterations (Domisch *et al.*, 2013) are expected to manifest particularly in montane and submontane regions (Domisch *et al.*, 2011; Monbertrand *et al.*, 2019), as well as in headwaters (Baranov *et al.*, 2020). There may also be other impacts as a result of climate change, such as a decrease in organism size (*e.g.* Jonsson *et al.*, 2015; Jourdan *et al.*, 2019), changes in the composition of the benthic invertebrate community (*e.g.* Durance *et al.*, 2009, Woodward *et al.*, 2010; Moss, 2014;), and changes in the distribution of individual species (*e.g.* Hickling *et al.*, 2005; 2006), including upstream shifts in range in montane rivers, or phenological changes (Thackeray *et al.*, 2010; Everall *et al.*, 2015).

The vulnerability of freshwater invertebrates to climate change, particularly increased water temperature, has been investigated by a number of authors who have identified both taxa and areas of increased vulnerability. Comprehensive assessments of vulnerability covering the whole of Europe are available for Trichoptera (Hering *et al.*, 2009), Plecoptera (Tierno de Figueroa *et al.*, 2009), Ephemeroptera, Plecoptera and Trichoptera (EPT) (Conti *et al.*, 2014; Hershkovitz *et al.*, 2015) or identifying vulnerable catchments (Markovic *et al.*, 2017). Sandin *et al.* (2014) also focussed on EPT in Sweden, finding increased climate change sensitivity in areas with predicted increased temperatures. Bhowmik and Schäfer (2015) identified some relationships between climate change and functional traits of EPT, Diptera and Odonata in Germany, while Monbertrand *et al.* (2019) found areas of vulnerability to climate warming of EPT in the Swiss Alps. The Europe-wide assessments are based on the 25 ecoregions defined by Illies (1978), however, to understand and target where mitigation measures should be implemented, a more precise analysis is required. Several species have also been discovered in Great Britain since the completion of the European studies (*e.g.* *Baetis atlanticus*, *Siphlonurus aestivalis*, *Potamophylax nigricornis* and *Nemoura lacustris*) (Macadam *et al.*, 2018; Macadam and Farr, 2021; Hammett, 2012) and the number of endemic species present is under-reported within these wider scale assessments with *Brachyptera putata*, *Perlodes mortoni*, *Capnia vidua anglica*, *Taeniopteryx nebulosa britannica*, and *Rhyacophila septentrionis* all now considered endemic to the British Isles (Macadam, 2015; Valladolid *et al.*, 2021).

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Table 1. Criteria used to assess potential vulnerability of EPT species to climate change.

Field	Criteria
Stream zonation preference	Taxa with a preference for the eucrenal, hypocrenal or epirhithral zones classified as a total score of 5 or more in these zones according to Schmidt-Kloiber and Hering (2015)
Altitude preference	Taxa with a preference for altitudes of 450 metres and above classified as a total score of 5 or more in the montane zone (for low mountain ecoregions) and above according to Schmidt-Kloiber and Hering (2015)
Temperature range preference	Taxa classified as cold stenotherms
Life duration or Reproductive life cycles per year	Taxa which reproduce every year or every two years classified as univoltine or semivoltine or Taxa with a life span of more than one year.
Duration emergence period	Emergence period of 2 month or less
Restricted distribution	Classified as 'Nationally Rare' in Macadam (2015; 2016) or Wallace (2016)

In Great Britain, climate change is causing widespread changes in the abundance, distribution and ecology of a range of wildlife (*e.g.* Franco *et al.*, 2006; Morecroft and Speakman, 2015; Watts *et al.*, 2015; Morris, 2018; Hayhow et al., 2019) including invertebrates (*e.g.* Durance and Ormerod, 2007, 2008; Pearce-Higgins *et al.*, 2017; SEPA, 2019) and the importance of biological traits and environmental conditions when identifying indicator organisms for climate change investigated (Elliott, 1991; Pearce-Higgins *et al.*, 2015). The use of biological traits and ecological preferences to assess vulnerability to climate warming is well established (*e.g.* Domisch *et al.*, 2011, 2013, Conti *et al.*, 2014; Hershkovitz *et al.*, 2015). Species with specialist traits, such as low dispersal ability or intolerance to warm or highly variable temperatures, are likely to show range contractions or even local extinctions (Brittain, 2008), whereas generalist species are likely to be able to adapt to changing conditions (Townsend and Hildrew, 1994) and those with greater dispersal ability may find alternative locations (Hickling *et al.*, 2005). For aquatic invertebrates, these studies found that biological traits including emergence period, voltinism, oviposition behaviour, functional feeding type, thermal preference, and drought-tolerance influenced species abundance with increases in temperature and precipitation. However, there is no comprehensive assessment of the vulnerability to climate change of British EPT species. To address this knowledge gap we considered the potential vulnerability of British EPT species, based on functional ecological traits. We assessed 289 species present in British waters (both running and standing water habitats) using a selection of traits to investigate their vulnerability to climate warming and the geographical distribution of vulnerable species.

2 Methods

To identify the vulnerability of EPT species to climate warming in Great Britain we used six traits adapted from those identified by Hering *et al.* (2009) (Tab. 1).

We obtained the data on the various biological traits and ecological preferences for British EPT from data compiled for European taxa (Buffagni *et al.*, 2009; Graf *et al.*, 2008, 2009; Schmidt-Kloiber and Hering, 2015). For each species, traits were scored using a binary system where a score of 0 was assigned if the species did not satisfy the criteria for vulnerability and a score of 1 if the species satisfied the criteria. We used this absolute approach to ensure that we identified the most vulnerable species. Where trait information was not available the score was treated as 0 (*i.e.* the criteria was not satisfied). Whilst this had the potential to under-estimate the vulnerability of the species, none of the species with individual missing traits would have been considered vulnerable if the missing criteria had been satisfied. One species (*Baetis atlanticus*) was not included in the trait database and was therefore not assessed. The Vulnerability Score (VS) for each species was calculated by summing the individual scores of each trait, therefore giving a score between 0 and 6. The overall potential vulnerability of species to climate change was defined according to the VS with those scoring 6 as most vulnerable, 5 as highly vulnerable, 4 as vulnerable and 3 or less as invulnerable.

We obtained distribution records of Ephemeroptera, Plecoptera and Trichoptera species from the National Riverfly Recording Schemes (www.riverflies.org/Recording_Schemes). The bulk of these records are derived from the monitoring work of the statutory environment agencies and represent riverine species, with additional records from a range of freshwater habitats from local biological records centres, non-governmental organisations, museums and from individuals. Each species contained in the dataset was assigned the corresponding vulnerability score (VS). We linked the resultant dataset to Level 10 HydroBasins (Lehner and Grill, 2013) using QGIS. Summary data for the number of most vulnerable and highly vulnerable species, and the maximum VS was calculated for each of the 1676 HydroBasins present in Great Britain. The data ranged from 1970 to 2019. The median date of all records fell in 1997 so we used this year to split the dataset. We classified records from before 01/01/1997 as 'historic' and records from on or after 01/01/1997 as 'modern'. We then compared the historical and modern distribution of species potentially vulnerable to climate change.

3 Results

Trait data was available for 289 of the 290 EPT species found in British waters (52 Ephemeroptera; 35 Plecoptera; 202 Trichoptera) (Tab. 2). Trait information for the mayfly

Table 2. Summary of trait data – number and percentage of species which satisfy the criteria in Table 1.

	N	Headwater preference	High altitude preference	Cold temperature preference	Long-lived	Short flight period	Restricted distribution
Ephemeroptera	52	2 (4%)	3 (6%)	2 (4%)	18 (35%)	35 (67%)	8 (15%)
Plecoptera	35	19 (54%)	5 (14%)	15 (43%)	21 (60%)	30 (86%)	5 (14%)
Trichoptera	202	48 (24%)	9 (5%)	23 (11%)	69 (34%)	84 (42%)	26 (13%)
Total	289	69 (24%)	17 (6%)	40 (14%)	108 (37%)	149 (52%)	39 (14%)

Baetis atlanticus, a relatively newly identified UK species (Macadam *et al.*, 2018) was not available. Plecoptera dominated the vulnerable species based on all traits apart from restricted distribution. In contrast, Ephemeroptera were poorly represented for most traits, apart from life history characteristics (*i.e.* voltinism and flight period). In total 16 EPT species were classed as vulnerable (13 spp.) or highly vulnerable (3 spp.), no species were classified as most vulnerable (Tab. 3; Supplementary information: Tab. 1).

585,807 species distribution records were available from the Riverfly Recording Schemes (111,032 Ephemeroptera; 49,670 Plecoptera; and 425,105 Trichoptera). Distribution data was available for 1585 (95%) HydroBasins (Fig. 1). Potentially vulnerable species (*i.e.* species with VS of 4 or more) were found in 579 HydroBasins distributed across Great Britain (Fig. 2). The greatest concentration of vulnerable species is in upland areas (Fig. 2) including Snowdonia, the Cairngorms, Peak District, and Lake District, however they also occur in lower numbers in lowland areas such as East Anglia where they are associated with springs and headwaters.

The comparison between the historical and modern distribution of species potentially vulnerable to climate change resulted in 332 (21%) HydroBasins with potentially vulnerable species in the historic period and 330 (21%) HydroBasins with potentially vulnerable species in the modern period. 106 (7%) HydroBasins have records of potentially vulnerable species in both periods indicating that vulnerable species have not yet been extirpated from the Hydrobasin due to climate change (Supplementary information: Figs. 1-4).

4 Discussion

Previous studies have provided an overview of climate vulnerability of Ephemeroptera, Plecoptera and Trichoptera (EPT) species across Europe (Tierno de Figueroa *et al.*, 2009; Hering *et al.*, 2009; Conti *et al.*, 2014; Hershkovitz *et al.*, 2015). Whilst these studies have included Great Britain, they have treated it as a single ecoregion as described by Illies (1978). To inform effective conservation action, a finer precision is required. Therefore, this study has identified the species likely to be vulnerable to climate change and the HydroBasins where they occur within Great Britain.

There were 16 EPT species recorded as vulnerable or highly vulnerable within this study. This compares with 157 species identified within a European study of Ephemeroptera with only one identified within Great Britain (Hershkovitz *et al.*, 2015–Appendix A). The Trichoptera recorded as vulnerable were 3, compared to 543 across Europe (Hering *et al.*, 2009) and 2 compared to 43 for Plecoptera (Tierno de Figueroa *et al.*, 2009). This difference likely reflects in part the discovery of new species in Great Britain since the completion of the European studies, and the consideration of previously overlooked endemic species. According to the river typology of Great Britain the vulnerable species identified in this study can be split into three categories:

4.1 Species that predominately occur in upland areas

Ameletus inopinatus (VS = 4) is recognised as a species likely to be affected by rising temperatures (Taubmann *et al.*, 2011) and, whilst still relatively common in Great Britain, the impact of rising water temperatures on this species is already evident (Kitchen *et al.*, 2010). This species was considered to have a vulnerability score of 2 on a range of 0–6, indicating a lower vulnerability across Europe (Hershkovitz *et al.*, 2015).

Glossosoma intermedium (VS = 5) has always had a very restricted distribution in Great Britain focussed on the Lake District. However, with no new records since 2001 it is feared that this species may already be extinct (Wallace, 2016). Whilst the pesticide Cypermethrin has been suggested as a possible cause of the decline in this species (Wallace, 2011), the effects of climate change may have contributed to its possible extinction in Britain. This species was considered to have a vulnerability score of 4, indicating a similar vulnerability across Europe (Hershkovitz *et al.*, 2015).

Protonemura montana (VS = 4) has generally been found in Great Britain at altitudes of 550 metres and above (Hynes, 1977). Recent surveys by one of the authors have failed to rediscover this species at many of its historical sites, suggesting that climate change may already be impacting upon this species. It scored 2 on a scale of 1 to 6, indicating a lower vulnerability across Europe (Hershkovitz *et al.*, 2015). *Diura bicaudata* (VS = 4) is another upland species, generally found in small stony streams and stony lake shores above 300 metres (Hynes, 1977). In contrast with *P. montana*, this species is still relatively widespread and common in suitable habitats. Similarly, *Capnia atra* (VS = 4) and *Capnia vidua anglica* (VS = 5) are both principally found in upland areas. *C. vidua anglica* is found in small streams at high altitude whereas *C. atra* is typically found in deep lakes of glacial origin, but may also be found in small high altitude streams. Records of both species are declining, despite seemingly suitable habitats

Table 3. Species assessed as vulnerable to climate change.

Order	Species	Headwater preference	High altitude preference	Cold temperature preference	Long-lived	Short flight period	Restricted distribution	VS	Vulnerability	Vulnerability scores (0-6) from Hershkovitz *et al.*, 2015
Ephemeroptera	*Ameletus inopinatus*	1	1	1	1	0	0	4	Vulnerable	2
Plecoptera	*Capnia atra*	1	1	1	1	0	0	4	Vulnerable	3
	Capnia vidua anglica	1	1	1	1	1	0	5	Highly vulnerable	3
	Diura bicaudata	1	0	1	1	1	0	4	Vulnerable	3
	Leuctra moselyi	0	1	1	1	1	0	4	Vulnerable	2
	Nemoura avicularis	1	0	1	1	1	0	4	Vulnerable	2
	Nemoura erratica	0	1	1	1	1	0	4	Vulnerable	2
	Protonemura montana	1	1	1	1	0	0	4	Vulnerable	2
	Protonemura praecox	1	0	1	1	1	0	4	Vulnerable	3
	Rhabdiopteryx acuminata	0	0	1	1	1	1	4	Vulnerable	2
	Xanthoperla apicalis	0	0	1	1	1	1	4	Vulnerable	2
Trichoptera	*Adicella filicornis*	1	0	1	1	1	1	5	Highly vulnerable	3
	Ernodes articularis	1	0	1	1	1	0	4	Vulnerable	3
	Glossosoma intermedium	1	0	1	1	1	1	5	Highly vulnerable	4
	Potamophylax nigricornis	1	1	0	1	0	1	4	Vulnerable	2
	Synagapetus dubitans	1	0	1	1	0	1	4	Vulnerable	2

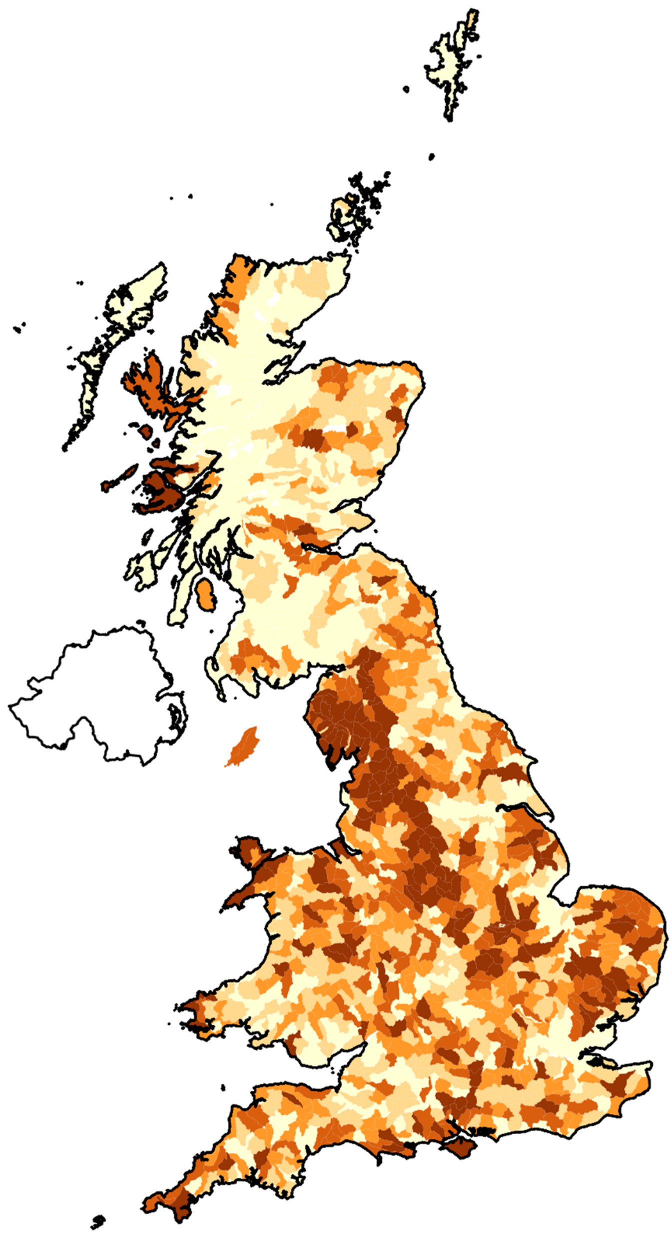

Fig. 1. Distribution of records obtained from the riverfly recording schemes.

being present, possibly reflecting climate change impacts. These three stoneflies were all scored 3 by Hershkovitz *et al.* (2015) indicating similar or slightly lower vulnerability across Europe.

4.2 Species that predominately occur in small streams of lowland areas

The three other potentially vulnerable caddisfly species are all associated with small streams in lowland areas. In the case of *Synagapetus dubitans* (VS = 4) and *Ernodes articularis* (VS = 4), and at some sites for *Adicella filicornis* (VS = 5), the streams are travertine depositing waters (Wallace, 2016). At all

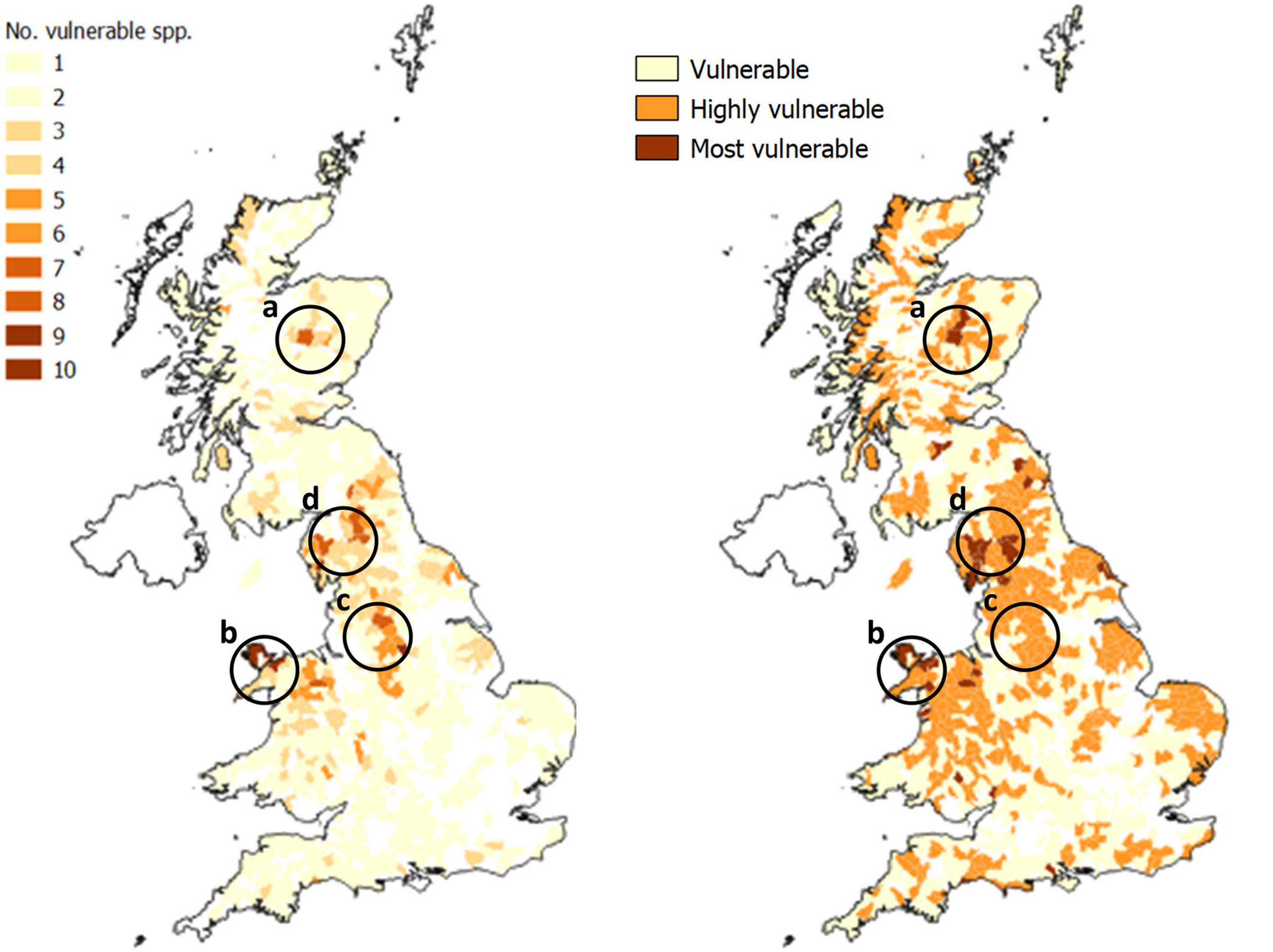

Fig. 2. (Left) Number of potentially vulnerable species (right) Vulnerability in Hydrobasins. Areas circled = a) Cairngorms; b) Snowdonia; c) Peak district; d) Lake District.

sites the species are found close to the spring head of the streams, which may result in a very narrow range of cool groundwater temperatures. In addition, most sites are associated with woodland which further regulates local temperatures through shading (Dohet *et al.*, 2015). Their preference for spring heads means that there is no opportunity for individuals to move further upstream as water temperatures rise, leaving them trapped in a warming environment. These species were all considered less vulnerable across Europe (Hershkovitz *et al.*, 2015).

Rhabdiopteryx acuminata (VS = 4) has a relatively restricted distribution in Wales and England where it occurs in the middle reaches of small, often calcareous, streams (*e.g.* Kimmins, 1943; Bratton, 1990). Whilst now considered extinct in Great Britain, the stonefly *Xanthoperla apicalis* (VS = 4), which is found in lowland rivers, is also highlighted as potentially vulnerable. This contrasts with the situation across Europe where they were assessed as having a lower vulnerability to climate change (Hershkovitz *et al.*, 2015).

4.3 Species found at various altitudes

Protonemura praecox (VS = 4) and *Leuctra moselyi* (VS = 4) are both widespread and relatively common species. They are both found in small, fast flowing streams from the middle reaches up to high altitudes. *Nemoura avicularis* (VS = 4) and *N. erratica* (VS = 4) are also both widespread and common species. *N. avicularis* is found in springs and headwaters, as well as in lakes and other standing waters from sea level to high altitudes. *N. erratica* is predominately found in fast flowing smaller streams at mid to high altitudes. The latter is also a common component of cool water in low altitude spring heads. The caddisfly *Potamophylax nigricornis* (VS = 4) has recently been discovered in England, where it was found in a small limestone spring. These species were all found to have a lower vulnerability to climate change across Europe (Hershkovitz *et al.*, 2015).

Geographically, potentially vulnerable species are concentrated mainly in upland areas (~450–1300m above sea level), such as the Cairngorms, Lake District, Snowdonia and north Wales, and the Peak District (Fig. 2). Whilst the number of HydroBasins with potentially vulnerable species in the historic and modern periods is almost identical (332 *vs.* 330), under a third of these HydroBasins (106) contain potentially vulnerable species in both time periods. This suggests that the distribution of the potentially vulnerable species, and therefore the occupied HydroBasins, has changed. A recent focus on monitoring in smaller watercourses and upland areas has resulted in an increase in modern records of species identified as potentially vulnerable in this study. However, there have been decreases in the number of potentially vulnerable species in some areas. For example, in Wales the number of potentially vulnerable species present in HydroBasins is far less for modern records compared with historical records (Fig. 3). This reduction in records may indicate the effects of other pressures such as land use and riparian habitats which are known to be partly important to insect populations in streams (Staponites *et al.*, 2019; Goss *et al.*, 2020) and warrants further investigation. Equally the change may reflect a difference in sampling effort between the two investigation periods within Wales.

4.4 Application of the results

The results of this study have the finer precision than the European studies (*e.g.* Hershkovitz *et al.*, 2015) needed to inform management actions at a national scale. Our findings highlight where HydroBasins are vulnerable to climate change impacts. Knowing where vulnerable species are located or have been recorded in the past can be used to target surveys to track their distribution and population strength and to better understand their ecological requirements and actions needed to conserve them. This understanding will allow land-owners and river managers to identify where measures can be implemented to help these river systems adapt to climate change and where increases in river temperature could be mitigated. In particular planting riparian woodlands, which provide shade to watercourses, is an important measure (Bowler *et al.*, 2012; Broadmeadow *et al.*, 2010; Kristensen *et al*., 2013). Such planting will need a strategic approach and take time to have an effect, so will need to be put in place at the earliest opportunity to ensure success (Wilby and Johnson, 2020). However, when targeting such actions, it is also important to consider the impact on aquatic invertebrate species composition due to increased coarse organic matter such as dead leaves and other woody debris in the watercourse (Thomas *et al.*, 2016). Species associated with headwaters and springs dominated those considered vulnerable within this study. This highlights the importance of such water courses and the need for their restoration and protection (Riley *et al.*, 2018).

Reducing other pressures, such as over-grazing, pollution, and abstraction, which interact with climate change, and creating more heterogeneity in the landscape in HydroBasins with potentially vulnerable species are also important actions (Clarke, 2009). As water temperature is strongly controlled by climate variability and change but mediated by catchment properties, incorporating an integrated approach is needed for measures to be effectively implemented to increase ecological resilience (Wilby and Johnson, 2020). An improved mechanistic understanding of how climate change may impact on particular species will help target adaptation measures more effectively. This, combined with extending the analysis presented here to different invertebrate groups will help provide the evidence needed to ensure that climate change adaption measures are implemented in a more coherent and effective way.

Supplementary information

Figure S1: Comparison of historic and modern records of vulnerable species in Wales

Figure S2: Comparison of historic and modern records of vulnerable species in northern England

Figure S3: Comparison of historic and modern records of vulnerable species in England and Wales

Figure S4: Comparison of historic and modern records of vulnerable species in Scotland

Table S1: Trait and preferences for 289 EPT species plus assessment of vulnerability to climate change.

The Supplementary Material is available at https://www.kmae.org/10.1051/kmae/2022003/olm.

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