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ABSTRACT

Aim To assess the exposure of 10 spider species to two drivers of global change (climate and land use), the suitability of the current network of protected areas with respect to this exposure, and the implications for a national conservation programme.

Location The western Palearctic and France.

Methods We predicted the current and future potential distributions of 10 spider species using species distribution models (SDMs). We explicitly quantified uncertainties in the models and estimated the future environmental suitability with discounted uncertainty. We analysed the predicted future suitability for protected versus unprotected occurrence cells.

Results In this first forecast of the future of multiple spider species in the face of environmental changes, we showed that environmental changes could be confidently predicted to have serious impacts on all the studied species, with significant range contractions and expansions within a relatively short time-scale (up to 2050). We predicted that for seven of the 10 species, the current network of protected areas will conserve at least one occurrence cell in suitable conditions in the future. However, we showed that there is considerable room for improvement.

Main conclusions This study illustrated how SDMs could be applied to a conservation programme for an understudied taxon such as spiders, in spite of significant uncertainties in their predictions. In addition, the uncertainties raised here compel us to emphasize the pressing need to improve our knowledge on understudied taxa such as spiders. We advocate the necessity of increasing monitoring schemes, experiments and forecasts of environmental change effects on a larger and more diversified range of species than is currently the case in the literature.

INTRODUCTION

Land use change is considered as the primary contemporary threat to terrestrial species world-wide (Sala *et al.*, 2000), while climate change is likely to supersede it in the future (Thuiller, 2007; Bellard *et al.*, 2012). Future forecasts of climate change have demonstrated that climate change may threaten conservation areas and therefore should become a part of conservation planning (Araújo *et al.*, 2011); similar recommendations have emerged for land use change (Visconti *et al.*, 2011). In general, new policies and conservation strategies are advocated to address the emergent threats that global changes pose to biodiversity (Lawler, 2009). Even though a variety of studies recommend taking climate change

into account for species conservation goals, to our knowledge, most of the studies examining the upcoming effects of global change have focused on mammals (e.g. Visconti *et al.*, 2011), birds (e.g. Jetz *et al.*, 2007) and plants (e.g. Bakkenes *et al.*, 2002). Of all the literature on the modelling of protected areas under climate change from 1998 to 2010, only one species of insect was studied, versus thousands of plants, mammals and birds (Sieck *et al.*, 2011). In fact, most invertebrate taxa have been omitted in future forecasts of global change effects (Bellard *et al.*, 2012). Yet, invertebrate taxa constitute 75% of all animal species on earth (Chapman, 2009; Scheffers *et al.*, 2012) and perform vital roles in all ecological systems (Losey & Vaughan, 2006). Most invertebrate species are silently disappearing at similar or even higher rates than better-known taxa (Cardoso *et al.*, 2011), which emphasizes the necessity to give them a legitimate place in future forecasts of global change effects.

Forecasts of global change effects have been based dominantly on species distribution models (SDMs) (Thuiller *et al.*, 2009; Araújo *et al.*, 2011; Leroy *et al.*, 2013). These models relate environmental predictor variables with the occurrences of species to predict the current and future potential ranges of species under different gas emission scenarios. The major advantage of these models is that they only require occurrence data, which make them generalizable to a large number of taxa (Graham *et al.*, 2004), thereby making it possible to include numerous invertebrate groups (Cardoso *et al.*, 2011). As such, SDMs can be a valuable tool for conservation problems, although successful examples are still scarce in the literature (Guisan *et al.*, 2013).

In this paper, we apply SDMs to predict the impacts of climate and land use change on 10 species of the notably omitted spider taxon (see Leroy *et al.*, 2013), which are subject to a conservation programme in France, the Strategy of Creation of Protected Areas (SCAP). The SCAP aims to increase the current network of protected areas by a total of 2% of the French metropolitan territory (i.e. 10879 km^2) by 2020 (Coste *et al.*, 2010). The protected areas will be designed to protect a set of species selected across diverse groups (vertebrates, invertebrates and plants), among which 10 spider species were chosen. Their choice was based on expert decisions by the French Society of Arachnology, on the basis of their biotope specificity or emblematic nature (Coste *et al.*, 2010). One of the species is among the very few spiders of the IUCN red list (*Dolomedes plantarius*, vulnerable status), and six of the species are listed on national red lists in Europe. This conservation programme provides an unprecedented conservation opportunity for spiders, as it is the first large-scale conservation programme in France including spider species. However, protection measures for the SCAP species will be applied only if these species are proven to be inadequately represented in the current network of protected areas or are predicted to be sensitive to environmental changes (Coste *et al.*, 2010). Therefore, we have made use of this conservation programme to try to reduce the taxonomic gap in the literature on protected areas and climate

change (Sieck *et al.*, 2011) by proposing the first study combining them on multiple spider species.

Our objectives are to study forecasted climate and land use change impacts on the SCAP spiders, given that the spiders are highly sensitive to habitat change (Marc *et al.*, 1999; Prieto-Benítez & Méndez, 2011). We aim to apply SDMs to the SCAP spiders to (1) assess their exposure to future climate and land use changes (2050s) and (2) assess the current and future suitability of the existing network of protected areas for each species. We specifically quantify the uncertainties in model outcomes to make appropriate conservation recommendations (Schwartz, 2012). We conduct our study at two spatial scales: the Western Palearctic scale, which encompasses most of the distribution ranges of these species, and the French scale, relevant to the French conservation programme.

METHODS

Species data

We gathered the available knowledge and global distribution data on each of the 10 species of the SCAP through an extensive search for records of presence in the published and grey literature, on internet databases and with arachnologists (see Appendix S1 in Supporting Information). Inaccurate or uncertain records were discarded on the basis of a combined automatic- and expert-based procedure, as were records preceding 1950. Data were gathered throughout the Western Palearctic distribution of each species to avoid misleading conclusions due to the use of data from a restricted range of occurrence (Barbet-Massin *et al.*, 2010; Sánchez-Fernández *et al.*, 2011). The number of retained records ranged from 71 (*Pardosa oreophila*) to 1936 (*Trochosa spinipalpis*) (Table 1). Eight of the species are widespread throughout the Western Palearctic; only two have restricted ranges: *Arctosa fulvolineata*, which is mostly restricted to littoral areas in Western Europe, and *P. oreophila*, which is the only mountain restricted species (recorded only in the Alps and the Pyrenees). Most of the species are from wetland or moist habitats, except for *P. oreophila* and *P. bifasciata*. Six of the species are on national red lists in Europe (Table 1).

Climate data

We used bioclimatic variables (temperature and precipitation, see Table S2.1 in Appendix S2) averaged for the period 1950–2000 from the WorldClim database (Hijmans *et al.*, 2005) for model training and projection of the current potential distribution of the 10 spider species. All the climatic variables were resampled at 0.1 degree resolution by bilinear interpolation to match the resolution of land use variables (see below).

Two emission scenarios were used for the projection of future climate (IPCC, 2007): A1B (i.e. maximum energy requirements, emissions balanced between fossil and non-fossil sources) and B2A (lower energy requirements and thus

Table 1 Summary of knowledge about the studied spider species and number of records gathered

	Family	Known habitats	Distribution range	Total number of records	Number of kept records	Number of 0.1° cells	Presence on red lists
Arctosa fulvolineata (Lucas, 1846)	Lycosidae	Halophytic coastal habitats	Restricted to coastal areas	196	172	44	United Kingdom (Rare)
Argyroneta aquatica (Clerck, 1757)	Cybaeidae	Strictly aquatic, oligotrophic ponds and marshes	Wide	1633	1544	821	Carpathian mountains (CR), Germany (Threatened)
Dolomedes plantarius (Clerck, 1757)	Pisauridae	Mesotrophic-eutrophic wetlands	Wide	480	418	174	IUCN (VU), Czech Republic (VU), United Kingdom (EN), Germany (Endangered with extinction)
Enoplognatha mordax (Thorell, 1875)	Theridiidae	Coastal wetlands, inland meadows	Wide	368	352	184	Czech Republic (CR), Poland (VU), Germany (Strongly threatened)
Icius subinermis Simon, 1937	Salticidae	Moist habitats, synanthropic habitats	Wide	89	72	44	
Neon valentulus Falconer, 1912	Salticidae	Bogs, fens, wet heathlands, forests	Wide	231	221	89	Poland (EN), United Kingdom (VU), Germany (Threatened)
Pardosa bifasciata (C.L. Koch, 1834)	Lycosidae	Meadows, dry and sandy areas, grasslands	Wide	672	650	287	Germany (Threatened)
Pardosa oreophila Simon, 1937	Lycosidae	Alpine meadows and open areas	Restricted to mountain areas	74	73	41	Germany (Rare)
Pirata uliginosus (Thorell, 1856)	Lycosidae	Bogs, damp habitats	Wide	3185	3148	690	Norway (NT)
Trochosa spinipalpis (F. O. P.-Cambridge, 1895)	Lycosidae	Wet heathlands, wet meadows	Wide	1934	1871	581	

Abbreviations for the red list statuses: CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened.
Source for National Red List data: http://www.nationalredlist.org [accessed 11/10/2013] and Platen *et al.* (1996).

lower emissions than A1B). The 2050s were chosen as the future projection period (averaged from 2040 to 2069), and we used three different global circulation models that simulated the impact of A1B and B2A scenarios on future climates because uncertainty in forecasting future distributions is partly related to global circulation models (Buisson et al., 2010). The models that were available for both our climate scenarios were chosen: Hadley Centre coupled model version 3 (HADCM3), Coupled Global Climate Model [CGCM, A1B: version 3.1 (t47), B2A: version 2] and the Commonwealth Scientific and Industrial Research Organisation model (CSIRO, A1B: Mk3.0, B2A: Mk2). These models were downscaled statistically using the delta method (Ramirez-Villegas & Jarvis, 2010) and downloaded from the global climate model data portal (http://www.ccafs-climate.org/).

Land use data

Land use variables from the GLOBIO3 land use model (Alkemade et al., 2009) were used for model training and projection of the current potential distribution of the 10 spider species (see Table S2.1 in Appendix S2). Current land use variables were obtained from the GLOBIO3 output for the year 2000, and water body data (sum of lakes, reservoirs and rivers) was also included from the Global Lakes and Wetlands Database (Lehner & Döll, 2004).

Regarding the future projections of land use areas, we used two scenarios of the latest Rio+20 pathways based on the GLOBIO3 land use model (PBL Netherlands Environmental Assessment Agency, 2012). The *Trend* scenario followed the current trend in emissions and was therefore similar to the A1B scenario. Conversely, the *Decentralised solutions* scenario was similar to the B2A scenario. Therefore, we associated climate data to land use data according to the similarity between scenarios: A1B with *Trend* and B2A with *Decentralised solutions*. Land use data were projected for the 2050s. Protected areas were accounted for in the projected land use changes (from less to no changes depending on the protection category).

Modelling process

To limit the sampling bias towards better sampled areas in SDMs, species records were aggregated into 0.1 degree cells corresponding to the resolution of our environmental variables. As a result, the number of 0.1 degree cells used to train models ranged from 41 (*P. oreophila*) to 821 (*Argyroneta aquatica*).

Ecophysiological knowledge for spiders is basic: temperature is known to be a limiting factor (Marc et al., 1999), as well as moisture (Entling et al., 2007); in addition, spiders are very sensitive to habitat change (Marc et al., 1999). Consequently, no sound ecophysiological knowledge could be used to select environmental variables. We therefore defined a protocol to select nine environmental variables that were

not intercorrelated (Pearson's $r < 0.70$) (Braunisch et al., 2013) and best predicted the distribution ranges of each species (see Appendix S2).

The current and future distributions of the 10 spider species were projected under the BIOMOD platform (Thuiller et al., 2009) version 3.0.3, using eight modelling techniques: (1) generalized linear model (GLM); (2) generalized additive model (GAM); (3) generalized boosted models (GBM); (4) classification tree analysis (CTA); (5) flexible discriminant analysis (FDA); (6) multivariate adaptive regression splines (MARS); (7) random forests (RF); and (8) maximum entropy (MaxEnt).

As the chosen models required data on both species presence and the available environmental conditions in the prediction area, we generated three sets of 1000 randomly selected pseudo-absences with equal weighting for the presence and the absence (Barbet-Massin et al., 2012). The models were calibrated with 70% of the data selected at random, and then, the predictive performance of each model was evaluated on the remaining 30% (Guisan & Thuiller, 2005) with two evaluation metrics: the area under the relative operating characteristic curve (AUC, Fielding & Bell, 1997; but see Lobo et al., 2008) and the true skill statistic (TSS, Allouche et al., 2006). This process was repeated three times.

To produce robust forecasts of the distribution of the 10 SCAP species, we applied an ensemble forecast method to combine the eight modelling techniques (Araújo & New, 2007; Thuiller et al., 2009). Models with TSS evaluations below 0.6 were discarded, and the current and future consensus distributions were obtained by averaging distributions with weights proportional to their TSS evaluation. Future probability maps were therefore averaged per year and per scenario. Probability maps were transformed into maps of suitable versus non-suitable areas by choosing the probability threshold that maximized the TSS value. This should provide the most accurate predictions because it is based on both sensitivity and specificity (Liu et al., 2005; Jiménez-Valverde & Lobo, 2007).

Protected areas

The number of occurrence cells per species located in high protection areas was assessed. Data on the global network of protected areas were obtained from the World Database on Protected Areas (IUCN & UNEP, 2010). We used the IUCN categories of protected areas (Dudley, 2008) to assess the inclusion of occurrence cells per species in the current network of protected areas, both at the Western Palearctic and French scales. Areas were considered as protected with respect to the spider species if they were classified in categories Ia, Ib and II of IUCN protected areas, because these are the strictest categories, providing a high certainty that species occurring in these areas are protected (Dudley, 2008). Conversely, areas protected under categories III, V and VI

do not explicitly protect species, and thus, species may be harmed by the usages of these areas. Category IV aims to manage areas for a particular species or habitat, and the management measures may have negative impacts on the spider species considered, given that they are not target species (except for *D. plantarius* in United Kingdom). Consequently, we excluded categories III, IV, V and VI because these areas provide no certainty that species are protected. Regarding the French SCAP programme, the criterion for an inadequate representation of species in the network of protected areas is a representation in less than 20% of the current network throughout the French territory (Coste *et al.*, 2010). A cell was considered protected when at least 50% of its area was within a protected area, as in Sánchez-Fernández *et al.* (2013).

Accounting for uncertainties

Uncertainties in our future predictions were accounted for and quantified at two different steps of the modelling process. First, we exhaustively projected the range of possible outcomes on the basis of our modelling process (8 modelling techniques 9 3 pseudo-absence runs 9 3 cross-validation runs 9 3 global circulation models = 216 future projections per species and per scenario). Then, for each species and each scenario, the estimated changes in species range size on the basis of the ensemble model (which represented our nominal best estimate) were provided, along with uncertainty intervals based on 95% of the future projections (from 2.5 to 97.5 percentiles). Although we did not study the dispersal capacities of species, we studied range change according to two opposite dispersion scenarios: (1) no dispersion at all (i.e. only range contraction occurs) and (2) full dispersion. Secondly, to account for uncertainty in our conservation recommendations, we discounted variation between modelling techniques, pseudo-absence runs, cross-validation runs and global circulation models in estimates of environmental suitability (Kujala *et al.*, 2013). Distribution discounting penalizes predicted occurrence probabilities according to a measure of uncertainty associated with the prediction. As detailed in Kujala *et al.* (2013), the weighted standard deviation of predictions was subtracted from the weighted mean prediction (with weights proportional to the TSS evaluations of models), which represented our ensemble modelling estimate. The weighted standard deviations and means were calculated with the R package SDMTools (Vanderwal *et al.*, 2012).

RESULTS

Model accuracy

Similar variables were selected for the SCAP species: three to five temperature variables, only one precipitation variable and three to five land use variables (in most cases: tree cover, herbaceous cover and cultivated and managed areas) (see

Appendix S2). The models performed well for each spider species according to the cross-validation results, with only a few models discarded from the ensemble modelling (see Appendix S3). All the ensemble models had TSS values above 0.8 and AUC values above 0.9.

Predicted impacts of environmental changes

Although the distributions of the 10 spider species differed widely in shape and size, ensemble models predicted that in 2050 (scenario A1B), all may be affected by climate and land use changes with both a significant loss of suitable areas and the apparition of newly suitable areas, generally to the north of their current range (Fig. 1a–j), but sometimes to the south (e.g. Fig. 1f, g). Two species were predicted to be less affected with small decreases in southern parts of their range (Fig. 1a, e); six species were predicted to have important decreases in southern parts of their range (Fig. 1b, c, d, g, i, j); and two species were predicted to be more strongly affected with high decreases throughout their range (Fig. 1f, h). On the other hand, almost all species were predicted to have an emergence of newly suitable areas connected to their suitable current range.

The predicted species turnover showed that France, where the conservation programme for these species takes place, was predicted to be among the most affected areas with a predicted local extirpation of up to seven species (Fig. 1k). Conversely, for most species, newly suitable areas were predicted to stack in the Alps, in Scandinavia and in north-eastern Europe. The predicted impacts for scenario B2A were similar to scenario A1B, with slightly smaller changes predicted (see Fig. S4.1).

The predicted values of range contraction according to ensemble models (i.e. our nominal best estimates) ranged from 20% to 35% for eight of the species according to both scenarios (Fig. 2). Two species were predicted to have stronger contractions, from 50% (*P. oreophila*) to 75% (*Neon valentulus*). Conversely, the predicted values of range expansion according to ensemble models differed markedly between scenarios, with a greater expansion predicted for scenario A1B than B2A. The predicted values of range expansion ranged from 5% (e.g. *N. valentulus*, *P. bifasciata* and *T. spinipalpis*) to 55% (e.g. *Icius subinermis* and *A. fulvolineata*). Approximately half of the species would experience negative net change and the other half a positive net change, according to a hypothetical full dispersion scenario (Fig. 2).

The uncertainty intervals were relatively large for both expansion and contraction values, with larger intervals predicted for range expansions (Fig. 2 and Appendix S5). Despite these large intervals, for eight of the 10 species, a contraction value above 10% was always predicted, with the notable exceptions of *A. fulvolineata* and *I. subinermis*, for which some models predicted no contraction. Under the hypothetical full dispersion scenario, the uncertainty intervals ranged from negative to positive changes for all the species.
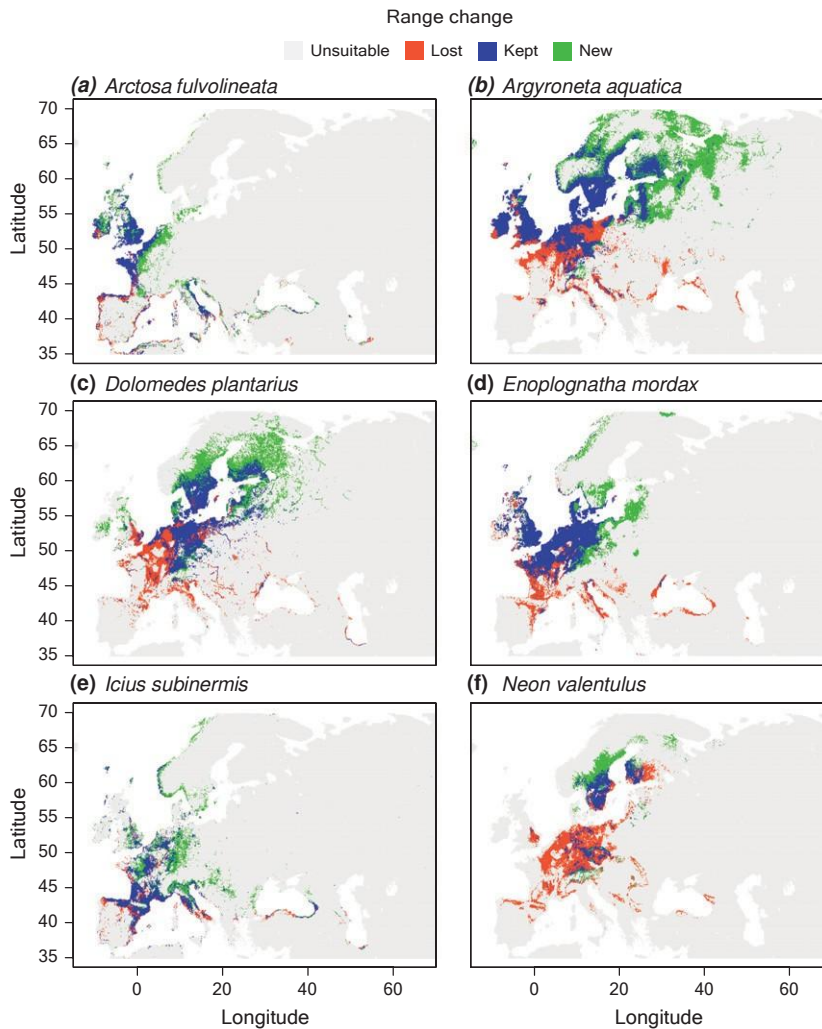
Figure 1 (a–j) Predicted range change of the 10 spider species by 2050 according to scenario A1B. (k) Summed values of predicted range changes of the 10 spider species by 2050. Unsuitable: areas that are currently unsuitable and would remain unsuitable in the future; Lost: areas currently suitable that would lose their suitability in the future; Kept: areas that are currently suitable and would still be suitable in the future; New: areas that are currently not suitable but would become suitable in the future.

Protected areas and environmental changes

Total study area

Our first result regarding protected areas was that two species (*A. fulvolineata* and *I. subinermis*) did not occur in protected areas (Figs 3 & S4.2). The most important result was the prediction that, with the exception of *N. valentulus*, all species would keep occurrence cells with a high suitability in 2050, according to the probabilities of occurrence calculated with discounted uncertainty. Furthermore, all species (except the two unprotected species) were predicted to keep at least a few protected occurrence cells above the suitability cut-off (Figs 3 & S4.2). Nevertheless, for six species, the occurrence cells with the highest environmental suitability were those not located in protected areas: *D. plantarius*, *Enoplognatha mordax*, *N. valentulus*, *P. bifasciata*, *P. oreophila* and *T. spinipalpis*). In addition, for all species, a large number of protected occurrence cells had uncertain futures (i.e. probabilities of occurrence with penalized uncertainty equal to 0), whereas numerous unprotected occurrence cells were confidently predicted to remain in suitable environments (Figs 3 & S4.2 and maps in Appendix S6).

France

None of the French occurrence cells of the 10 species were located in protected areas (Fig. 3). Our models predicted that half of the species would have at least a few occurrence cells that would remain above the suitability cut-off in 2050, according to the probabilities of occurrence calculated with discounted uncertainty. The other half did not have any occurrence cell predicted to remain suitable in 2050, with the extreme case of *N. valentulus* for which all the French occurrence cells had uncertain futures (i.e. probabilities of occurrence with penalized uncertainty equal to 0).

DISCUSSION

In this paper, we developed an approach combining both predicted consequences of future climate and land use changes with the current network of protected areas on 10

Range change

Unsuitable | Lost | Kept | New

(g) *Pardosa bifasciata*

(h) *Pardosa oreophila*

(i) *Pirata uliginosus*

(j) *Trochosa spinipalpis*

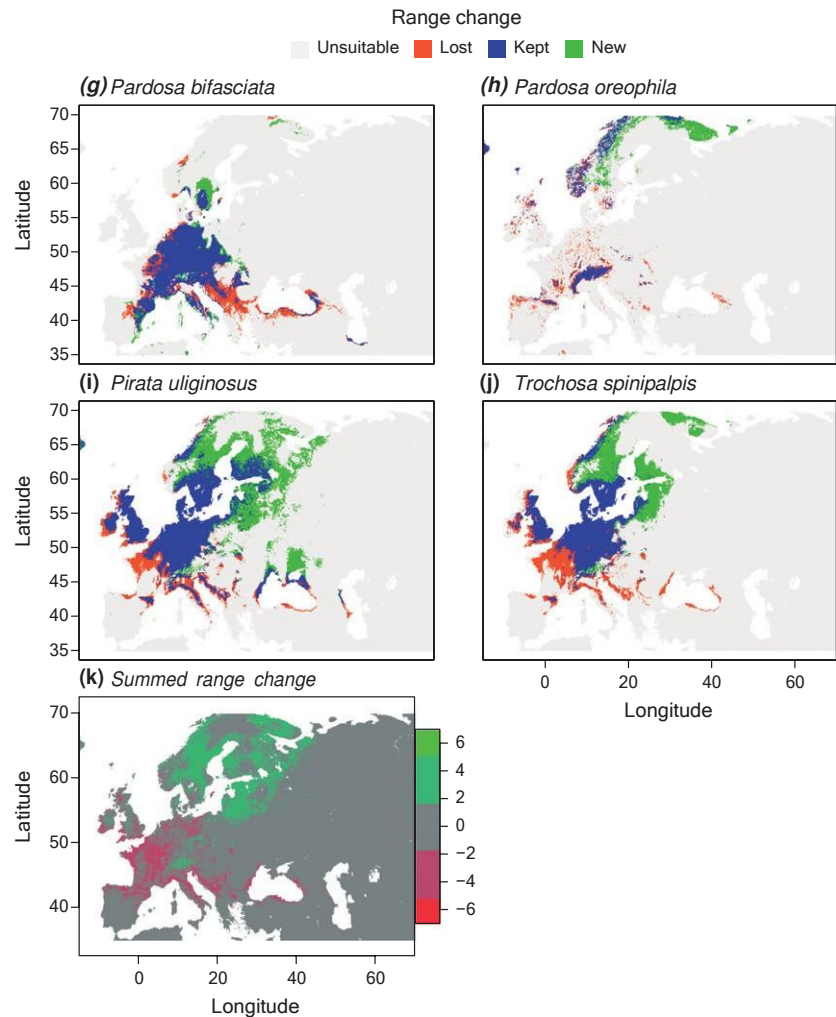**(k)** *Summed range change*

Figure 1 Continued.

spider species. This study is the first forecast of the future of multiple spider species in the face of environmental changes and provides an example for a concrete conservation programme. Our predictions showed that within a relatively short time-scale, to 2050, environmental changes are predicted to have serious impacts on the 10 species. In addition, nine of the 10 species were predicted to maintain occurrence cells in areas of high suitability in the next decades. However, our models predicted that protected occurrence cells were not necessarily located in areas with the highest environmental suitability, and two species (*A. fulvolineata* and *I. subinermis*) did not occur in protected areas. Consequently, at the Western Palearctic scale, there are opportunities to designate protection areas for these species that are likely to succeed with respect to the ongoing environmental changes. However, at the French scale, where the SCAP conservation programme is being implemented, most of these species were predicted to experience a strong impact of environmental changes by 2050. For half of the species, we could not predict with confidence that they would keep French occurrence cells in suitable environments by 2050.

These results emphasize both the need and possibility of including forecasted effects of global changes in conservation studies for taxa with limited knowledge, as increasingly advocated in the conservation literature (Heller & Zavaleta, 2009; Lawler, 2009; Araújo *et al.*, 2011; Sieck *et al.*, 2011). These results were obtained on the basis of SDMs, which have been criticized because of their inherent uncertainties, especially when applied to conservation problems (Schwartz, 2012). As a result, more complex approaches integrating various components of species vulnerability to climate change are increasingly advocated (see Dawson *et al.*, 2011 for a review). Nevertheless, such integrative approaches are still being developed on the best studied plant taxa (e.g. Kremer *et al.*, 2012), so we predict that their generalization to most invertebrate taxa is unlikely in the near future, because of the lack of appropriate resources and data (see Cardoso *et al.*, 2011). Given the pressing need to incorporate climate change into conservation strategies (Lawler, 2009), SDMs remain an appropriate tool to include climate change in conservation decisions (Guisan *et al.*, 2013), provided that appropriate methodologies are applied (Araújo *et al.*, 2011), uncertainties and methodological choices are exhaustively described
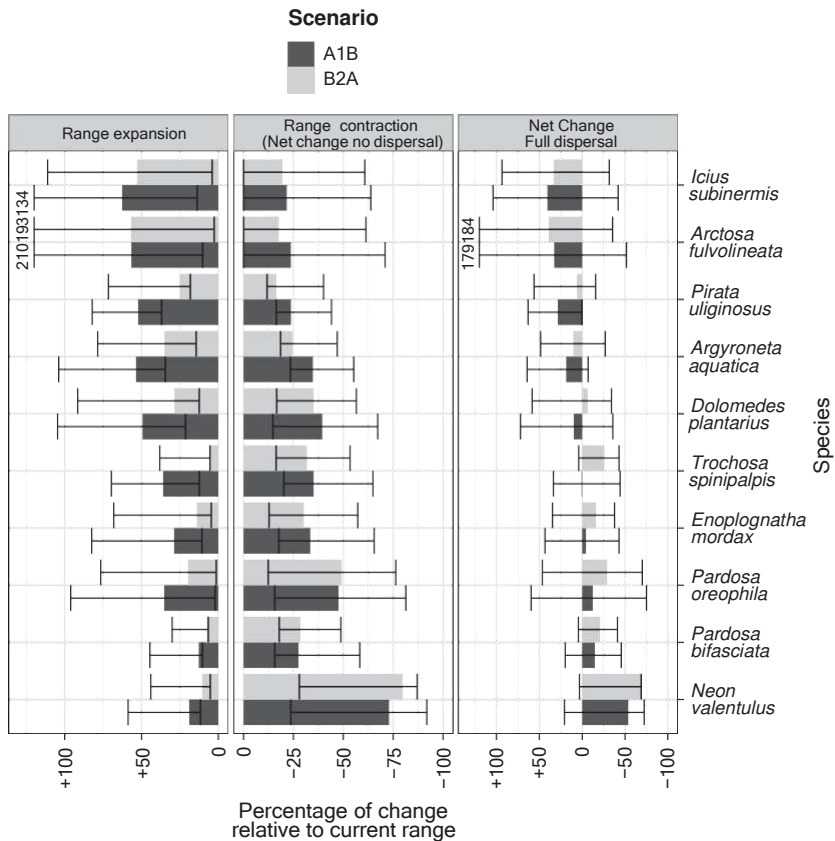
Figure 2 For each spider species, predicted percentages of changes in suitable areas by 2050 according to scenarios A1B and B2A. The error bars represent the uncertainty intervals based on 95% of the future projections for our modelling protocol (from 2.5 to 97.5 percentiles).
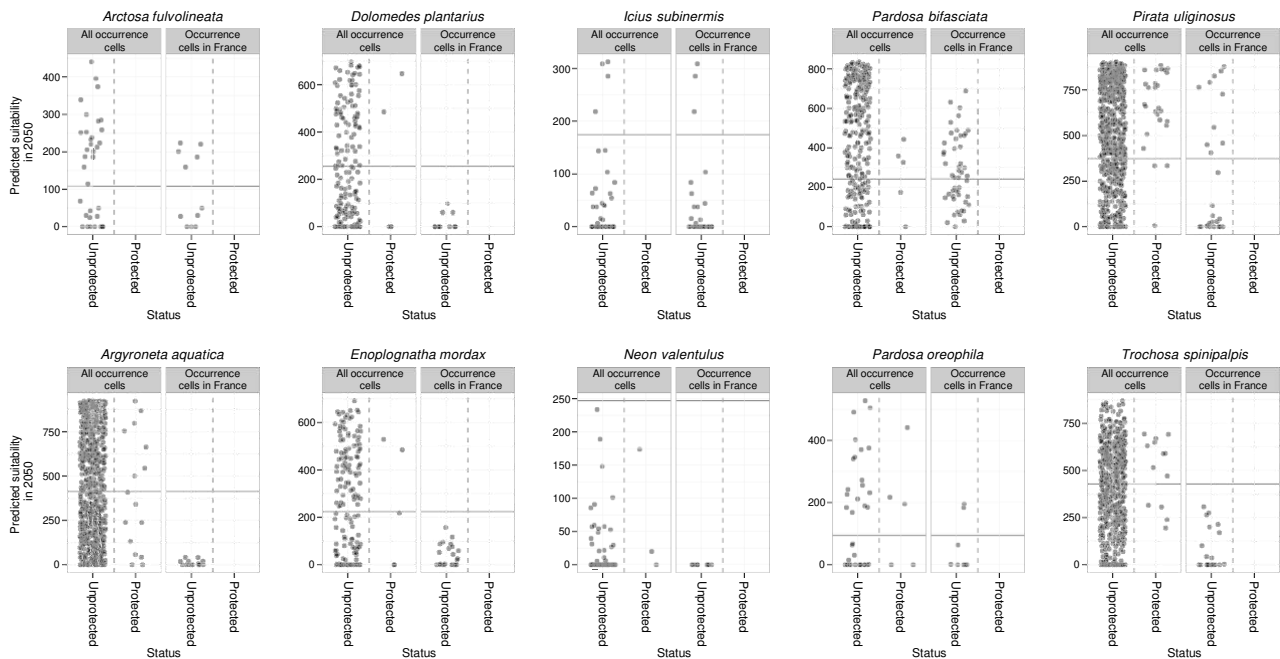

Figure 3 For each species, predicted future (2050) environmental suitability of occurrence cells (with discounted uncertainty; see Methods) at the Western Palearctic scale and at the French scale in relation to their protection status, according to scenario A1B. Each point is a 0.1 degree occurrence cell. The horizontal line represents the cut-off of suitability below which conditions are predicted to become unsuitable. Protected: occurrence cells considered protected at a threshold of 50% coverage by protected areas of IUCN categories Ia, Ib, II. Unprotected: occurrence cells in areas without protection (or below the threshold of 50% coverage), or with protection belonging to IUCN categories III, IV, V or VI (see Methods).

(Rodríguez-Castañeda et al., 2012), and the results are conservatively interpreted (Schwartz, 2012). Hence, we have chosen to discuss the uncertainties underlying our predictions first and then make conservation interpretations with respect to these uncertainties.

Taking uncertainty into account

Foremost, the adaptive response of populations to changes in environmental conditions was not predicted. In the race to track the moving optima in time and space, the responses of species are likely to be simultaneous shifts in ranges and adaptation to the new conditions (Kremer et al., 2012). Yet, the prediction of these responses is often impeded by the lack of appropriate data (e.g. Bateman et al., 2013), as is the case for our target group. Whether local populations will be able to adapt is beyond our current knowledge for spiders. Current species have already undergone changes in their distribution due to human mediated historical land use changes. They are likely to be impacted by climate and land use changes with a time-lag, as this was suggested for the spider *Argiope bruennichi* (Kumschick et al., 2011; Krehenwinkel & Tautz, 2013). Hints of genetic impoverishment in populations of the red-listed vulnerable species *D. plantarius* have been reported (Vugdelić, 2006). Such genetic impoverishments are likely to increase because of habitat fragmentation which disrupts gene flows and may therefore hinder the capacity of species to adapt, especially given that the predicted rates of environmental changes might exceed historical ones. Nevertheless, this assumption is speculative, and we highlight the pressing need for further research towards a better understanding of the capacity of spiders to cope environmental changes, for example on their capacity to persist (Arribas et al., 2012). Besides, our results showed that if species are able to disperse and track environmental changes, then the effects of environmental changes may eventually be beneficial for some of them under a full dispersal scenario. However, such a scenario is often unrealistic (Bateman et al., 2013). Some species are unlikely to disperse (e.g. *D. plantarius*; see discussion in Leroy et al., 2013), but others might be able to. For example, spiders of the genus *Pardosa* are well known for air dispersal (Richter, 1970). This dispersion mechanism, called 'ballooning', may explain the observed poleward shifts in Britannic distributions of spiders during the last 50 years (Hickling et al., 2006). Bonte et al. (2004) discovered a relationship between the propensity of spiders to disperse via ballooning and their ecological specialization (the more specialized, the less ballooning). Such a relationship could be explored in the future to assess the likelihood of spider dispersal. To this end, the specialization of spiders might be assessed with the IndVal method (Dufrene & Legendre, 1997). These improvements can be developed in the future with hybrid models coupling SDMs with spatially explicit simulations (Travis et al., 2013). In addition, such improvements may lead to better identifications of migration pathways for preservation, with potential impacts on the adaptation capacity of species, with a reduction in gene flow disruption.

Another major issue with SDMs is the uncertainty in the predicted outcomes. Biases in distribution data used for model calibration impact model outcomes. To minimize this impact, we searched extensively for all the known records of the SCAP species as advised by Sánchez-Fernández et al. (2011). Nevertheless, some countries have lower sampling intensities (see e.g. France and Poland in Figs S6.9 & 10), which may reduce the estimated suitability in these countries. Improving monitoring schemes for these species will be required to achieve better predictions. We explicitly quantified the other major sources of uncertainty, that is, the modelling techniques and the general circulation models (Buisson et al., 2010) as well as the different datasets used for calibration and evaluation. The divergence of possible outcomes confirmed the important uncertainty regarding the actual changes which may occur in the future. Nevertheless, in spite of the uncertainties, significant contractions were always predicted for eight out of the 10 species. Similarly, range expansion was almost always predicted, although with varying degrees of confidence across species. As a result, our predictions provide reliable evidence that the spider species studied will experience changes in environmental suitability because of climate and land use environmental changes, which will probably result in alterations and shifts in distribution ranges.

However, we cannot confidently quantify the actual degree of range change that will affect these species. Hence, to provide reliable estimates of environmental suitability, we penalized the estimated suitability by subtracting the standard deviation of suitability across projection maps (Kujala et al., 2013). This penalized suitability provides highly reliable future estimates of locations where environmental conditions are the most likely to remain suitable for the species. As such, it is a powerful tool to make conservation choices with respect to future environmental changes.

Implications of for the conservation of spider species

The choice of relying on suitability with discounted uncertainty therefore implies an interpretation oriented towards locations where conditions are most likely to remain suitable, rather than towards locations where conditions are likely to become unsuitable. This orientation towards suitable locations prevents any hazardous recommendations, such as ceasing conservation where it is predicted to fail (Schwartz, 2012). Rather, our results highlighted the capabilities of the existing network of protected areas to maintain suitable conditions for occurrence cells of seven of the 10 spider species throughout the Western Palearctic. Yet, there is considerable room for improvement, because for most species, only a small number of protected occurrence cells were predicted to remain highly suitable. On the other hand, a large number of unprotected occurrence cells were predicted to remain highly suitable in the future and thus offer numerous

opportunities to improve the representation of these species in protected areas (e.g. Appendix S6). Similar outcomes were obtained for other arthropod species (Iberian water beetles), using different methodologies (Sánchez-Fernández *et al.*, 2013). Protected areas are an appropriate answer to conserve species under global changes, because they preserve populations from additional threats, thereby improving their ability to adapt and disperse when facing environmental changes (Thomas *et al.*, 2012). We believe that such protection measures are the best chance for species to sustain environmental changes, even for the extreme case of *N. valentulus*, for which no occurrence cell was confidently predicted to remain suitable by 2050. In our opinion, proactive conservation actions such as improvements of the current network of protected areas are better suited than higher-cost and higher-risk actions such as translocations (Webber *et al.*, 2011).

Regarding the French conservation programme, we showed that none of the 10 species were currently protected in France, and we predicted considerable changes for all 10 species. In addition, the two species predicted to be least impacted (*A. fulvolineata* and *I. subinermis*) were not represented at all in the Western Palearctic network of protected areas. As such, all the species fulfil the criteria of the SCAP conservation programme, that is, an inadequate representation in the current network of protected areas and an expected exposure to environmental changes. Our models predicted that half of the species had at least a few occurrence cells that would remain in suitable conditions by 2050 in France and that only *N. valentulus* had and uncertain future for all of its occurrence cells. Hence, to maximize the chance of success of the SCAP conservation programme, we recommend protecting occurrence cells where their environmental suitability (with discounted uncertainty) is highest, even if they are below the suitability cut-off. In addition, it should be remembered that our predictions reflect the climatic and land use conditions at a relatively coarse resolution, while microclimatic and habitat conditions may retain suitability for populations at a local scale. Thus, protection measures should also be considered where populations appear healthiest, especially for the critical case of *N. valentulus* which requires close monitoring, given our pessimistic predictions.

Concluding remarks

Given that all of the 10 spider species studied here have been predicted to be significantly impacted by environmental changes within a short time-scale, significant modifications are to be expected in the spider fauna of the Western Palearctic. Incidentally, the choice of species in the SCAP conservation programme was biased: only a few spider families were represented, most of the species are ground-dwelling species, occur in moist habitats and are widespread throughout the Western Palearctic. In addition, the uncertainties raised here compel us to emphasize the pressing need to improve our knowledge on understudied taxa such as spiders. Hence, we advocate the necessity of increasing

monitoring schemes, experiments and forecasts of environmental change effects on a larger and more diversified range of species than is currently the case in the literature. At present, our ability to forecast the future of spider biodiversity, as well as many other invertebrate taxa, is impeded by the lack of studies such as this (Bellard *et al.*, 2012).

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