

# Scientific Report

as part of the application for the position “Junior Research Scientist in ecology - Vulnerability and resilience of ecosystem services in Mediterranean context” (Profile number: CR-2024-ECODIV-2)

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## Summary

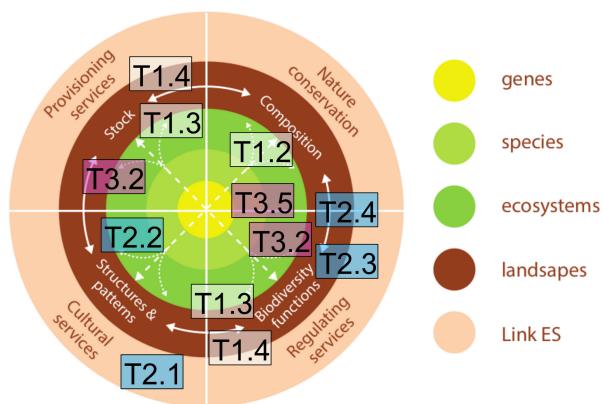
My previous and current research can be divided into three broad themes (T), discussed in detail in the sections below. Taken together, these themes aim at understanding of how ecosystems and their functions and services emerge from local processes and how anthropogenic disturbances have impacted them, providing also novel tools and ideas for theoretical and practical applications. As a general overview, these themes are:

- T1 - To understand **how biotic and abiotic factors influence species' distribution and community structure, and how these upscale to ecosystem functions and services**. This, in order to advance our fundamental understanding of how community are organised and ecosystems function, which provide societies of their services.
- T2 - To investigate **how biodiversity and humans interact and how ecosystems have been impacted by anthropogenic global changes**. This, in order to identify potential solutions to promote human-wildlife coexistence and reduce the negative effects that human societies have on ecosystems.
- T3 - To conceptualise and formalise basic ecological theory and develop novel methodologies and software for ecological research. This, in order to **advance ecological theory and to improve how we model ecological processes, needed for testing hypotheses** about ecosystems.

These themes strongly align with the planned research and overlap with the interests of the RECOVER research unit and of the EMR team. In particular:

- T1 - Ecosystem services emerge from ecological processes that shape species composition and community assembly and how these upscale to the ecosystem and landscape level (Burkhard & Maes, 2017). Therefore, **T1 is necessary for a deeper understanding of how ecosystems provide their services and how to quantify and map their indicators**. My previous experience with how environmental, biotic, and climatic factors influence species' suitability, community assembly, ecosystem functions, and the delivery of ecosystem services aligns with the planned research and the goals of the EMR team.
- T2 - Ecosystem services are essential for societies, but societies often have negative impacts on ecosystems and we urgently need a sustainable solution for coexistence. **T2 is needed to understand how human societies have affected ecosystems and their services and for proposing sustainable solutions for coexistence**. My experience in assessing the impacts of anthropogenic disturbances on ecosystems and with including societal aspects in socio-ecological theory and modelling aligns with the planned research and the objectives of the EMR team and, more generally, of the RECOVER unit and INRAE.
- T3 - Ecosystem services are emerging properties of complex ecosystems. Therefore, **T3 is required to develop the technical apparatus for modelling ecological processes and services**. My experience in mathematical and statistical modelling and software development will allow a steady and proficient progress in the development of the theory and models for quantifying and mapping ecosystem services.

An overview of how the themes and projects fit into ecosystem services assessments is illustrated in Fig. 1 and Table 2. This scientific report consists of 10 pages of text plus 16 figures, 2 tables, and 3 pages for references. To make it easier to follow the report, I organised the figures within the body of the text. For the personal pronouns, I adopted the following convention: I used "I" when I was the person in charge of the task or I was the leading author of the study. I used "we" when my role in the study was a supporting one; for these cases, I specified my contribution.



**Figure 1: Relevance of the themes and projects for assessing ecosystem services.**

Only the most relevant projects are shown, with colours referring to their overall theme: T1 (From community assembly to ecosystem functions and services) is shown in white, T2 (Anthropogenic disturbances, people's perception, and restoration opportunities) in blue, and T3 (Theory and models for ecology and biodiversity conservation) in pink. Adapted from (Burkhard & Maes, 2017).

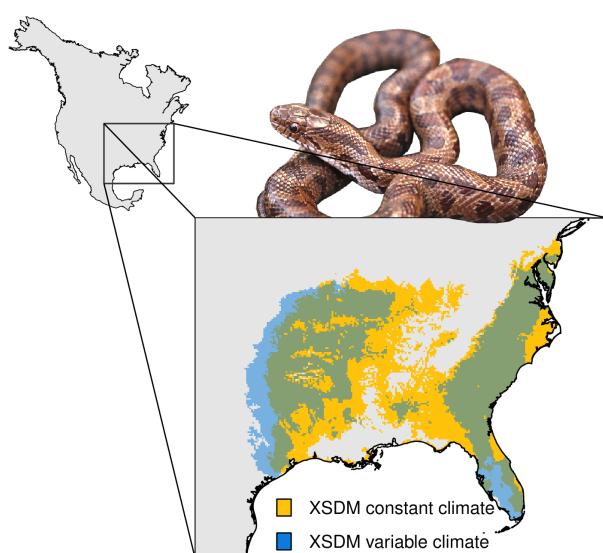
## T1 – From community assembly to ecosystem functions and services

Ecosystem services emerge from local ecological processes that upscale to generate and regulate ecosystem functions at the landscape level. Therefore, to assess ecosystem services and understand how they are influenced by environmental and biotic processes, we need to investigate what shapes local community processes and how these generate ecosystem functions. Yet, we have only a limited understanding of how communities are organised and of their impacts on ecosystem functions and services. To fill these gaps, my previous research investigated the drivers shaping species distribution and community organization, their effects on ecosystem functioning, and quantified indicators for assessing ecosystem services. T1 is divided into five projects. The first four show a progression from understanding how climate variability affects species suitability (T1.1), the role of environmental and biotic factors in determining community assembly (T1.2), how this affects ecosystem processes and functions, such as primary productivity (T1.3), and how we can use these to quantify and map ecosystem services (T1.4). The last project focuses on animal movement strategies in real landscapes, providing an initial concept for integrating animal movement in ecosystem services assessments.

### T1.1 – Climate variability impacts the suitability and distribution of species

Species suitability to climatic conditions is usually evaluated based on long-term climatological normals, i.e. climatic values averaged over multiple decades (e.g. 1970–2000). However, this ignores inter-annual climate variability, i.e. climate fluctuations that occur across the years, which we know is important for determining the long-term viability of populations (Caswell & Caswell, 2006). This likely generates biases in the predicted distributional ranges of species. Importantly, as global change will

also affect climate variability in addition to its average values, we need to incorporate inter-annual climatic fluctuations when predicting species' ranges and their change.

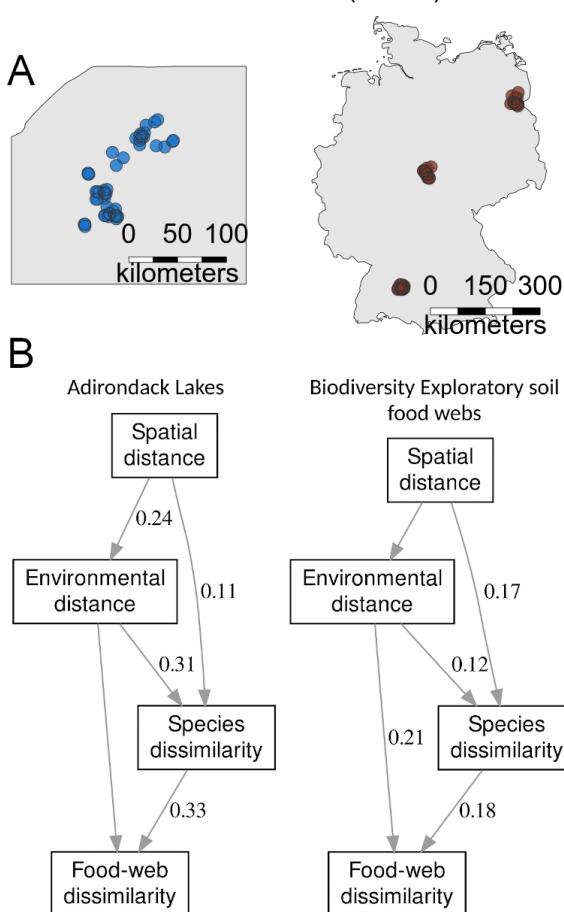


**Figure 2: Potential distribution of the yellow-bellied kingsnake (*Lampropeltis calligaster*) using the XSDM framework.** Blue shade shows the potential distribution when accounting for climate and its inter-annual variability and yellow shade shows the potential distribution assuming constant climate. The two distributions differ markedly. Notably, the distribution accounting for climate variability (blue) can explain observed patterns of genetic divergence among *L. calligaster* populations.

In this ongoing project, in collaboration with Prof. Daniel Reuman at Kansas University (KS, USA), I expand the concept of the fundamental niche of species to account for inter-annual climatic variability and develop a novel SDM framework (XSDM) that can account for it. This is achieved by integrating the two fields of species distribution models and stochastic demography (see also T3.5). This allows, using a Bayesian framework, to estimate the fundamental niche and distributional range of species while accounting for climate variability. Analyses so far showed promising results for XSDM. I applied this framework to the yellow-bellied kingsnake (*Lampropeltis calligaster*) and found that **inter-annual climate variability strongly affects its distributional range, explaining the genetic divergence among its populations** (Fig. 2).

#### T1.2 – Community assembly is determined by abiotic drivers and limiting similarity

Community assembly, i.e. how species organise themselves to form a community, has been extensively studied, yet it still remains unsolved. In particular, there is a long-standing debate on the relative importance of abiotic factors, e.g. environmental conditions, and biotic interactions in shaping community assembly (Chase & Myers, 2011). Niche theory predicts that biotic interactions are fundamental in determining community assembly and that species that are too similar should not coexist. This is the *limiting similarity* principle first proposed by MacArthur (MacArthur & Levins, 1967). Testing this theory, however, is a challenging task and often hindered by practical limitations. To shed light into community assembly, I assessed the relative importance of abiotic and biotic factors in determining the community composition and emerging food web properties of two ecosystems (Fig. 3A), the Adirondack lakes in USA and the forest soil communities in Germany (Bauer et al., 2022). In particular, I investigated if the community composition in local patches for the lake food webs ( $n = 50$ ) and the forest soil food webs ( $n = 48$ ) was determined by the limiting similarity principle and, thus, by biotic interactions.



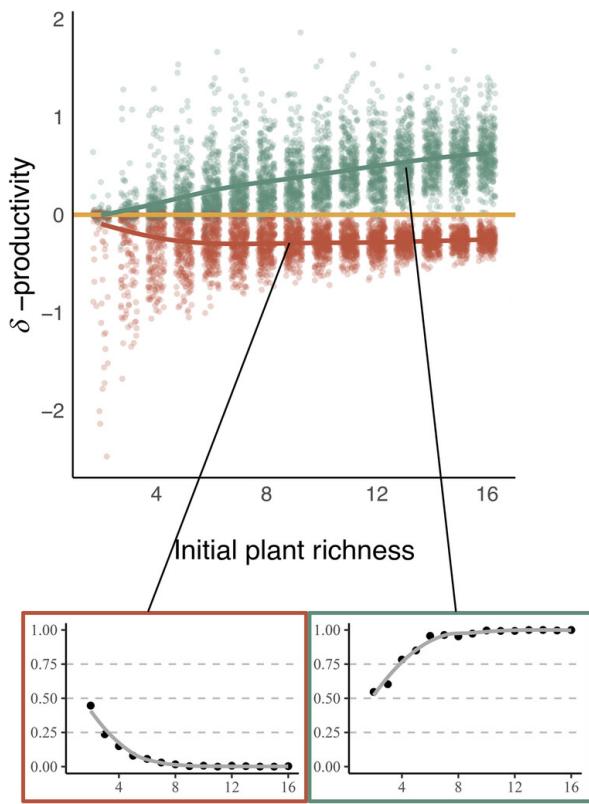
Additionally, I quantified the influence of spatial distance, environmental distance, and community dissimilarity on food web properties. I found that for both ecosystems **biotic filtering played a major role in shaping community composition and that this influenced the structural properties of the food webs** (Fig. 3B). This suggests that community composition is structured by competition among species with similar traits or functional roles. In addition, environmental filters and spatial processes of species distribution affected the communities and food web properties in both ecosystems.

**Figure 3: Limiting similarity determines community assembly and food web properties in two ecosystem types.** A) The communities studied for the two ecosystems, the Adirondack Lakes (blue) and forest soil food webs (Biodiversity Exploratory soil food webs; brown). B) Results from the structural equation modelling, showing that abiotic and biotic filters shape community composition and food web structure. Adapted from (Bauer et al., 2022).

### T1.3 – Limiting similarity enhances biodiversity-ecosystem functioning (BEF)

It is well known that biodiversity has a positive effect on the delivery and resilience of ecosystem functions. For instance, primary productivity increases with species richness (Hooper et al., 2005), suggesting potential facilitation effects among plant species. However, how community assembly, especially niche complementarity among plants, affects BEF relationships was not well understood. In (Amyntas et al., 2023), we built on (Bauer et al., 2022) and complemented it with a theoretical model of trophic interactions (Gauzens et al., 2023) in order to understand how community assembly influences BEF relationships. In particular, we investigated if selection of species that have complementary trophic niches during community assembly affects the primary productivity of the ecosystem.

We found that **BEF relationships became stronger when plants had more complementary niches, i.e. communities that assemble according to limiting similarity were more productive** (Fig. 4). My contribution in this study was to advice on theory and methodology of community assembly and species' biomass dynamics and how to upscale these to calculate primary productivity at the ecosystem scale. I also contributed R code for the simulations.



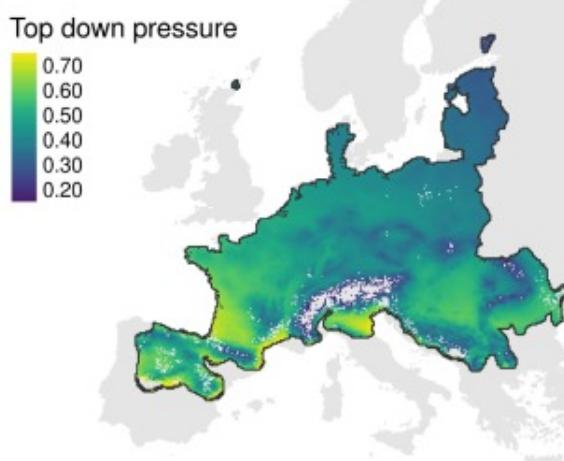
**Figure 4: Community assembly influences the relationship between plant richness and primary productivity.** The difference ( $\delta$ ) in primary productivity when plant complementarity increases through niche packing (red points) or divergent adaptation (green points) relative to the control (yellow line). The red and green insets show the proportion of positive changes for each scenario. Primary productivity is higher in communities shaped by limiting similarity, which reduces niche overlap and increases functional diversity of species, strengthening the BEF relationship. Adapted from (Amyntas et al., 2023).

### T1.4 – From food webs to ecosystem functions: mapping ecosystem services

There is still a lack of consensus on how to quantify and map some of the proposed ecosystem services and their indicators (Burkhard & Maes, 2017), preventing us from assessing and mapping their delivery. In (Antunes et al., 2024), by taking a food web perspective, we tackled this problem and showed how to quantify ecosystem functions that rely on energy fluxes between species and mapped the ecosystem services that depend on such functions. We proposed a **conceptual and practical framework that can be used to map several ecosystem services that rely on energy fluxes and on biomass production**. A summary of the proposed ecosystem services that this approach can quantify is provided in Table 1. My contribution was to develop the conceptual and analytical framework and programmatic pipeline to synthesise databases of abundance, distribution, trophic interactions, and climate in order to predict energy fluxes and quantify the regulating ecosystem service “pest control” of the studied species *Microtus arvalis* in Europe (Fig. 5). I also contributed in defining the links between energy fluxes and ecosystem services (Table 1).

The focus of T1.4 was on animal communities across Europe, but it can be tailored to Mediterranean ecosystems, including plants. The workflow is easily scalable to other spatial and temporal scales and can account for climate, e.g. how temperature influences primary productivity, and anthropogenic disturbances, e.g. how human land-use impacts species' distribution. Therefore, **this framework can be applied to quantify the current delivery of ecosystem services and how these will be affected by climate change and socio-ecological transformations.** For example, it

could be applied to forecast the capability of Mediterranean ecosystems to deliver ecosystem services for increasing temperatures and altered precipitation patterns.



**Figure 5: Pest control of the common vole (*Microtus arvalis*) in Europe.** Top-down pressure represents the sum of energy fluxes between *M. arvalis* and its predators and is an indicator for pest control. The lighter the colour, the greater the top-down pressure. This example shows how the framework from (Antunes et al., 2024) can be applied to quantify ecosystem services that depend on flux of energy and nutrients.

**Table 1: Ecosystem services that can be quantified using the workflow described in T1.4**

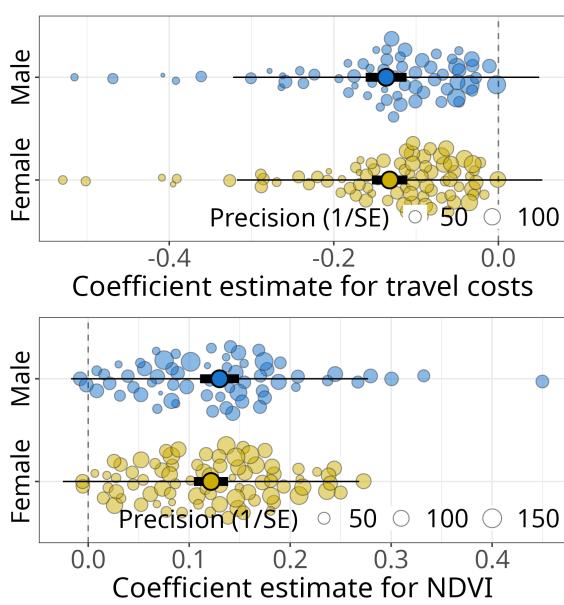
Ecosystem service	Ecosystem function	Indicator
Regulation of population dynamics	pollination and seed dispersal	fluxes between plant and pollinator
Climate regulation	carbon sequestration	fluxes to primary producers
Nutrient regulation	soil formation, decomposition, regulation of forest succession	non-assimilated fluxes to decomposers
Wood production		
Control of erosion risk	primary production	fluxes to primary producers
Food and feed		
Food and feed	livestock production	fluxes to livestock species
Regulation of pests species	regulation of population dynamics	fluxes between pest and its consumers

Adapted from (Antunes et al., 2024).

#### T1.5 – Energy landscapes determine animal movement strategies

During my PostDoc period, I have investigated the influence of energy costs of travelling on animal behaviour, particularly how terrestrial animals' strategies are shaped by energy landscapes, i.e. the energy costs of moving mapped to a geographic area (Shepard et al., 2013). Despite the recognition that energy landscapes should play a crucial role for animal movement, its application in movement ecology have been limited due to the lack of a scalable framework. To fill this gap, I developed a framework and R package that integrates a locomotory model for terrestrial animals (Pontzer, 2016) with GIS tools to quantify energy landscapes (Berti et al., 2022) (see also T3.1). This allows theory and concepts of energy landscapes to be applied to terrestrial mammals, scaling its application to a

broader taxonomic range and spatial and temporal scales. I applied this framework to an extensive dataset of 155 GPS collared elephants in Northern Kenya and showed that individuals **optimise their movement strategies by minimising the energy costs of moving** (Berti et al., 2023; Fig. 6). I also found that NDVI, a proxy for primary productivity obtained through remote sensing, affects landscape use of elephants, which tend to favour, as expected, highly-productive habitats.



This study, in collaboration with Prof. Fritz Vollrath at Oxford University (UK), has important implications for conservation, especially for corridor and protected area planning, as energy costs can be used to map species-specific landscape connectivity (see also T2.4).

**Figure 6: Habitat preferences for 155 elephants in Northern Kenya.** Circles show the coefficient estimates of the preference model, with colours indicating the sex of individuals and size proportional to uncertainty in the estimates. Elephants tend to avoid areas with high cost of travel and prefer habitats with high primary productivity, highlighting that animals choose movement strategies to optimise their energetic trade-offs. Adapted from (Berti et al., 2023).

### **Relevance of T1 for the planned research and synergies with the working groups**

T1 establishes a basis for a deeper understanding of the fundamental processes that generate ecosystem services, namely how to link species-level processes, e.g. environmental suitability, to community structure and functioning. Specifically, T1 shows that communities with species having complementary functional niches, as observed empirically, have higher primary productivity, indicating that functional diversity promotes several provisioning and regulating ecosystem services. Moreover, T1 establishes a clear link between species suitability and climate variability, which is needed to better understand and predict the impacts of future global changes. Therefore, T1 is highly relevant for the planned research and constitutes a core of conceptual and practical knowledge that can be used to:

1. **Develop concepts, theory, and methodologies** to quantify how species- and community-level processes upscale to ecosystem functions and the delivery of ecosystem services.
2. Progress **from expert based opinions to indicators of ecosystem services that rely on testable models**. In particular, to identify, quantify, and map selected ecosystem services related to fluxes of energy and matter.
3. Set up a scalable and reproducible pipeline to **map and monitor ecosystem services**.
4. Understand and predict the **impacts of global changes** on ecosystem services.
5. Add a temporal component in ecosystem services assessments, e.g. by expanding the workflow of T1.4 to accommodate for climate variability. This will allow us to understand **how ecosystem services change throughout the year and on longer time scales**. Specifically, T1.1 is based on integrating climate time series with a Bayesian framework for inferring species distribution. Although different in scope, this has several methodological and conceptual similarities with temporally-explicit modelling of ecosystem services.
6. Include **animal movement for assessing the delivery of ecosystem services** that depend on biotic connectivity and the functions it supports, such as nutrient and seed dispersal. This can be relevant for later stages of the planned research, e.g. once several ecosystem services have been assessed and mapped and the workflow is mature and stable.

## T2 – Anthropogenic disturbances, people's perception, and restoration opportunities

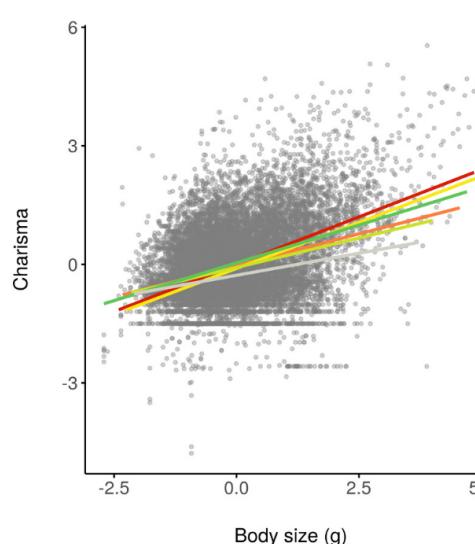
In addition to advancing theory and understanding of community processes and how these upscales to ecosystem functions and services, my research is also focused on understanding how people perceive biodiversity and have impacted ecosystems, their functions, and the delivery of their services. This has tremendous importance in today's world, because only by understanding what has been lost can we set objective baselines for restoration (Papworth et al., 2009). Moreover, to protect and restore ecosystems effectively and sustainably, we need to take into account the role human societies play in them. During my PhD under the supervision of Prof. Jens-Christian Svenning at Aarhus University (Denmark), I was exposed to novel ideas on how this can be achieved, e.g. by restoring ecosystems to a feasible natural state and minimising subsequent human interventions (Svenning et al., 2016). To accomplish this or any other sort of sustainable nature conservation plan, we need to understand how societies and biodiversity interact, which influences conservation and management outcomes. To expand our understanding of socio-ecological systems, **my previous research focused on how people perceive biodiversity and the impacts that societies have had on large scale biodiversity patterns**. This is crucial to improve our understanding of how societies react to potential biodiversity changes and to propose solutions to mitigate the risks of biodiversity losses and decline of ecosystem services associated with such socio-ecological transformations.

T2 is divided into five projects that focus on understanding the biases of people's opinion towards wildlife, accounting for it in socio-ecological assessments, and quantifying the impacts that human activities have had on ecosystems. Specifically, these projects aim at: Assessing biases of people's perception towards biodiversity (T2.1). Integrating such biases into habitat suitability models to identify opportunities for sustainable coexistence (T2.2). Quantifying the losses of biotic connectivity due to human-driven species' extinctions (T2.3). Assessing the effectiveness of designated connectivity corridors in relation to human activities, which interfere with optimal dispersal strategies of species (T2.4). And quantifying the global patterns and drivers of lead concentration in inland waters (T2.5).

### T2.1 – People's interest is biased towards large animals

Any visit at a zoo will suggest that some animals attract more attention than others. Species that are more charismatic, i.e. more popular among people, attract more visitors. This is not limited to zoos, but affects all interactions between animals and people and determines how much we are willing to invest in seeing, studying, and protecting them. In turn, this has important repercussions for biodiversity conservation, as more funds are allocated towards charismatic species, irrespective of conservation priorities (Colléony et al., 2017; Martín-López et al., 2007). Previous studies quantified animal charisma by means of complex statistical models (Macdonald et al., 2015), which were however specific for few mammals and that could not be used for broader assessments. I hypothesised that a simple relationship existed between animal charisma and their body size, e.g. due to their sublime aesthetic (*impressing the mind with a sense of grandeur or power; inspiring awe, veneration, etc.*). I synthesised nine studies that assessed people's perception of animals in one large database that I used to test this hypothesis (Berti et al., 2020).

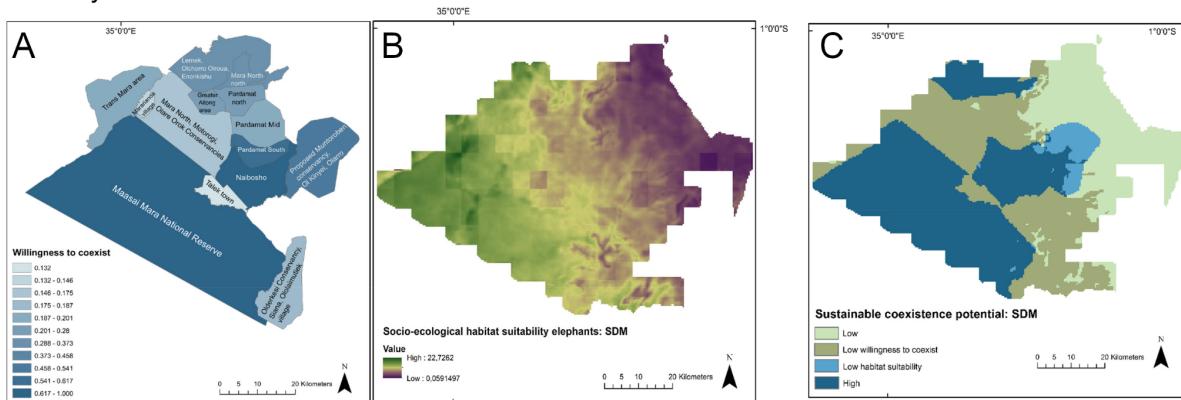
I found that not only large animals are more charismatic, but that **there is a linear relationship between animals' body size and their perceived charisma** (Fig. 7). This relationship has good explanatory power ( $R^2=0.69$ ) and holds for mammals, birds, reptiles, and amphibians and can be used to quantify the charisma of species. This is important not only for conservation, but also for basic research, as scientists are also biased towards large, charismatic megafauna, as confirmed by a later analysis (Tam et al., 2022). Animal charisma determines how much people, including scientists, are willing to put effort and allocate money for their conservation. Notably, my findings also highlight that species that should be prioritised by conservation efforts are not necessarily more charismatic, highlighting a mismatch between where conservation funds are potentially being allocated and where they would be more useful to protect biodiversity.



**Figure 7: Relationship between animal charisma and body size.** Data was obtained from nine datasets for amphibians, birds, mammals, and reptiles. Circles show species data points, with charisma being normalised relatively to each dataset. Lines show the relationship between charisma and body size, with colours indicating the IUCN threat category.

## T2.2 – Identifying sustainable coexistence potential for megafauna in Kenya

Understanding how people perceive biodiversity and how much they are willing to tolerate it is crucial for planning and managing sustainable conservation and restoration projects. However, one major limitation of such assessments is that they often lack a societal component, specifically how tolerance towards wildlife affects biodiversity conservation (Frank, 2016). In (Vogel et al., 2023), we developed a holistic approach that integrates people's willingness to coexist with ecological factors. **We assessed the socio-ecological coexistence potential for elephants (*Loxodonta africana*) and black rhinoceros (*Diceros bicornis*) in Kenya.** In particular, we show that perceived threats to human life and activities determine the willingness to coexist in human-wildlife ecosystems (Fig. 8). Importantly, this highlights the importance of using a holistic perspective in order to identify areas where targeted conservation actions can improve a sustainable coexistence between people and wildlife. In this project, I advised and performed preliminary analyses on how to integrate the willingness to coexist metric, obtained from field surveys of people's opinions, with ecological suitability models.

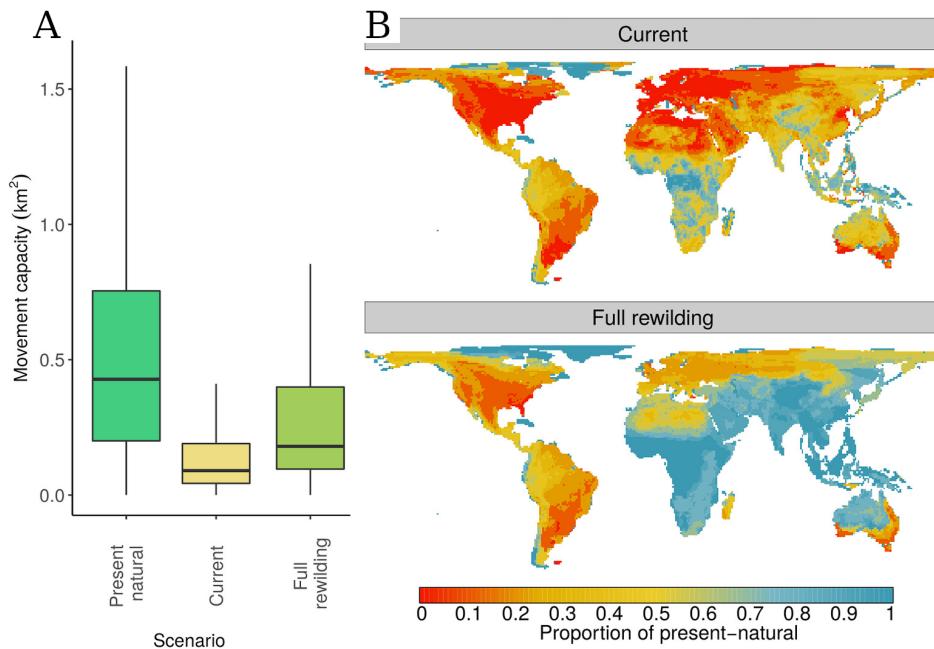


**Figure 8: People's tolerance determines the potential for sustainable coexistence between societies and megafauna in Kenya.** **A)** Willingness to coexist measure, quantified using field surveys of people's opinions. Darker shades of blue show higher tolerance of people towards wildlife. **B)** Socio-ecological potential habitat suitability for elephants. Violet shows areas with low suitability and green areas with high suitability. **C)** Potential for sustainable coexistence between human societies and elephants in Kenya, obtained integrating A and B. Green shades show low coexistence potential and blue shades high coexistence potential. Adapted from (Vogel et al., 2023).

### T2.3 – Declines of biotic connectivity due to human-driven extinctions

Today's biodiversity decline has been compared in magnitude to previous mass extinction events (Dirzo et al., 2014). This extinction event started several millennia ago, following the spread of modern humans worldwide and has particularly affected megafauna (Lemoine et al., 2023; Martin & Klein, 1989). This caused substantial changes in the composition and functional structure of communities. When I started my PhD, however, it was not clear how this affected biotic connectivity, which is essential for ecosystem functioning and stability, including ecological functions that promote several ecosystem services necessary for societies (Brudvig et al., 2009; Gravel et al., 2016; Lundberg & Moberg, 2003). Because large animals use disproportionately more area to fulfil their energy demands (Jetz, 2004), I hypothesised that megafauna extinctions have severely reduced biotic connectivity worldwide. I tested this hypothesis by integrating a scaling model for animal home range (Kelt & Van Vuren, 2015) with a GIS approach to quantify how much connectivity has been lost due to human-driven extinctions. In addition, I assessed how much of the potential declines could be restored by means of species reintroduction into their native ranges.

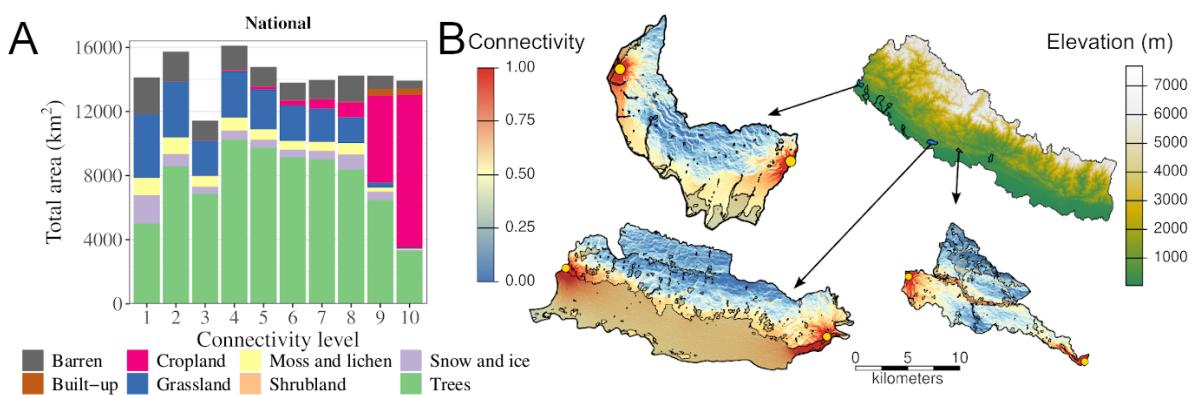
I found that **74% of biotic connectivity has potentially been lost worldwide due to human-driven species' extinctions and extirpations** (Berti & Svenning, 2020; Fig. 9A). These declines were particularly severe in Europe and the Americas (Fig. 9B), consistent with where megafauna extinctions have been more severe. Importantly, biotic connectivity can be partly restored to twice its current value if species would be allowed to reoccupy their native ranges. This is important for ecosystem functioning and resilience, as many ecological processes, such as nutrient and energy dispersal, depend on biotic connectivity. More broadly, these results highlight that **ecosystem functions and services depending on biotic connectivity are today drastically downgraded** and that, even if these losses can be partly reverted, it will require great and sustained efforts to achieve partial restoration.



**Figure 9: Declines of biotic connectivity caused by human-driven extinctions and restoration opportunities.** A) Global movement capacity, a proxy for biotic connectivity, under three scenarios: present-natural (assuming anthropogenic extinctions and extirpations did not occurred); current; and full rewinding, showing the maximum connectivity that can be restored if all existing animals are allowed to occupy their native ranges. B) Geographic distribution of the loss of biotic connectivity. Colours show the proportion of connectivity that we would have today without anthropogenic disturbances (present-natural) compared to what we have today (current) and to what can be restored (full rewinding scenario). Red indicates low, yellow intermediate, and blue high connectivity.

#### T2.4 – Dispersal corridors for tigers in Nepal: how effective are they?

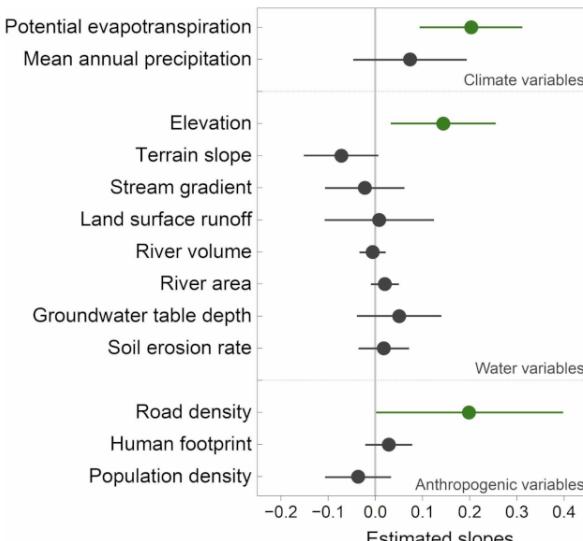
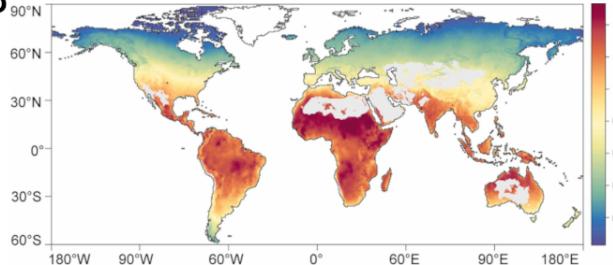
The population of tigers has been growing steadily in Nepal during the last decade. Tiger individuals have started to disperse Northward, partly to avoid conflicts with people in the human-dominated landscapes further South. In (Carter et al., 2024), I quantified landscape connectivity for tigers based on the energy costs of travel (Berti et al., 2022). Moreover, using remote sensing approaches, I assessed how human activities and land-cover use affected high-connectivity areas at the national level and within the network of protected areas. I found that **most of the areas with high connectivity are currently used by people** and that tigers would need to adjust their movement strategies in order to avoid conflicts, at the cost, however, of increased energy costs (Fig. 10A). Importantly, this also happens within designated corridor areas (Fig. 10B), where most of the high-connectivity regions are used by human activities.



**Figure 10: Landscape connectivity for tigers in Nepal.** **A)** Land-cover zonal statistics grouped by connectivity levels. Stacked bars show the area covered by land-cover types for each connectivity level, with 1 indicating lowest and 10 highest connectivity. **B)** Landscape connectivity for tigers travelling through three designated areas of the Terai-Arc dispersal corridor. Connectivity was calculated using as resistance matrix the energy costs of travelling across the landscape. Gray shades show areas of human land-use, such as croplands and settlements. Adapted from (Carter et al., 2024).

#### T2.5 – Global patterns and drivers of lead concentration in inland waters

Chemical pollution of rivers is one the main anthropogenic stressors of freshwater ecosystems. In particular, lead (Pb) has received considerable attention as one of the main pollutants in rivers. Yet, we did not have a quantitative assessment of the patterns and drivers of lead concentration in inland waters at the global scale. I was invited to participate in a study in collaboration with Prof. Kai Yue at Fujian University (China) that aimed at assessing lead concentration patterns and drivers globally by using an extensive dataset compiled from published literature (Wei et al., 2023). In particular, I performed the mixed modelling approach used in the meta-analysis, which revealed that **lead concentration was positively driven by potential evapotranspiration, elevation, and road density** (Fig. 11). Additionally, lead pollution was particularly high in rivers near industrial areas, where most of the water for drinking and agriculture is collected.

**A****B**

**Figure 11: Results from the meta-analysis on patterns and drivers of lead concentration.** A) Overall effects of the 13 predictors used for estimating lead concentration in global inland waters. Circles show mean estimated effects ( $\pm 95\%$  confidence intervals), obtained using mixed linear models. Gray colour indicates a statistically non-significant effects on lead concentration ( $p \geq 0.05$ ) and green colour a significant positive effects on ( $p < 0.05$ ). B) Predicted global pattern of Pb concentration in inland waters ( $\mu\text{g} / \text{L}$ ) obtained using linear mixed models. Colours indicate the lead concentration, with blue showing low levels and red high levels of lead concentration. Gray cells indicate areas without inland waters. Adapted from (Wei et al., 2023).

### **Relevance of T2 for the planned research and synergies with the working groups**

T2 explores how human societies and biodiversity interact. This is needed to identify potential sources of conflicts and to mitigate the risks of biodiversity declines and of ecosystem services losses. Specifically, T2 highlights biases in people's perception towards wildlife and how such biases can influence biodiversity patterns. Moreover, T2 identifies past losses and potential restoration opportunities for biotic connectivity, which promotes several ecosystem functions and services. The themes and projects of T2 are relevant for the planned research as they identify:

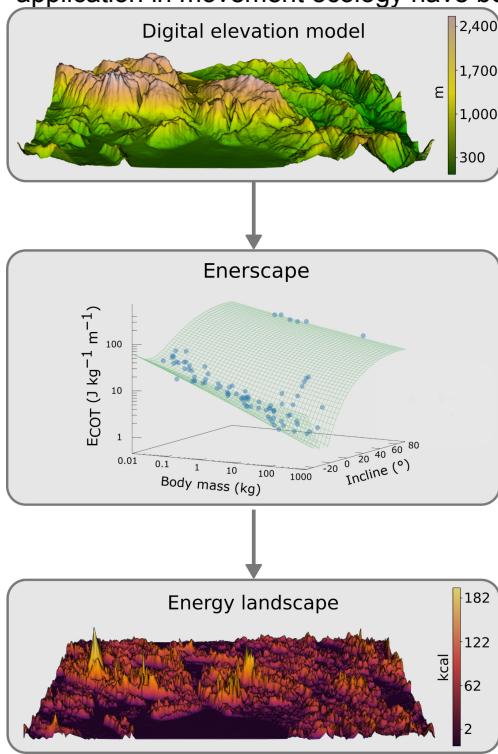
- 1. Biases in people's perception of biodiversity affecting human-wildlife coexistence.** It may be relevant for the planned research to assess similar biases in the perception and opinion of local stakeholders and the general public towards species and habitats in Mediterranean ecosystems. This will allow to identify potential biases that may hinder the effective delivery of ecosystem services.
- 2. Potential ways to promote human-wildlife coexistence.** This is highly relevant to **achieve sustainable policies for managing ecosystem services** and for the well-being of ecosystems and societies.
- 3. Anthropogenic losses of biotic connectivity, with consequent downgrading of several ecosystem services.** Moreover, T2.4 identifies **potential issues with design of dispersal corridors**. Such assessments may be relevant in later stages of the planned research in order to assess the delivery of ecosystem services that depend on animal movement and biotic connectivity (see also T1.5 and T3.1).
- 4. T1.5** Is unrelated to the planned research, but it highlights my capability to **adapt to new topics and work well in a diverse network of collaborators**.

### T3 – Theory and models for ecology and biodiversity conservation

Ecology is a relatively new discipline which still lacks a unified fundamental theory. Incredible advances have been made in the last century, yet theory and methodologies are still partly inadequate for achieving a coherent integration. This is particularly relevant for ecosystem services assessment: because they emerge from complex relationships among ecological actors at different scales, **we need to advance the theory and develop the tools needed to quantify and assess ecosystem services**. During my career, I have conceptualised and formalised several novel ideas, advanced basic ecological theory, and developed methods and software for its application. T3 brings together these achievements into five projects: Developing of a GIS framework to quantify the energy costs of moving for terrestrial animals (T3.1). Developing a standardised framework for simulating biomass dynamics in food webs (T3.2). Proposing a practical approach for taxonomic harmonization (T3.3). Advancing current theory on animal locomotion and movement ecology (T3.4). And developing a novel approach for ecological niche and distribution modelling (T3.5).

#### T3.1 – The R package enerscape for quantifying energy costs of movement

Despite the recognition that energy landscapes, i.e. the energy cost of travelling mapped on a geographic landscape, should play a crucial role for animal movement (Shepard et al., 2013), its application in movement ecology have been limited due to the lack of a scalable framework. To fill this

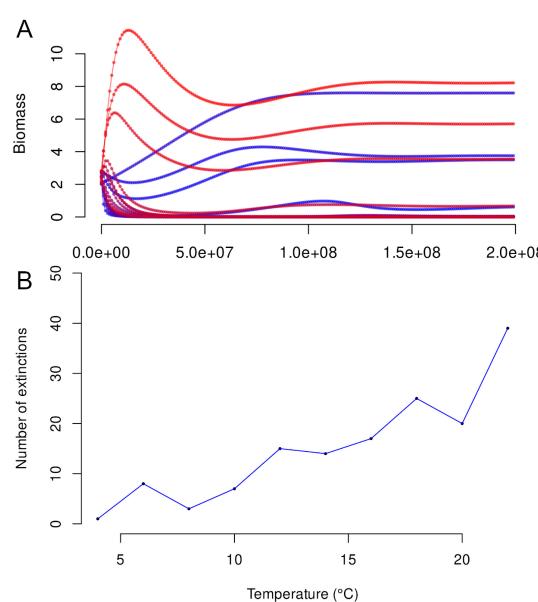


**Figure 12: Illustration of the workflow of the R package enerscape.** The energy landscape is computed starting from a raster of the digital elevation model (top) and animal body mass using a locomotory model to calculate the energy costs of transport ( $E_{COT}$ ). Green lines (middle) show the model from Pontzer (2016) for legged, terrestrial animals, with blue circles showing the data used for its validation. The output of enerscape is a raster of energy costs of travelling across the landscapes (bottom). From (Berti et al., 2022).

#### T3.2 – The R package ATNr for modelling biomass dynamics of food webs

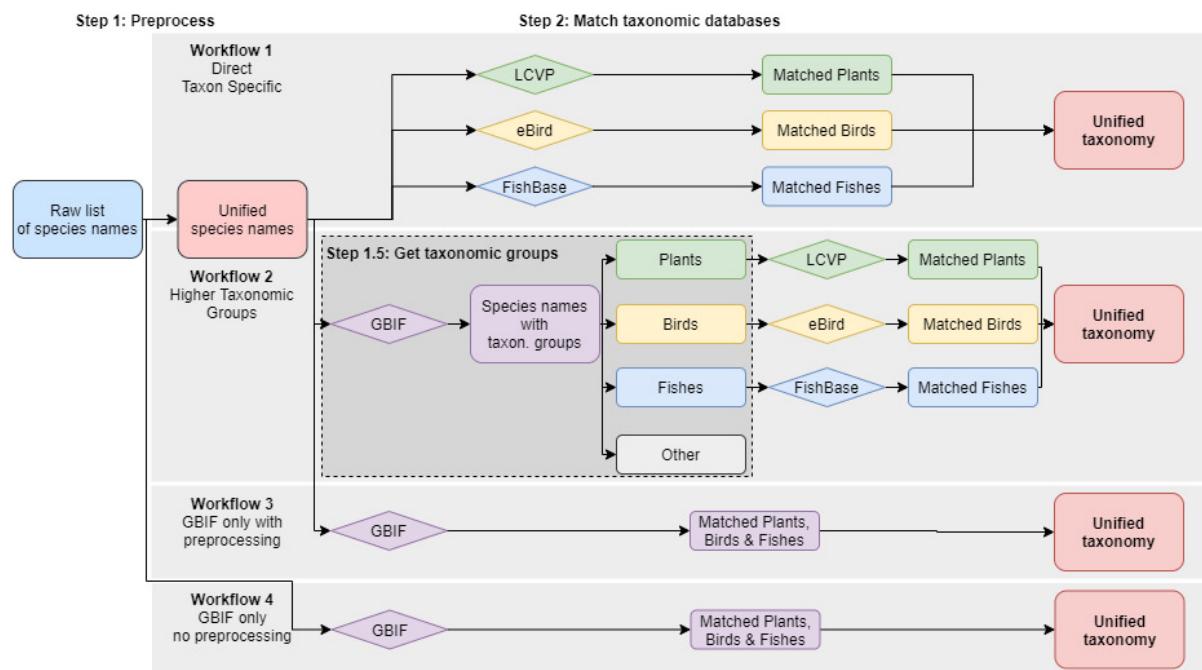
Allometric trophic network models (ATNs) are theoretical models for simulating the biomass dynamics of communities (Martinez, 2020). Although ATNs have been extensively used, we lacked a standardised framework to model them, with different studies using different underlying models and parametrizations. Moreover, ATNs were accessible only to advanced programmers, as coding in C++ was usually required, a skill that most ecologists do not have. To fill these gaps, we developed an R package hosted on CRAN that provides ready-to-use implementation for the three most commonly used ATNs (Gauzens et al., 2023) (Fig. 13). Importantly, ATNr comes with default parametrizations (customizable by users) extracted from literature and **allows to model biomass dynamics in communities while assuring high reproducibility**. My contribution to this project was to review code developed by Dr. Benoit Gauzens (iDiv), to help with the development of the package, e.g.

optimising the interface between R and C++, and to run the analyses and write text for the case examples in the publication (Gauzens et al., 2023).



**Figure 13: Examples of the output of ATNr and its applications.** A) ATNr simulates biomass dynamics through time using fast C++ code. Colours show different species, using a gradient from blue to red based on species' ranks in the food web matrix. B) Effect of temperature on species persistence using the unscaled ATN model with nutrients as implemented in ATNr. For increasing temperatures, more species go extinct (total species richness = 50). Adapted from (Gauzens et al., 2023).

have been harmonised against a common taxonomic backbone. However, it was unclear how to practically achieve this and we did not have a good overview of the available tools and resources to facilitate it. In (Grenié et al., 2023), **we reviewed existing literature, data sources, and software to harmonise taxonomic names and proposed guidelines and four practical approaches** that fit different goals (Fig. 14). In this study, I contributed in conceptualising the problem and solutions, I proposed the complementary Shiny App as a tool to guide users, and designed and carried out the examples for the four approaches used to achieve taxonomic harmonization.

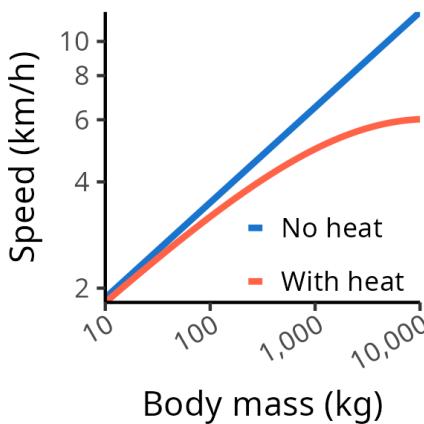


**Figure 14: Diagram of the four taxonomic harmonization workflows explored.** The workflows differ in the number of steps they consider and the taxonomic backbone they use. Rounded rectangles represent lists of taxon names and diamonds the taxonomic databases used. The different colours used at step 2 represent different taxonomic groups. From (Grenié et al., 2023).

### T3.4 – Sustained speed of animals is limited by heat dissipation capacity

In addition to topography (see T3.1 and T1.5), energy costs of travel depend on animal speed, with total costs being smaller at higher speeds (Taylor & Heglund, 1982). Moreover, heat produced by muscle contraction can be difficult to dissipate, imposing an additional limit to animal speed during sustained locomotion. Despite its potential importance, however, it was unknown how heat dissipation influenced sustained travel speed of animals. To fill this gap, we synthesised a large dataset of sustained travel speed for 532 species and **developed a mathematical and statistical model** to assess if heat dissipation limited sustained speed of animals (Dyer et al., 2023). We found that sustained speed showed a hump-shaped relationship with body mass, highlighting that the highest travel speeds are achieved by animals of intermediate body mass. Importantly, we found that **heat dissipation capacity is negatively related to body mass** and that large animals need more time to dissipate heat produced during locomotion, **limiting their sustained locomotion speed** (Fig. 15). This provides a mechanistic understanding of sustained travel speed that will facilitate more realistic predictions of biodiversity dynamics in fragmented landscapes. My contribution in this study was to help develop the mathematical model describing how speed relates with body mass and is influenced by heat dissipation capacity. We are currently expanding this model to account for environmental temperature, as this will influence the rate of heat dissipation. This will be particularly relevant to

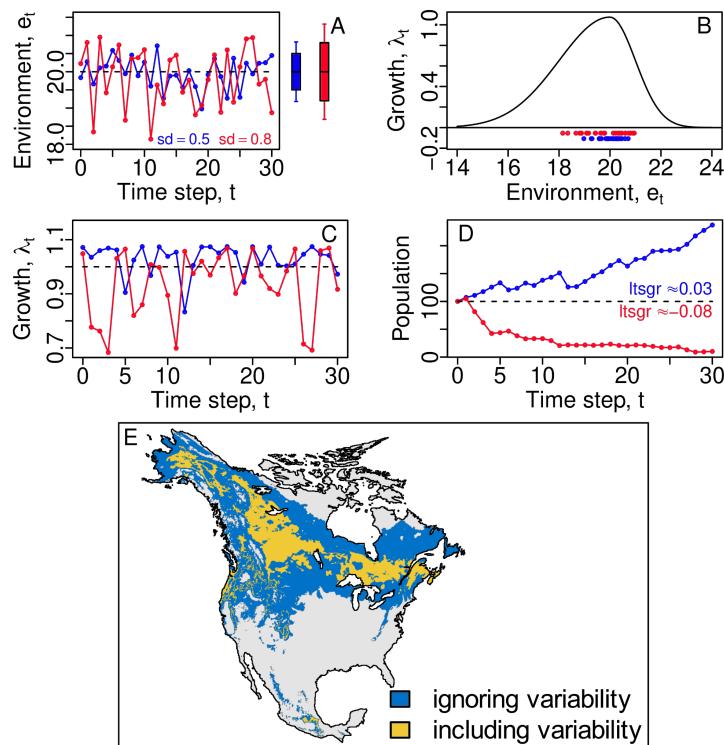
investigate the effects of climate change on the movement patterns of large animals in warm habitats, e.g. tropical and Mediterranean ecosystems.



**Figure 15: Predictions of sustained travel speed for terrestrial animals.** The two curves show the model commonly used in previous studies that does not include heat dissipation (blue) and the new model developed in (Dyer et al., 2023), which includes heat dissipation (red) and best explains empirical data. Sustained travel speed of large animals is influenced by heat dissipation processes. The coefficients of the curves were extracted from (Dyer et al., 2023).

### T3.5 – XSDM: a novel SDM to quantify the effects of climate variability

The novel XSDM framework introduced in T1.1 is part of an ongoing project to include inter-annual climatic variability in species distribution modelling (Fig. 16). This is achieved by integrating two established fields that have not been previously connected: stochastic demography and species distribution modelling (SDM). XSDM, currently in its pre-release stage, is based on a Bayesian framework implemented in Stan and callable from R that **quantifies how inter-annual climate variability influences the distributional range of species**. Notably, XSDM is computationally efficient and requires only widely available data (e.g. GBIF). Analyses so far showed promising results for XSDM. Importantly, this framework can be **expanded to include the demographic structure of populations** and to assess the influence of climate variability at different time scales, e.g. months or seasons, when relevant for the studied species. We received praise and strong encouragement from Prof. Peterson and Prof. Soberón, leading experts in the field of SDMs. I did not release a pre-print of this study, but I can provide a confidential copy of the current manuscript.



**Figure 16: Example of how inter-annual environmental variability alters population viability and how to account for it.** A) Two distinct locations (red and blue) have identical average environmental conditions, but different degrees of inter-annual variability ( $sd$  = standard deviation). If the annual net growth rate ( $\lambda_t$ ) is a function of the environment as in panel B, then differences in environmental variance can produce large differences in the time series of growth rates (C), leading to large differences in survival outcomes of the population (D). The long-term stochastic growth rate (Itsgr), a concept from stochastic demography, accurately captures population viability in these two scenarios. E) The projected suitability can drastically differ when accounting or not for climate variability.

### **Relevance of T3 for the planned research and synergies with the working groups**

T3 aims at developing fundamental ecological theory and at providing software and tools to facilitate testing ecological hypotheses and to forecast biodiversity patterns at large spatial and temporal scales. The themes and projects of T3 are relevant for the planned research as they highlight my experience with **software development, conceptualization and formalisation of new theory, and development of novel approaches and methods** for assessing several aspects of biodiversity and ecosystem functioning. Specifically, T3 highlights:

1. My previous **experience in developing stable and optimised packages in R**. Additionally, some of these packages (e.g., T3.2) can be used to assess biomass dynamics and related ecosystem functions (primary productivity, energy fluxes) that determine ecosystem services (wood production, climate mitigation, pest control) and can provide a **starting point for quantifying how ecosystem services change through time**.
2. My **skills in data science for ecological synthesis**, which can have synergies with the ECOSCOPE project (EMR team), aimed at standardising environmental data.
3. My **experience and abilities in conceptualising new theory and formalising it mathematically**. This is a highly transferable skill that will be useful in advancing theory and knowledge on ecosystem services.
4. Potential avenues for ecosystem services assessment, for example **modelling species distribution under climate change**, which is altering, in addition to average climatic conditions, also the intensity and frequency of extreme events, such as droughts and heat waves. This has several potential applications for the planned research, with many synergies with other projects conducted at the RECOVER unit and the EMR team. For instance, XSDM can be used to better understand **how changing climate variability will affect the suitability and distribution of Mediterranean species**, which are already facing extreme inter-annual variability in climate.

## Experience with lab and field work and database management

My research during my PhD and PostDoc periods has been mostly theoretical and oriented towards the synthesis and analysis of large amounts of data. In addition to this main line of research, I have been part of **several field expeditions during my MSc**, I have carried out **experimental work for both my BSc and MSc theses**, I have helped with field work during my PhD, and I led the **planning and coordination of a camera trapping experiment** in Italy during my PostDoc. Specifically:

- I extracted and prepared muscle fibres for analysis using the “striation follower” (Simmons, 2018) (BSc thesis).
- I joined an expedition to survey the distribution of an invasive ant in the [Casentino forests](#) (MSc).
- I joined an expedition to survey the species composition and distribution of Mediterranean plant species on [Capraia Island](#) (MSc).
- I sampled ants from two colonies of different species and recorded their movement behaviour and the dynamics of their aggressive interactions (MSc thesis).
- I assisted with the deployment of 4 GPS collars attached to four animals (PhD)
- I planned, coordinated, and performed field work for a [camera trap experiment](#) in the Central Apennines (Italy) that aimed at surveying animal composition and investigating how species interact (PostDoc). I also collected and organised spatial data ([Earth Engine app](#)) for assisting two MSc students involved in the project.
- I am managing the food web database [GATEWAY](#). In particular, I am developing a new harmonised and standardised version that can be hosted on a website (PostDoc).

This is relevant for the planned research as it highlights my **previous experience with field and lab work, database management, and spatial data**. It will be particularly promising to integrate models for indicators of ecosystem services with long-term monitoring and field surveys. This will allow to **continuously test models’ output with ground truth**, similarly to what currently done for climate simulations, and to set up a continuous integration between models and field measurements.

## Conclusion

Additionally to a strong scientific interest, I have a deep personal connection with Mediterranean ecosystems. I grew up in Tuscany, Italy, surrounded by Mediterranean forests. These forests are frequently perturbed by fires caused by humans, e.g. hikers or olive farmers burning branches after pruning. I witnessed three large fires during the period 2000-2014. After the fires, I frequently surveyed the burnt areas to assess the regrowth of vegetation. In recent years, extreme droughts and heat waves have severely impacted these forests. For instance, trees have been shedding their leaves early during the year; I recorded one of such episodes in late August. Human benefits have also been compromised: olive, wine, and chestnut production has steadily declined. Therefore, understanding how Mediterranean ecosystems deliver their services and how to mitigate the impacts of global changes is very important to me for helping the community I was born and raised in. Because of this deep personal connection with Mediterranean forests and ecosystems, I am extremely motivated and committed to the missions and goals of the planned research and shared by the RECOVER unit and the EMR team.

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**Table 2: Relevance of the themes for ecosystem services assessment.** Relevance is shown only for themes that directly link ecosystem functions to services.

Essential functions or structures for the supply of a service	Food	Wood production	Production energy crops	Venison	Pollination	Pest control	Global climate regulation	Nutrient regulation	Green space outdoor activities	Natura 2000	Green infrastructures
	Provisioning ES		Regulating ES			Cultural ES	Nature conservation				
Primary production			1.2, 1.3, 1.4, 3.2			1.2, 1.3, 1.4, 3.2					
Animal production	1.4, 3.2		1.4, 3.2			1.3, 1.4, 1.5, 2.3, 3.1					
Soil formation & Nutrient availability / -cycling						1.3, 1.4, 1.5, 2.3, 3.1					
Decomposition of organic material						1.3, 1.4,					

	Food	Wood production	Production energy crops	Venison	Pollination	Pest control	Global climate regulation	Nutrient regulation	Green space outdoor activities	Natura 2000	Green infrastructures
Essential functions or structures for the supply of a service											
Carbon storage & carbon stock							3.2				
Pollination					1.2, 1.5		1.3, 1.4, 3.2	1.3, 1.4, 3.2			
Pest control						1.2, 1.4, 3.2					
Regulate population dynamics			1.2, 1.4, 3.2		1.2, 1.5	1.2, 1.4, 3.2					
Regulating ecosystem dynamics, succession		1.2, 1.3, 1.4, 3.2						2.1, 2.2	2.4, 3.1		

Essential functions or structures for the supply of a service	Food	Wood production	Production energy crops	Venison	Pollination	Pest control	Global climate regulation	Nutrient regulation	Green space outdoor activities	Natura 2000	Green infrastructures
Stability ecosystem processes & Ecosystem resilience										1.1, 1.2, 1.5, 2.4	
Development of complex ecological networks								2.1, 2.2	2.2, 2.4	1.5, 2.4, 3.1	
Develop ecosystem diversity / habitat quality									1.5, 2.3	2.4	

Adapted from (Burkhard & Maes, 2017).

Colours are comparable with Fig. 1.