Ecography

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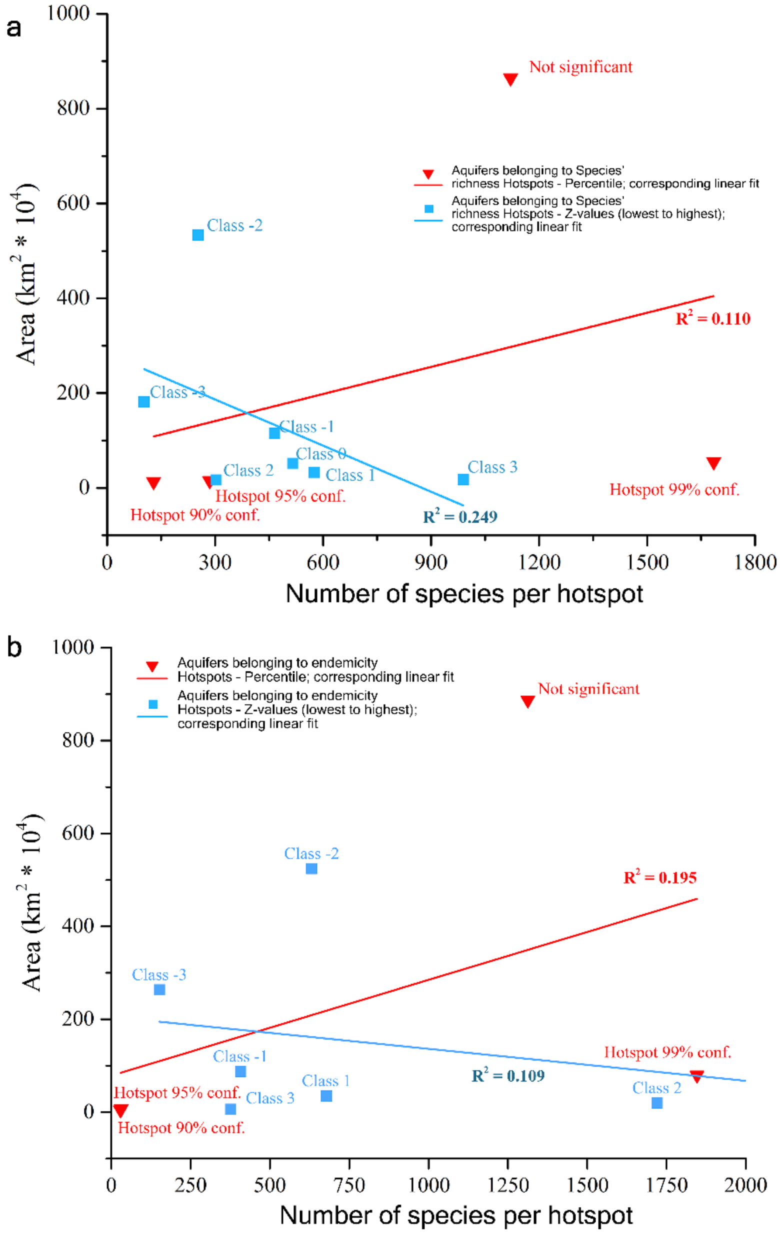
Supplementary material

Appendix 1

Figure A1

Area-effect linear fit. a Number of species – area extent linear fit for hotspots inferred on species richness, both for obtained *p*-values (red) and z-scores (blue); **b** number of species – area extent linear fit for hotspots inferred on endemicity, both for obtained *p*-values (red) and z-scores (blue).



Note A1

Gi* statistics. The Getis-Ord Gi* statistics (Getis and Ord 1992) allows to measure potential aggregation of quantitative data which can be represented in space.
Aside from the Global Moran's I statistic (ESRI 2010, Moran 1950), which returns whether a set of spatial data shows statistically-significant clustering or dispersion (which are the opposite of a complete spatial randomness), the 'Hot Spot Analysis (Getis-Ord Gi*)' tool (ESRI 2010) gives the chance to locate where significant clustering occurs. This analysis is based on the formula (Getis and Ord 1992):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}\, x_j - \bar{X}\sum_{j=1}^{n} w_{ij}}{S\sqrt{\frac{[n\sum_{j=1}^{n} w_{ij}^2 - (\sum_{j=1}^{n} w_{ij})^2]}{n-1}}}$$

where x_j is the value assigned to the *j*-th feature, w_{ij} is the spatial weight between the *i*-th and *j*-th feature, with $\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}$ and $S = \sqrt{\frac{\sum_{j=1}^{n} x_j}{n} - (\bar{X})^2}$.

It is worth to notice that this formula directly results in a *z*-score (and the corresponding *p*-value) for each geographic feature, which means that no other tests are required to infer statistical significance of the results (Getis and Ord 1992, ESRI 2010, Tegegne et al. 2019).

Note A2

Hotspots analysis

The Hot Spot analysis was conducted by using Gi* statistics (Supplementary Note 1), which works by looking at each patch within the context of neighbouring patches. Patches were the operational spatial units adopted upon selection of three macrocategories of groundwater habitat types (i.e. aquifers in consolidated rocks, aquifers in unconsolidated sediments, practically non-aquiferous rocks). The 'hottest hotspots' were derived by considering together, for each biodiversity indicator, the two highest confidence intervals (p = 99% and p = 95%, respectively) and their associated z-scores.

Hotspots of species richness. The raw species richness found in each locality varied across Europe in the form of patchy clusters, with highest species-rich sites found in southern Europe. High raw values of species richness were found in aquifers in unconsolidated sediments of Denmark, The Netherlands, and northern Germany. According to the Jenks natural breaks for six ranges of species richness, the very high (10–13 species) and high (8–9 species) species-rich localities were found in central and eastern Pyrenees, French Pyrenees Mountains in Southern France, French Jura Massif, the Alpine arc, central-western Italy, the Dinarides from Croatia to Albania, the Carpathians Mountains, the Danube plain in Romania, the Balkan Mountains embracing Bulgaria and Serbia. The Scandinavian Peninsula showed low species richness related to the high number of localities for which a few and recurrent species were recorded; the habitat types involved were primarily aquifers in consolidated rocks and, to a less extent, practically non-aquiferous rocks. In central and southern Europe the higher raw species richness values were mainly associated with aquifers in consolidated rocks or at the boundaries between consolidated rocks and practically non-aquiferous rocks or alternatively aquifers in unconsolidated sediments.

The 'hottest hotspots' were scattered across habitat types. The ones showing highest significance (p = 99%) and highest standard deviations which are a measure of their relative strengths (z-score natural break = 9.90–15.50) were distributed in the Pyrenees, in aquifers in consolidated rocks merging into practically non-aquiferous rocks, and along the Alpine arc, reaching the Slovenian Classical Karst, embracing southward the River Po alluvial plain in aquifers in unconsolidated sediments; in central Apennines, predominantly in aquifers in consolidated rocks and in practically non-aquifers rocks (igneous rocks in the western part). A second group of hotspots (confidence interval = 95%, z-score natural break = 6.23–9.89) was apparent in the Sardinia Island and in the Balkan peninsula. Small hotspots were inferred in Romania (mainly in aquifers in consolidated rocks, at the contact with aquifers in unconsolidated sediments and practically non-aquiferous rocks, and in Bulgaria and northern Macedonia in aquifers in consolidated rocks or at the boundaries with practically non-aquiferous rocks).

Hotspots of endemicity.

The groundwater habitats showing from very high to high raw endemicity scores were distributed throughout the study area in small and rather dispersed patches. The hotspots of endemicity showed minor extensions if compared to the hotspots of species richness, albeit reflecting their spatial topology. The 'hottest hotspots' of endemicity (p = 99%; z-score natural break: 12.46–19.38, and p = 95%; z-score natural break: 7.71–12.45, respectively) were found in the Pyrenees (aquifers in consolidated rocks and practically non-aquiferous rocks), Corse and Sardinia islands (practically non-aquiferous rocks), the Alpine arc including the Slovenian External Dinarides and southward the River Po alluvial plain; central and southern Apennines (aquifers in consolidated rocks and practically non-aquiferous rocks), the Carpathian and Balkan mountains in Romania and Bulgaria (mainly aquifers in consolidated rocks).

Hotspots of evolutionary origin.

The raw patches of evolutionary origin included areas not covered by high raw values of species richness and/or endemicity, such as the southern coastal part of the Iberian peninsula in front of the Alboran

Sea, the Apulia karst in south-eastern Italy, and the northern part of Turkey. The hottest hotspots of evolutionary origin, with p = 99%; z-score natural break: 13.71–24.28, and p = 95%; z-score natural break: 7.70–13.70, respectively, mirrored only in part the pattern resulting from the endemicity scores, with the Pyrenees (aquifers in consolidated rocks and practically non-aquiferous rocks), Germany (aquifers in unconsolidated sediments), the Sardinia Island (practically non-aquiferous rocks), and central and southern Apennines (aquifers in consolidated rocks and practically non-aquiferous rocks). Significant hotspots were detected in small areas of southern Spain (mainly aquifers in consolidated rocks), the External Dinarides, the Carpathian and Balkan mountains in Romania and Bulgaria (mainly aquifers in consolidated rocks).

Hotspots of phylogenetic rarity.

Raw phylogenetic rarity scores were higher in central Germany, Czech Republic and Hungary (mainly aquifers in unconsolidated sediments and, to a lesser extent, aquifers in consolidated rocks or at the boundary with practically non-aquiferous rocks). The hottest hotspots of phylogenetic rarity, defined by p = 99% and z-score natural break: 14.68–25.07 and p = 95%; z-score natural break = 8.48–14.67, respectively, were inferred in central-northern Europe (from west to east direction: aquifers in unconsolidated sediments in the Netherlands, Denmark and northern Germany, extending southward to aquifers in consolidated rocks in Central Germany); a small portion of the Pyrenees (aquifers in consolidated rocks and practically non-aquiferous rocks), the Alpine arc including the Dinaric karst and the River Po alluvial plain (aquifers in consolidated rocks and in unconsolidated sediments), central Apennines (aquifers in consolidated rocks and practically non-aquiferous rocks), followed by the Sardinia Island (mainly practically non aquiferous rocks).

Hotspots of taxonomic distinctness.

Raw values of taxonomic distinctness were higher in south-eastern France, including aquifers in practically non aquiferous rocks, with most species recorded at the boundary between aquifers in consolidated rocks and unconsolidated sediments; Corse, Sardinia and Sicily islands, in practically non aquiferous rocks, predominantly at the boundary with aquifers in consolidated rocks. The 'hottest hotspots' of taxonomic distinctness (p = 99%; z-score natural break: 10.29–16.62 and p = 95%; z-score natural break: 6.75–10.28) revealed a pattern overlapping those found for endemicity and evolutionary origin, including the Pyrenees (consolidated rocks and practically non-aquiferous rocks); small patches in western and eastern Germany (aquifers in consolidated rocks and at the boundary between aquifers in consolidated rocks and unconsolidated sediments); Sardinia Island (practically non-aquiferous rocks), central Apennines (aquifers in consolidated rocks and practically non-aquiferous rocks); a small area in the Italian Alps embracing southward the River Po alluvial plain; the Carpathian and Balkan mountains in Romania and Bulgaria (mainly aquifers in consolidated rocks).

Hotspots of habitat specificity.

Raw habitat specificity values were high in the Dinarides; small areas of relatively high habitat specificity scores were detected in the French Pyrenees, and a small portion of the Jura Massif (France). The 'hottest hotspots' of habitat specificity (p = 99%; z-score natural break: 7.81–13.36 and p = 95%; z-score natural break: 2.66–7.80) were restricted to the north-eastern side of the Pyrenees (aquifers in consolidated rocks and practically non-aquiferous rocks); the Jura Massif (France); the Alpine arc and the River Po alluvial plain (aquifers in consolidated rocks and in unconsolidated sediments), and a vast portion of the Dinaric Alps (aquifers in consolidated rocks).

References

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