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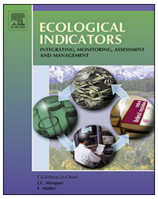

Original Articles

A generic method to assess species exploratory potential under climate change

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ABSTRACT

Climate, by altering the spatio-temporal distributions of suitable habitats, leads to modifications in a multitude of species ranges. In recent years, the ability of species to adjust to changing climatic conditions is of growing concern. In the present study, a generic trait-based method to assess species exploratory potential under climate change is proposed. "Exploratory potential" is here defined as the capacity of species to initiate the act of leaving their current habitats and to reach new ones outside of their range, at a rate fast enough to keep pace with climate change. The presented method is based on the calculation of the Exploratory Potential Index (EPI), a metric that combines several life-history traits into a single numeric value. Both coefficients and variables of this composite metric are flexible. They depend on the set of species under consideration through a two-step participatory expert-based procedure. A panel of experts on the species' biology, ecology and conservation is first to be constituted. Then, experts are separately consulted to validate the variables to be integrated in the composite EPI index and are asked to rank the importance of these variables relative to each other following an Analytic Hierarchy Process. Coefficients in the EPI index and scores are given a credibility distribution using a Bayesian inference model. Anadromous species are chosen as a first application case. Scripts and raw survey data are made available to readers to ease applications to other species groups.

1. Introduction

Evidence that species are shifting their latitudinal distributions, elevation ranges, phenologies (Parmesan, 2006; Poloczanska et al., 2013), and body sizes (Daufresne et al., 2009; Gardner et al., 2011) in response to recent climate change is accumulating rapidly. However, given the rapid rate at which climate is changing, the ability to move in response to environmental change does not necessarily mean that all

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taxa will track those changes appropriately to survive (e.g. Bertrand et al., 2011; Comte and Grenouillet, 2013).

The exploration of the environment by individuals through any movement phenomena is a central process for biodiversity to adapt to environmental variability and change (Jeltsch et al., 2013), but remains generally poorly known due to methodological and technological challenges related to tagging and tracking, creating data-poor situations (i.e. few quantitative estimates of dispersal (Bradbury et al., 2008)) and often leads to strong assumptions in range shift modeling (e.g. Bateman et al., 2013; Hellmann et al., 2016). As such, bringing valuable and substantial insight on the exploration of new and alternative territories by a large set of species at a time is a core challenge in the anticipation of biodiversity distributional response to climate change (Travis et al., 2013). This challenging task could be envisaged through trait-based approaches. Indeed, various studies have demonstrated that species' traits can be good predictors of response to climate change with methods relatively rapid to implement (Angert et al., 2011; Chessman, 2013; Jiguet et al., 2007; Pearson et al., 2014; Perry et al., 2005; Sunday et al., 2015). However, linking the exploratory potential to biological traits for a given set of species requires conceptual and methodological developments that are addressed in the present paper. We make this effort more tractable by working initially on: (i) species that travel long distances to complete their life cycle, are characterized by populations with multiple migratory strategies and thus are more likely to respond to climate change by modifying their distribution range within a rather short time frame; and (ii) species for which comprehensive information on species traits can be easily found in open-access biodiversity databases.

Anadromous fishes, i.e. species that reproduce in continental watersheds and mature in marine waters (McDowall, 1988), appear particularly suitable to formalize the influence of traits in predicting the ability of species to move towards the poles in response to climate change. During past glaciations, they retracted to southern refugia and then, as the ice sheets retreated, reinvaded the river systems (McDowall, 1988). The contemporary success of anadromous species in reaching a new location and establishing a population has been recently demonstrated with various examples (e.g. Hasselman et al., 2012; Labonne et al., 2013). In addition, their breeding migration is often characterized by high site fidelity, with most adults returning to the river of their birth (i.e. natal homing) and a few individuals straying to other spawning areas (Cury, 1994; McDowall, 2001). In some cases, this homing rate has been precisely estimated (Walther et al., 2008) and appears variable among species, an interesting feature when investigating links that exist between life history traits and distribution changes. More broadly, anadromy and homing/straying are two behavioral life-history traits for which our understanding benefits from decades of worldwide studies (Keefer and Caudill, 2014; Roule, 1914). Moreover, multi-species trait-based approaches have unequivocally identified diadromous fish as high conservation concern (Branco et al., 2008) and high vulnerability to climate change (Hare et al., 2016). But beyond that, focusing on diadromous fish is relevant given their low number of representatives (Eschmeyer and Fong, 2016), their poor conservation status (Limburg and Waldman, 2009) and their enormous economic value (e.g. Amin et al., 2004; Kobayashi et al., 2015).

The aim of this method paper is to develop a generic, trait-based metric to score species by their exploratory potential. To increase reliability, the proposed metric combined several ecologically meaningful variables (life-history traits hereafter) into an overall species score to represent the consensus emerging from specialists. To increase applicability, the proposed metric had to be adjustable to be used on a wide range of taxa following a standardized and fully detailed protocol. A first numerical application of the method and the metric was made on North Atlantic Ocean anadromous fishes, identified as relevant biological models.

2. Material and methods

The exploratory potential index (EPI) that we developed in the present work relied on a conceptual framework and an expert-based participatory procedure adapted from analytical hierarchy process (AHP) theory (Saaty, 1987; Saaty, 2008). The approach can be summarized in four main phases: (i) problem modeling/conceptualization (Section 2.2); (ii) elicitation of experts' opinions (Section 2.3); (iii) 'translation' of these expert opinions into weights (Section 2.4); and (iv) calculation of the final EPI index for each species of interest, based on weights, and data on life-history traits (Section 2.5).

2.1. Exploratory potential definition and limits

Within the diversity of range shift patterns that were described in the scientific literature, half of them involved expanding leading edges (Maggini et al., 2011), driving species towards the poles (Parmesan, 2006). As such, we focused on species life-history traits that enhance the intrinsic capacity of populations to send individuals outside of the current species distribution range. The selection of life-history traits is thus confined to the departure and transfers during the dispersal process (Clobert et al., 2012), as the subsequent establishment phase is characterized by extrinsic parameters such as habitat connectivity and suitability. Complex mechanisms such as adaptive evolution and phenotypic plasticity, by which species can track changing environments and also increase their exploratory potential, are not considered at this stage (Fig. 1).

2.2. The 'problem' modeling/conceptualization phase

The originality of the AHP method consists in decomposing a complex issue into a hierarchy of more easily comprehensible subproblems, with the possibility to analyze them independently. The present 'problem' was structured into three fixed levels (Fig. 1). Level I is the goal itself that is comparing the exploratory potential of different species. Level II corresponds to the decomposition of the core problem into ecological mechanisms applicable to a large range of taxa. Three mechanisms (i.e. level II in Fig. 1) were predefined by the project leaders (i.e. persons who initiated the process for a given species group) based on major syntheses on dispersal and climate change biology (e.g. Clobert et al., 2012; Lenoir and Svenning, 2013; Pearson, 2006): (i) the ability for populations at the leading edge to initiate the act of leaving their current habitats (departure); (ii) the ability to 'physically' reach new suitable habitats (transfer), and (iii) the ability to match this range shifting response with climate change velocity (turnover rate). Level III is constituted of life-history traits which depend in numbers and nature upon case studies (i.e. the species group under interest) and data availability (Fig. 1).

2.3. Eliciting experts' opinions

Formal elicitation methods have increasingly been developed and applied to incorporating expert knowledge in ecology (Fletcher, 2005; Kuhnert et al., 2010; Martin et al., 2012; McBride et al., 2012; Roy et al., 2014; Uusitalo et al., 2005).

A preliminary list of species and a geographic area should be set by project leaders. In accordance with these elements, a panel of experts must be then constituted. The questions that experts will be asked to answer will reflect, to some point, their in-depth knowledge of the species biology and ecology, and their understanding of climate change impacts (Fazey et al., 2006). As such, one of the main criteria for panel constitution is that experts come from various institutions and countries covering, among other things, a large part of the investigated species ranges.

The interview was structured into four successive tasks (see form in Appendix A). The first task was to learn about the definition and limits