

# Microclimate, an important part of ecology and biogeography

Julia Kemppinen<sup>1</sup>  | Jonas J. Lembrechts<sup>2</sup>  | Koenraad Van Meerbeek<sup>3</sup>  |  
 Jofre Carnicer<sup>4</sup>  | Nathalie Isabelle Chardon<sup>5</sup>  | Paul Kardol<sup>6</sup>  | Jonathan Lenoir<sup>7</sup>  |  
 Daijun Liu<sup>8</sup>  | Ilya Maclean<sup>9</sup>  | Jan Pergl<sup>10</sup>  | Patrick Saccone<sup>11</sup>  |  
 Rebecca A. Senior<sup>12</sup>  | Ting Shen<sup>13,14</sup>  | Sandra Słowińska<sup>15</sup>  | Vigdis Vandvik<sup>16</sup>  |  
 Jonathan von Oppen<sup>17</sup>  | Juha Aalto<sup>18</sup>  | Biruk Ayalew<sup>19</sup>  | Olivia Bates<sup>20</sup>  |  
 Cleo Bertelsmeier<sup>20</sup>  | Romain Bertrand<sup>21</sup>  | Rémy Beugnon<sup>22,23,24</sup>  |  
 Jeremy Borderieux<sup>25</sup>  | Josef Brůna<sup>10</sup>  | Lauren Buckley<sup>26</sup>  | Jelena Bujan<sup>20</sup>  |  
 Angelica Casanova-Katny<sup>27</sup>  | Ditte Marie Christiansen<sup>28</sup>  | Flavien Collart<sup>20</sup>  |  
 Emiel De Lombaerde<sup>29</sup>  | Karen De Pauw<sup>29</sup>  | Leen Depauw<sup>29</sup>  |  
 Michele Di Musciano<sup>30</sup>  | Raquel Díaz Borrego<sup>31</sup>  | Joan Díaz-Calafat<sup>32</sup>  |  
 Diego Ellis-Soto<sup>33</sup>  | Raquel Esteban<sup>34</sup>  | Geerte Fälthammar de Jong<sup>35</sup>  |  
 Elise Gallois<sup>36</sup>  | Maria Begoña García<sup>37</sup>  | Loïc Gillerot<sup>29</sup>  | Caroline Greiser<sup>38</sup>  |  
 Eva Gril<sup>39</sup>  | Stef Haesen<sup>3</sup>  | Arndt Hampe<sup>40</sup>  | Per-Ola Hedwall<sup>32</sup>  |  
 Gabriel Hes<sup>21</sup>  | Helena Hespanhol<sup>41</sup>  | Raúl Hoffrén<sup>42</sup>  | Kristoffer Hylander<sup>19</sup>  |  
 Borja Jiménez-Alfaro<sup>43</sup>  | Tommaso Jucker<sup>44</sup>  | David Klimes<sup>45</sup>  |  
 Joonas Kolstela<sup>18</sup>  | Martin Kopecký<sup>46</sup>  | Bence Kovács<sup>47,48</sup>  | Eduardo Eiji Maeda<sup>49</sup>  |  
 František Málíš<sup>50</sup>  | Matěj Man<sup>10</sup>  | Corrie Mathiak<sup>51</sup>  | Eric Meineri<sup>52</sup>  |  
 Ilona Naujokaitis-Lewis<sup>53</sup>  | Ivan Nijs<sup>54</sup>  | Signe Normand<sup>55</sup>  | Martin Nuñez<sup>56</sup>  |  
 Anna Orczewska<sup>57</sup>  | Pablo Peña-Aguilera<sup>58</sup>  | Sylvain Pincebourde<sup>59</sup>  |  
 Roman Plichta<sup>60</sup>  | Susan Quick<sup>61</sup>  | David Renault<sup>62</sup>  | Lorenzo Ricci<sup>30</sup>  |  
 Tuuli Rissanen<sup>49</sup>  | Laura Segura-Hernández<sup>63</sup>  | Federico Selvi<sup>64</sup>  |  
 Josep M. Serra-Diaz<sup>65</sup>  | Lydia Soifer<sup>45</sup>  | Fabien Spicher<sup>66</sup>  | Jens-Christian Svenning<sup>67</sup>  |  
 Anouch Tamian<sup>68</sup>  | Arno Thomaes<sup>69</sup>  | Marijke Thoonen<sup>69</sup>  | Brittany Trew<sup>9</sup>  |  
 Stijn Van de Vondel<sup>70</sup>  | Liesbeth van den Brink<sup>71,72</sup>  | Pieter Vangansbeke<sup>29,73</sup>  |  
 Sanne Verdonck<sup>74</sup>  | Michaela Vitkova<sup>75</sup>  | Maria Vives-Inglá<sup>31,76</sup>  |  
 Loke von Schmalensee<sup>77</sup>  | Runxi Wang<sup>78</sup>  | Jan Wild<sup>10</sup>  | Joseph Williamson<sup>79</sup>  |  
 Florian Zellweger<sup>80</sup>  | Xiaqu Zhou<sup>81</sup>  | Emmanuel Junior Zuza<sup>82</sup>  |  
 Pieter De Frenne<sup>29</sup> 

Julia Kemppinen, Jonas Lembrechts and Koenraad Van Meerbeek should be considered joint first authors.

For affiliations refer to page 13.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2024 The Authors. *Global Ecology and Biogeography* published by John Wiley & Sons Ltd.

**Correspondence**

Julia Kemppinen, Geography Research Unit, University of Oulu, Oulu FI-90014, Finland.  
Email: [julia.kemppinen@oulu.fi](mailto:julia.kemppinen@oulu.fi)

**Funding information**

Honours Programme for Future Researchers at the Friedrich-Schiller-University; ED2021-132007B-I00; Région Sud Provence-Alpes-Côte d'Azur, Grant/Award Number: 02697; Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung, Grant/Award Number: 193645; ANILLO ACONCAGUA ANID ACT, Grant/Award Number: 210021; New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund; Slovak Research and Development Agency project, Grant/Award Number: APVV-19-0319; Fonds Wetenschappelijk Onderzoek, Grant/Award Number: 1221523N, 1590923N and ASP035-19; BiodivClim, Grant/Award Number: TACR SS70010001; Research Council of Finland, Grant/Award Number: 337552 and 349606; Ministerio de Ciencia e Innovación, Grant/Award Number: FPU17/05869; Grantová Agentura České Republiky, Grant/Award Number: 20-28119S; PID2020-117636GB-C21; NERC, Grant/Award Number: NE/S01537X/1; Akademie Věd České Republiky, Grant/Award Number: RVO 67985939; FOVI, Grant/Award Number: 210043; FLOF fellowship of the KU Leuven, Grant/Award Number: 3E190655; Independent Research Fund of Denmark, Grant/Award Number: 7027-00133B; Zone Atelier CNRS Antarctique et Terres Australes; MCIN/AEI/10.13039/501100011033, Grant/Award Number: PID2020-113244GA-C22 and UPV/EHU-GV IT-1648-22; FWF Austrian Science Foundation, Grant/Award Number: M2714-B29; Svenska Forskningsrådet Formas, Grant/Award Number: 2021- 01993 and 2021-00816; National Science Centre in Poland, Grant/Award Number: 2022/45/B/ST10/03423; Agence Nationale de la Recherche, jeunes chercheuses et jeunes chercheurs, Grant/Award Number: ANR-21-CE32-0003; H2020 European Research Council, Grant/Award Number: 864287; ASICS project, Grant/Award Number: ANR-20-EBI5-0004; Agence Nationale de la Recherche, Grant/Award Number: ANR-19-CE32-0005-01; Institut Polaire Français Paul Emile Victor, Grant/Award Number: 136-SUBANTECO; CNRS; Doctoral Programme in Geosciences at the University of Helsinki; Swiss National Science Foundation Postdoc Mobility Fellowship, Grant/Award Number: 194331; NASA FINESST, Grant/Award Number: 80NSSC22K1535;

**Abstract**

**Brief introduction: What are microclimates and why are they important?** Microclimate science has developed into a global discipline. Microclimate science is increasingly used to understand and mitigate climate and biodiversity shifts. Here, we provide an overview of the current status of microclimate ecology and biogeography in terrestrial ecosystems, and where this field is heading next.

**Microclimate investigations in ecology and biogeography:** We highlight the latest research on interactions between microclimates and organisms, including how microclimates influence individuals, and through them populations, communities and entire ecosystems and their processes. We also briefly discuss recent research on how organisms shape microclimates from the tropics to the poles.

**Microclimate applications in ecosystem management:** Microclimates are also important in ecosystem management under climate change. We showcase new research in microclimate management with examples from biodiversity conservation, forestry and urban ecology. We discuss the importance of microrefugia in conservation and how to promote microclimate heterogeneity.

**Methods for microclimate science:** We showcase the recent advances in data acquisition, such as novel field sensors and remote sensing methods. We discuss microclimate modelling, mapping and data processing, including accessibility of modelling tools, advantages of mechanistic and statistical modelling and solutions for computational challenges that have pushed the state-of-the-art of the field.

**What's next?** We identify major knowledge gaps that need to be filled for further advancing microclimate investigations, applications and methods. These gaps include spatiotemporal scaling of microclimate data, mismatches between macroclimate and microclimate in predicting responses of organisms to climate change, and the need for more evidence on the outcomes of microclimate management.

**KEYWORDS**

animal ecology, biodiversity, biogeography, climate change, data acquisition, ecosystem management, microclimate, modelling, plant ecology

Villum Fonden, Grant/Award Number: 16549; Danmarks Frie Forskningsfond, Grant/Award Number: 0135-00225B; Spanish Association of Terrestrial Ecology; PID2021-129056OB-I00, Grant/Award Number: REFUGIA project; Conaf; Saxon State Ministry for Science, Culture and Tourism, Grant/Award Number: 3-7304/35/6-2021/48880; AgroParisTech/Région Grand-Est joint grant, Grant/Award Number: 19\_GE8\_01020p05035; Danmarks Grundforskningsfond, Grant/Award Number: DNRF173

Handling Editor: Brian J. Enquist

## 1 | BRIEF INTRODUCTION: WHAT ARE MICROCLIMATES AND WHY ARE THEY IMPORTANT?

Microclimates refer to the local climate conditions that organisms and ecosystems are exposed to. In terrestrial ecosystems, microclimates often differ strongly from the macroclimate, that is, the climate representative of a large geographic region. Microclimates are chiefly mediated by topography, vegetation and soil, and they are a combination of local temperature, water (precipitation, air humidity, water availability), solar radiation, cloud, wind and evaporation conditions (Bramer et al., 2018). This fine-scale variation of microclimates is not captured by coarse-resolution macroclimatic data, because microclimates can vary over very short spatial and temporal extents. Microclimates directly influence the eco-physiology of individuals across taxa, and in turn, indirectly affect the dynamics of populations, communities and ecosystems across biomes.

Microclimates enable organisms to develop, survive and reproduce, for instance, below and near the soil surface, and in tree canopies and cavities in an otherwise unsuitable macroclimate (Bramer et al., 2018). Conversely, the same organisms can be absent in places and times where the microclimatic extremes exceed their limits. Additionally, microclimates dictate many ecosystem functions and processes, such as biogeochemical cycles. These local climatic conditions can be captured by microclimatic measurements, not by standard weather stations above short grass in the open. Thus, merging microclimate methods with ecological and biogeographic investigations and applications can provide valuable insights.

Recently, methods have become widely available for ecologists and biogeographers to inspect their study objects in relation to microclimates at high spatio-temporal resolutions and at large spatial and temporal extents (Lembrechts, Nijs, et al., 2019). Consequently, microclimate science has rapidly shown its high relevance to ecological and biogeographical investigations and applications (De Frenne et al., 2021). Now, microclimate science is recognized as an integral component of ecology and biogeography, and is used to investigate

local ecological manifestations of the global climate and biodiversity patterns (Riddell et al., 2021; Zellweger et al., 2020), and to improve ecosystem management (Hylander et al., 2022).

Microclimate science has a long tradition. Already in the mid-20th century, microclimatology was identified as an important subfield of meteorology, with clear repercussions for ecology and biogeography (Geiger, 1942; Geiger et al., 1995). The physics of microclimate (Baum & Court, 1949), the appropriate spatial scale and the challenges of measuring microclimates (Geiger, 1942; Geiger et al., 1995; Shanks, 1956) have been studied for decades. Recent reviews have highlighted the importance of microclimate over macroclimate (Bramer et al., 2018), and discussed microclimate in relation to remote sensing (Zellweger et al., 2019), measurement techniques (Maclean et al., 2021), species distribution modelling (Lembrechts, Nijs, et al., 2019) and forest ecology (De Frenne et al., 2021). Following these examples, we consider that the microclimate scales and boundaries are highly dependent on the ecological context (Pincebourde & Woods, 2020; Potter et al., 2013), for example, ranging from minutes and cubic millimetres for within-leaf herbivore insects to monthly averages and hectares for understory communities in forests (Pincebourde & Woods, 2020; Zellweger et al., 2020b).

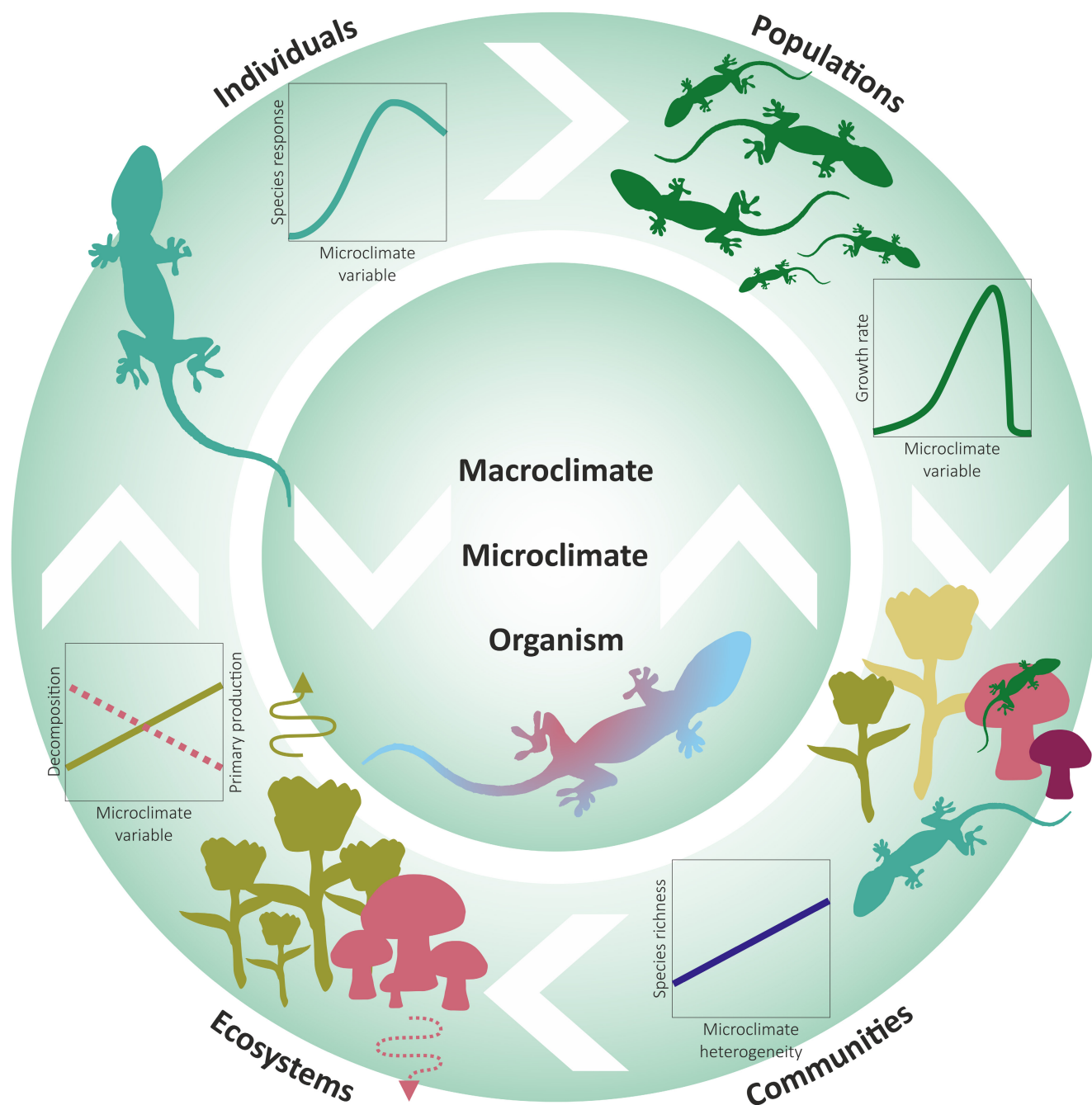
Here, our aim was to provide an overview of the current status of microclimate ecology and biogeography, and where this field is going next, from the perspective of researchers investigating diverse topics related to terrestrial microclimates (read more about the authors in Supplementary information [Figures S1](#)). In this perspective article, we focus on terrestrial ecosystems. However, we acknowledge that microclimates are crucial for aquatic ecosystems as well and that there is active microclimate research on, for example, freshwater, riparian, intertidal, coastal and marine ecosystems (e.g. Bentley et al., 2020; Enriquez-Urzelai et al., 2019; Judge et al., 2018; Nadeau et al., 2022). We discuss recent research on terrestrial ecosystems that shows when and how incorporating microclimate science into ecological and biogeographical questions can increase knowledge and predictability of fine-scale phenomena and processes that generate larger or even global patterns. Recently, microclimate science has taken

major strides forward, especially at the following three frontiers: (1) investigations of microclimate ecology and biogeography, (2) microclimate applications in ecosystem management and (3) methods in microclimate science. For each of these themes, we identify a set of knowledge gaps to fill before microclimate data and concepts become a common option in ecology, biogeography and related fields, from fine scale to global scale. We herewith highlight the maturation of microclimate ecology and biogeography into a global discipline, with microclimates being investigated across taxa, ecosystems and biomes.

## 2 | MICROCLIMATE INVESTIGATIONS IN ECOLOGY AND BIOGEOGRAPHY

### 2.1 | Organisms drive microclimates

Organisms play a pivotal role in shaping microclimates and have the capacity to establish mosaics of microclimates within ecosystems (Figure 1). One important example involves the creation of distinct microclimatic gradients by grass and forest canopies (De Frenne et al., 2021; Vandvik et al., 2020), which generates



**FIGURE 1** Microclimate investigations in ecology and biogeography. The conceptual figure highlights that microclimate is the link between macroclimate and the ecophysiology of organisms. We show examples of how microclimates influence individuals, populations, communities and ecosystems and their processes.

both vertical and horizontal variations within relatively confined geographic extents (Ozanne et al., 2003). These microclimatic variations become particularly crucial in mediating the impact of climate change on understory organisms (Dobrowski et al., 2015), and thus, the mosaics of microclimates offer a mechanism for adaptation to broader climatic shifts (Basham et al., 2023; Scheffers et al., 2013). Furthermore, also animals modulate microclimates, from large herbivores affecting microclimates through grazing and trampling vegetation, to insects regulating their nest temperatures through wing fanning and building temperature-modulating mounds (Gordon et al., 2023; Jones & Oldroyd, 2006; Joseph et al., 2016). These examples highlight how diverse and active the role of organisms is in shaping microclimates.

## 2.2 | Microclimates influence individuals and populations

Microclimates are a non-negotiable aspect of biophysical ecology across taxa, biomes and scales (Briscoe et al., 2023). The impacts of microclimates on individuals are diverse, as microclimates influence, for instance, performance (Poorter et al., 2019), structural characteristics (Kemppinen & Niittynen, 2022), organs (Opedal et al., 2015) and cellular functions (Zweifel et al., 2007). Recent research on ectotherms and insects showcases how microclimate impacts on individuals are reflected on their populations. Ectothermic organisms, in particular, experience the significant influence of microclimates through thermoregulation and temperature-dependent sex determination (Carter & Janzen, 2021; Sears et al., 2016; Stark et al., 2023). Darker ants tend to dominate tree canopies due to melanism, which provides them protection against UV radiation and reduces moisture loss (Law et al., 2020). The vertical variation in microclimates within forests has furthermore contributed to the evolution of thermal performance and desiccation resistance in ant populations (Bujan et al., 2016; Kaspari et al., 2016), which highlights the interconnectedness between biophysical adaptations and the ability to withstand thermal, hydrological and light-related stressors. Across taxa, thermal tolerance of individuals can serve as a predictor for performance, behaviour and adaptability (Bert et al., 2022; Kim et al., 2022; Pincebourde & Casas, 2019; von Schmalensee et al., 2021). The impacts of microclimates however extend beyond individuals, populations and single ecosystems, as microclimates have broader implications for global biodiversity (Trew & Maclean, 2021). Consequently, microclimate models have become invaluable tools in the field of biophysical ecology (Briscoe et al., 2022; Carter & Janzen, 2021; Sears et al., 2016), because these tools help understanding and predicting interactions between organisms and their environmental conditions.

Through individuals, microclimates have a significant impact on the growth and survival of populations. The microclimatic control of the biophysical processes of individuals influences their recruitment and survival, and in turn, microclimates indirectly

influence demographic rates (Goodwin & Brown, 2023; Oldfather & Ackerly, 2019). Plant populations are a great example of this, as recent discoveries show that crucial processes like seed germination and seedling establishment depend on specific temperature, humidity and light conditions (Davis et al., 2016; Graae et al., 2022). Water availability is another factor that has been shown to affect the growth and mortality of plants (Liu et al., 2018), and water availability also controls the regeneration of trees after disturbances (Lloret et al., 2004; Thom et al., 2022). Besides affecting many physiological processes, microclimates also influence behavioural responses across taxa. For instance, butterflies employ strategies such as clustering at different heights in trees to avoid frost (Brower et al., 2011), birds take into account wind characteristics when selecting nest sites (Momberg et al., 2023) and stomatal responses in plants are regulated by microclimate conditions (Zweifel et al., 2007).

## 2.3 | Microclimates structure communities

The individual-level effects of microclimates ultimately shape the composition and dynamics of communities. Microclimates serve as an important determinant in structuring communities, by influencing both species distributions and patterns of species richness (Checa et al., 2014; le Roux et al., 2013; Ma et al., 2022; Momberg et al., 2021; Niittynen et al., 2020). Recent investigations on plant communities show how microclimates shape species richness, turnover and the composition of vascular plants (Opedal et al., 2015; Shen, Song, et al., 2022), bryophytes (Man et al., 2022; Shen, Corlett, et al., 2022) and lichens (Kemppinen et al., 2019). Knowledge on how microclimates structure communities and their dynamics is increasingly more important in the light of ongoing rapid environmental changes. Ultimately, this means that the heterogeneity of microclimates can mediate how species respond to climate change (Zellweger et al., 2020a), see also (Bertrand et al., 2016), and this heterogeneity can also play a critical role in the context of land use changes (Christiansen et al., 2022). Consequently, the incorporation of microclimate data is crucial for increasing ecological realism of species distribution models across taxa and ecosystems, particularly when investigating environmental changes (Haesen, Lenoir, et al., 2023; Massimino et al., 2020; Niittynen & Luoto, 2018; Stickley & Fraterrigo, 2023).

Species interactions are influenced by microclimate conditions through a variety of mechanisms, encompassing behavioural, phenological and ecophysiological processes. The influence of microclimates on species interactions has been well illustrated by recent evidence on how microclimates significantly shape the habitat preferences of insects (Carnicer et al., 2019; Vives-Ingla et al., 2023) and influence the timing of plant phenological events (Kankaanpää et al., 2018), and how all this ultimately leads to cascading effects on community structures across multiple trophic levels (Kankaanpää et al., 2020). Microclimates can significantly modify species interactions by altering phenological responses, and also by influencing the development



of chemical defence traits, impacting colonization patterns and competitive processes (Greiser et al., 2021; Sanczuk et al., 2021; Willems et al., 2021). Furthermore, microclimates play a critical role in determining facilitation. For instance, shrubs and cushion plants modify their below-canopy microclimates which facilitate the growth of seedlings (Cavieres et al., 2014; Vega-Álvarez et al., 2019).

## 2.4 | Microclimates control and create ecosystems

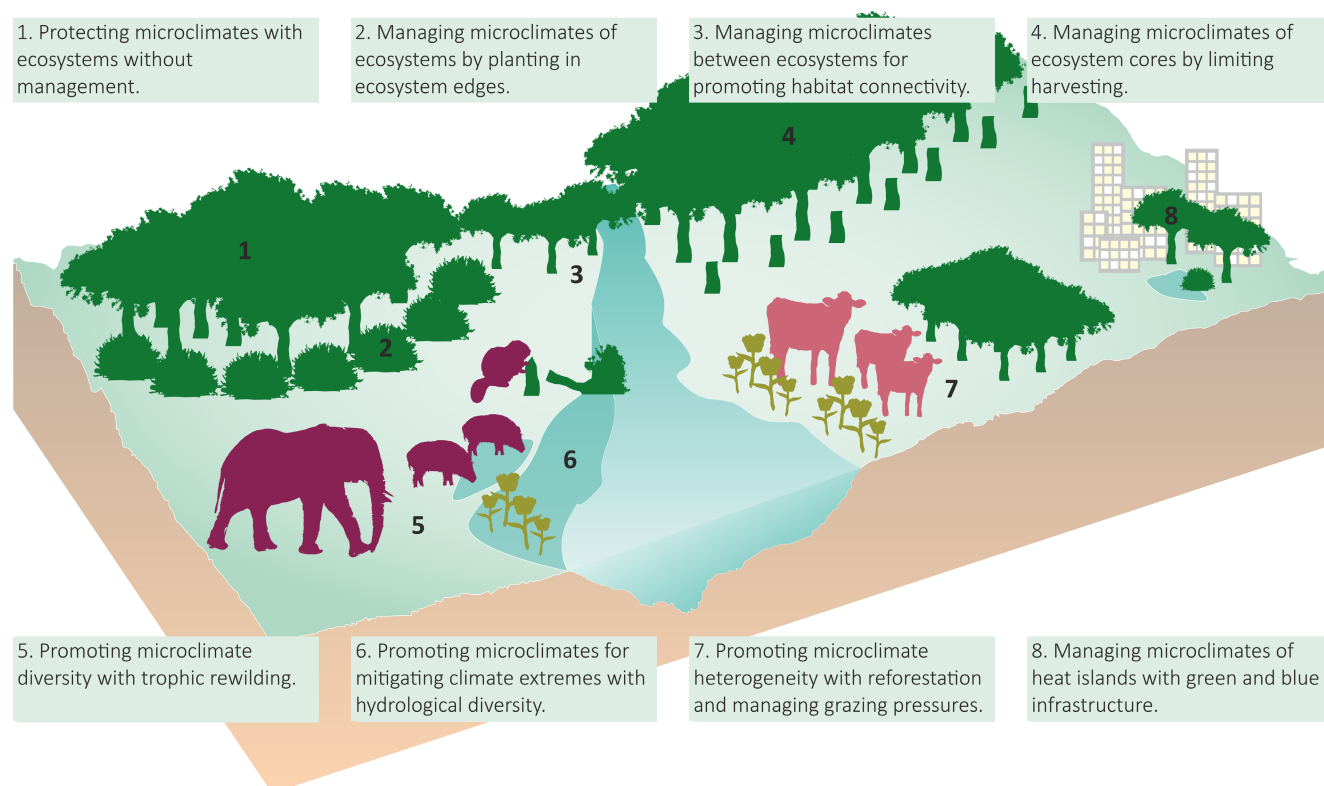
Microclimates control ecosystem processes, the most essential of these being the cycles of energy, water and matter, such as the carbon cycle (Cahoon et al., 2012; Gora et al., 2019; Meeussen et al., 2021). Microclimates can regulate litter decomposition (Chen et al., 2018), heterotrophic and autotrophic soil respiration (Fernández-Alonso et al., 2018), and photosynthesis (Poorter et al., 2019). Hence, microclimatic temperatures drive biogeochemical cycles, such as greenhouse gas fluxes, and fine-scale moisture conditions determine local methane sinks and sources (Virkkala et al., 2024). Overall, microclimates are important to consider in investigating ecosystem processes, since they regulate resources for primary production and regulate many ecosystem functions.

Through the many impacts on plant and animal individuals, populations and communities, microclimates support microrefugia, small ecosystems buffered from climate change. In microrefugia,

temporal changes in local temperature, water and light conditions are smaller than in the surrounding areas (Ashcroft, 2010; Keppel et al., 2012; McLaughlin et al., 2017). Thus, microrefugia can buffer climate change impacts (Morelli et al., 2020), and preserve biodiversity and ecosystem functions (Ashcroft, 2010; Ellis & Eaton, 2021). Microrefugia affect seed survival and plant growth and can create opportunities for animals to hide, feed and reproduce (Checa et al., 2014; Frey, Hadley, & Betts, 2016; Lucid et al., 2021). Microrefugia can be identified using thermal imaging (Hoffrén & García, 2023), high-resolution gridded microclimate products (Haesen, Lenoir, et al., 2023), topographic data (Ashcroft et al., 2012; Meineri & Hylander, 2017), or exploring disjunct populations (Finocchiario et al., 2023). Overall, microrefugia can shape species redistributions under climate change (Lenoir et al., 2017; Stark et al., 2022). Thus, microrefugia are important for maintaining biodiversity (Dobrowski, 2011; Maclean & Early, 2023; Suggitt et al., 2018), and can have the same importance as larger ecosystem management activities for nature conservation across scales (Ackerly et al., 2020; Thorne et al., 2020).

## 3 | MICROCLIMATE APPLICATIONS IN ECOSYSTEM MANAGEMENT

Microclimates are pivotal in ecosystem management, especially in the face of climate change (Figure 2). The question of how



**FIGURE 2** Microclimate applications in ecosystem management. The conceptual figure presents examples of biodiversity conservation, forestry and urban ecology maintaining and promoting microclimate heterogeneity for the benefit of biodiversity.

management practices affect microclimates has been discussed for decades (Geiger, 1942; Kraus, 1911). Similarly, managing microclimates has long been part of land-use practices, especially in agriculture. In agriculture, microclimates can be managed, for example, by planting shade trees for enhancing the growing conditions of crops, such as coffee and vanilla (Beer et al., 1998; Lin et al., 2008). Microclimate management can help pest management by creating microclimates beneficial for retaining natural enemies (Begg et al., 2017), and planting trees or small forest patches can also benefit agrobiodiversity (Wurz et al., 2022). Overall, more focus has recently been drawn to managing microclimates for mitigating climate change and for promoting and protecting biodiversity.

### 3.1 | Microclimate management in biodiversity conservation

Microclimate management is crucial for protecting biodiversity under climate change (Greenwood et al., 2016) and land use change (Williamson et al., 2021). Microclimate heterogeneity is an indicator of microrefugia (Keppel et al., 2015), and can reduce extinction risks (Moritz & Agudo, 2013; Suggitt et al., 2018). Microclimate heterogeneity can be increased by altering vegetation structure (Curtis & Isaac, 2015; Hylander et al., 2022). Vegetation structure can be modified using silvicultural practices, managing grazing pressure by livestock and trophic rewilding with wild megafauna (Malhi et al., 2022; Thers et al., 2019). For example, beaver constructions buffer microclimates from extreme fluctuations by increasing hydrological connectivity and creating floodplains (Larsen et al., 2021; Weber et al., 2017). Also, elephants, wild boars, horses and donkeys engineer microclimates by grazing and trampling on vegetation, and modifying topography and water availability (Gordon et al., 2023; Lundgren et al., 2021; Sandom et al., 2013). Maintaining and creating microclimate heterogeneity and habitat connectivity is an effective basis for future-proofing ecosystems which increases resilience to climate change (Hylander et al., 2022; Maclean & Early, 2023; Stark et al., 2023). Moreover, knowledge and data on microclimate heterogeneity can help identify organisms and ecosystems most vulnerable to climate change (McCullough et al., 2016), and when combined with biophysical ecology, this knowledge can improve and create new management practices to promote biodiversity (Briscoe et al., 2022; Ononye et al., 2023; Welman & Pichegru, 2023).

Microclimate management is used for buffering against gradual environmental change and short-term climate extremes, such as heat waves or droughts, and this increases resistance and enables the proactive transformation of managed ecosystems (Brang et al., 2014; Hylander et al., 2022). Proactive transformation considers the protection of cool microclimates which promotes microrefugia (Hylander et al., 2022; Schmalholz & Hylander, 2011).

Microclimate management is constantly evolving (Kermavnar et al., 2020; Thom et al., 2020), and is increasingly applied to principles of close-to-nature management (Brang et al., 2014; Hylander et al., 2022). For example, in selective logging, the post-logging recovery of forest microclimates can be rapid (Senior et al., 2018; Mollinari et al., 2019). This suggests that, in contrast to clear-cutting, selective-logging can provide timber while maintaining microclimate heterogeneity, if logging rotations allow sufficient space and time for regeneration of understorey vegetation (Menge et al., 2023).

### 3.2 | Microclimate management in forestry

Forestry is an excellent example of how ecosystem management affects microclimate heterogeneity (Menge et al., 2023; Scheffers et al., 2017). In forestry, microclimates are managed to reduce insect outbreaks (Kautz et al., 2013), support tree regeneration (Thom et al., 2022) and reduce frost damage (Örlander, 1993). Forest microclimates are affected by the diversity in tree species, forest structures, management practices (e.g. thinning) and distance to forest edge (Chen et al., 1993; Geiger, 1942; Meeussen et al., 2021). For example, cool and wet microclimates are lost when humid tropical forests are degraded (Senior et al., 2017), even where tree cover remains, such as within tree plantations (Luskin & Potts, 2011) and selectively logged forests (Blonder et al., 2018). This loss is consequential because it decreases the capacity of the forest to buffer climate change impacts and maintain biodiversity (Scheffers et al., 2014). Old-growth forests with diverse microclimatic conditions are especially important for climate change mitigation and biodiversity conservation (Frey, Hadley, Johnson, et al., 2016; Norris et al., 2011; Wolf et al., 2021). However, as temperatures increase and water availability is more limited, forests can lose their capacity to buffer climate extremes (Davis, Dobrowski, et al., 2019). Knowledge and practices found in forestry can be further applied also in other anthropogenically modified environments.

### 3.3 | Microclimate management in urban ecology

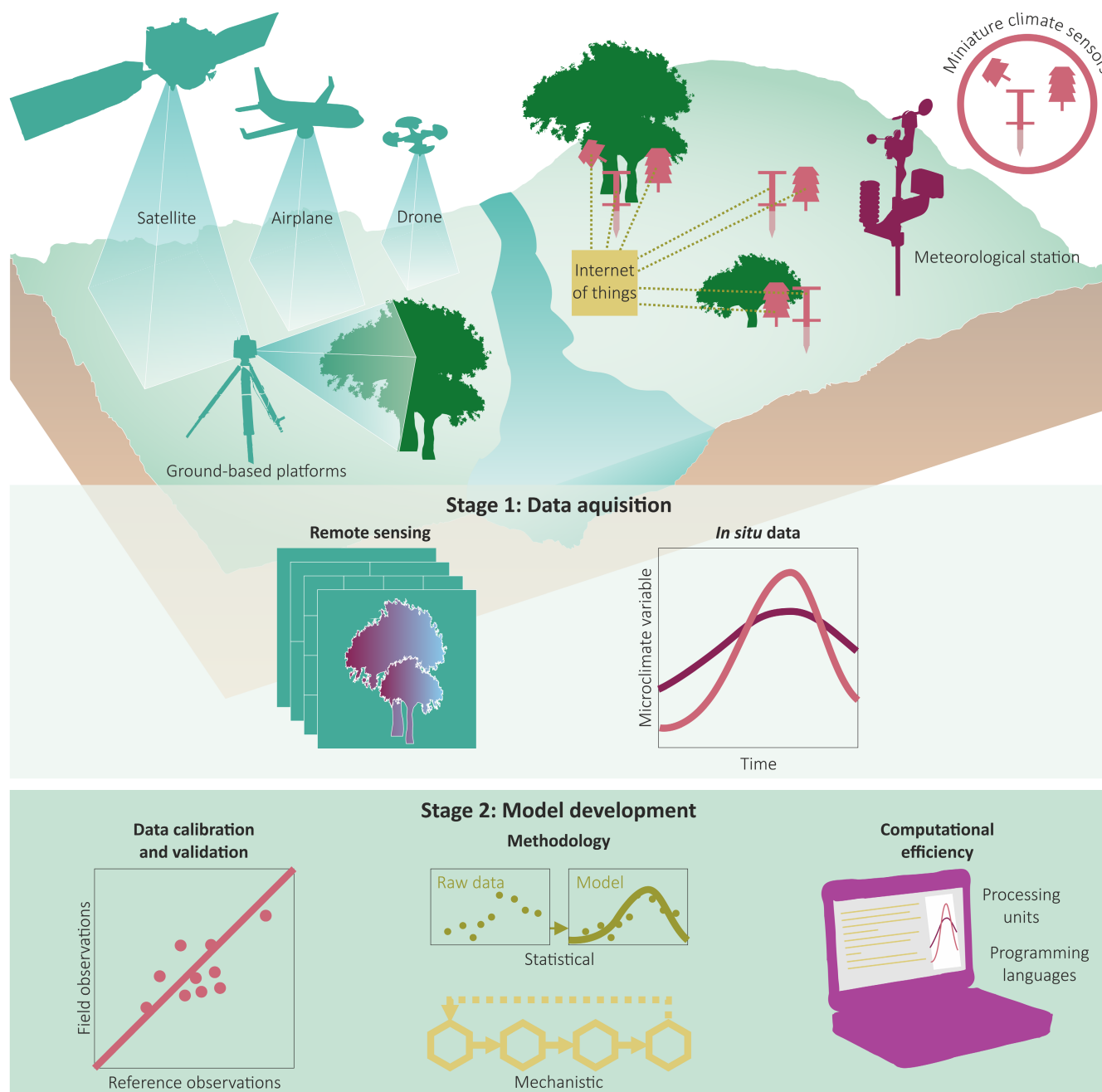
Increasing recognition of the importance of microclimates has led to a proactive approach also in urban ecology to achieve desired microclimate outcomes (Lai et al., 2019). Microclimate heterogeneity is particularly important to consider in rapidly urbanizing and densely populated areas (de Souza et al., 2016; Hartig & Kahn, 2016; Xue et al., 2017). In urban ecosystems, microclimatic anomalies are driven by the lack of vegetation and abundance of impervious, dark surfaces, which create heat islands (Schwaab et al., 2021; lungman et al., 2023). Recent discoveries show that urban heat islands affect organisms, including altering spider behaviour (de Tranaltes et al., 2022), and changing diversity in plant, bird and insect species

(Aronson et al., 2014; McGlynn et al., 2019). Management practices can optimize microclimate conditions of urban heat islands by using green and blue infrastructure (Bowler et al., 2010; Lin et al., 2020), which consists of water bodies, green roofs and facades, street trees and urban forests (Zölch et al., 2016; Taleghani, 2018; Lai et al., 2019). Responses to green infrastructure are taxa-specific, but overall, green infrastructure can significantly benefit urban biodiversity (Filazzola et al., 2019), and also improve human thermal comfort and decrease human heat mortality in cities (Gillerot et al., 2022; lungman et al., 2023).

## 4 | METHODS FOR MICROCLIMATE SCIENCE

### 4.1 | Advances in data acquisition

Microclimate measurements rely to a large extent on in situ sensors for obtaining data on local temperature, water, solar radiation, cloud, wind and evaporation conditions (Figure 3). In-situ sensors now form part of the toolkit of many ecological studies due to the improvements in chip devices, battery



**FIGURE 3** Methods for microclimate science. This conceptual figure presents examples discussed in the main text on how microclimate data and its explanatory variables are acquired from remotely sensed products and in situ measurements (Stage 1). We show examples of key areas where microclimate models have recently improved, from calibration to modelling methods and computational efficiency (Stage 2).



technology, cost-effectiveness and the miniaturization of sensors and their hardware (Mickley et al., 2019; Rebaudo et al., 2023; Wild et al., 2019). Moreover, advancements in wireless communications, such as the 'Internet of things' (Li et al., 2015), and data transmission using cellular technology or potentially via satellite, increasingly allow the deployment of these devices in ad hoc mesh networks across a landscape (Keitt & Abelson, 2021). Here, strategically planned study designs lay the foundations for representative microclimate networks (Lembrechts et al., 2021), and new methods are developed to make then most of sparse microclimate ground data, such as signal processing theory, which leverages cyclic microclimate patterns and temporally downscales sparse time-series (von Schmalensee, 2023). Also, animal-borne microclimate sensor networks can provide a biological lens to obtaining microclimate data from land and air (Ellis-Soto et al., 2023), and as a by-product, wildlife camera imagery can provide micrometeorological data on, for example, sunshine, snow and hail (Alison et al., 2023). However, the accuracy of low-cost loggers can be uncertain, and the reduction in size and costs affects the measurement accuracy of accompanying sensors (Maclean et al., 2021; Terando et al., 2017). Therefore, it is often advisable to calibrate sensors against laboratory measurements (e.g. climatic chambers for temperature sensors), to validate sensors by comparing them to a reference, and also to inter-calibrate sensors by comparing them to each other (Heinonen et al., 2014; Playà-Montmany & Tattersall, 2021). In the case of temperature measurements, standard weather station protocols including shading and ventilating thermometers often do not apply as measured microclimatic temperature variation mainly has its origin in low wind speed and variation in solar radiation (Maclean et al., 2021; Terando et al., 2017). Therefore, ultra-fine-wire thermocouples remain recommended for specific purposes, especially when sensors are subjected to direct sunlight (Maclean et al., 2021). Hydric microclimate data can also be challenging to calibrate and validate, both for air and soil humidity measurements. For instance, measurements of soil moisture are influenced by soil heterogeneity and stoniness that affect sensor-soil contact (Robinson et al., 2008; Wild et al., 2019).

Remote sensing allows researchers to capture leaf- to landscape-scale microclimate data with spatio-temporal representativeness, for instance on local temperature conditions (Faye et al., 2016; Zellweger et al., 2019). In structurally complex areas, such as forests, mountains or cities, measurements from a small number of sensors over a short time period will fail to adequately capture the range of microclimate conditions present (De Frenne et al., 2021; Scherrer & Körner, 2009; Zhou et al., 2011). This limitation can be overcome by linking microclimate measurements with remote sensing data on key predictors of microclimates (e.g. Haesen et al., 2021): vegetation and topographic features, and also snow in seasonally snow-covered areas. These data can be used for modelling microclimates across landscapes by filling the gaps between the microclimatic ground data. Spatially continuous structural or spectral data on vegetation and terrain structures can be obtained from satellites, aeroplanes and unoccupied aerial vehicles (UAVs) mounted with, for example,

thermal imaging or light detection and ranging (LiDAR) sensors (Båserud et al., 2020; Davis, Synes, et al., 2019; Kašpar et al., 2021). For instance, high-resolution LiDAR data are openly available for some countries, such as for >15 European countries (<5m resolution) (Kakoulaki et al., 2021). Terrestrial and mobile remote-sensing platforms can overcome canopy occlusion by obtaining measurements from a large range of viewpoints inside the canopy (Calders et al., 2020; Disney, 2019). UAVs enable obtaining data at even higher spatial resolution over limited spatial extents (Duffy et al., 2021; Faye et al., 2016; Hoffrén & García, 2023). Fusing these different types of remotely sensed data with novel approaches of radiative transfer modelling through canopies offers interesting new avenues for microclimate ecology (Jonas et al., 2020). Overall, there is great potential to exploit new modelling advances in further microclimate research.

## 4.2 | Advances in microclimate modelling and data processing

Microclimate models tend to be based on mechanistic understanding of the physical processes governing the energy balance. These models owe their origins to the pioneering work on weather forecasting by Richardson (1922), who demonstrated the application of energy balance equations for modelling the turbulent mixing of the atmosphere-biosphere boundary, and microclimate modelling by Porter et al. (1973), who developed a general microclimate model for solving the heat and water budgets of organisms. Thus, the most recent developments are not in the modelling of microclimate itself, but rather in making complex models more accessible to a wider audience. Recently, a series of microclimate models have been written using the R programming environment (R Core Team, 2022), enabling easy application by ecologists (Kearney et al., 2020; Maclean & Klings, 2021). There are also guides with interactive visualizations for selecting and accessing microclimate data (Meyer et al., 2023). In parallel, the climate modelling community has been including multi-layered canopy representations in multiple land surface models (CLM-ml, ORCHIDEE-CAN, CLM-FATES) (Lawrence et al., 2019) allowing for point site evaluation of coarse microclimate data (Bonan et al., 2021). Such models have the advantage to be directly embedded in earth system model frameworks, therefore opening avenues to study coupled vegetation-microclimate feedbacks from small to large spatial extents.

Microclimate varies considerably at fine temporal resolutions (Bramer et al., 2018). Therefore, mechanistic models are run in sub-daily time increments. It is, in turn, computationally challenging to model microclimate mechanistically over large areas, even with the ongoing rapid advances in computing power. Also, lack of data can hinder the use of mechanistic models that require a comprehensive set of predictors. In part for these reasons, ecologists and biogeographers have tended to seek statistical relationships between microclimates and their drivers, such as topography and vegetation features (Ashcroft et al., 2009; Davis, Synes, et al., 2019), or have

sought to establish these relationships through machine learning (Haesen et al., 2021; Lembrechts et al., 2022). The advantage of statistical and machine learning approaches is that bioclimatic variables of interest are not always needed at high temporal resolution (Hijmans et al., 2005), which can reduce the computational demands of the models. A significant drawback of statistical approaches is that the influence of variables used as predictors in statistical models, such as terrain and vegetation, varies in space and time. Thus, relationships derived at one location or time-period cannot necessarily be readily applied to others (Aalto et al., 2022). This could be overcome by modelling spatiotemporally varying relationships, that is, by using geographically weighted regression. Databases have emerged to provide the large precalculated microclimate datasets that are needed for modelling the relationships accurately across a range of spatial extents up to global coverage, including, for instance, projections of past and future microclimates (Levy et al., 2016), hourly estimates of historical microclimates (Kearney, 2019) and global soil temperatures (Lembrechts et al., 2020). However, the data can originate from different sources and require preprocessing. Also, microclimate data processing has advanced, for instance, with the advent of automated R packages that are suited for gap filling, flagging erroneous measurements, calculation of summary statistics and analysing thermal images (Senior et al., 2019), and for microclimate data handling and standardized analyses (Man et al., 2023).

The fusion of statistical and mechanistic approaches to model microclimates shows promise for developing mechanistically informed and computationally efficient methods. The application of statistical model emulation techniques that reproduce the behaviour of more complex models using techniques routinely adopted in other areas of climate modelling could significantly reduce computational run times (Baker et al., 2022). Further implementation requires a breakdown of traditional barriers between disciplines as far apart as ecology, meteorology and computer science (Briscoe et al., 2023). Also, recent developments in hardware and software provide potential solutions to the computational challenge of modelling microclimates. First is the modern computationally efficient programming language, Julia (Bezanson et al., 2018). Julia is similar to dynamic languages like Python and R, yet it compiles packages and user scripts down to machine code at run-time, thereby achieving speed comparable to Fortran or C++, and support for graphics processing unit-based programming geared at optimizing parallel computing is under active development (Besard et al., 2019; Schouten et al., 2022). Second is the burgeoning computational infrastructure for model processing, development and testing. Central to this infrastructure is the growing availability of affordable cloud-based computing and storage for back-end processing. Coupled with databases for model testing and comparisons (see e.g. Dietze et al., 2021), such frameworks provide a robust infrastructure for collaborative model development and processing at massive scales. These advancements in data collection, modelling and processing collectively enable us to attain microclimatic data at increasingly finer spatio-temporal resolutions and increasingly larger spatio-temporal extents, aligning more and more closely with the scales at which organisms operate.

### 4.3 | Finer resolution is not necessarily the better solution

Despite the importance of microclimates across many aspects of ecology and biogeography, we stress that a finer spatio-temporal resolution is not always necessary. Indeed, some organisms and ecosystem functions operate at spatial or temporal extents at which macroclimate data are more appropriate, thus, research questions do not automatically require a microclimate approach. In some cases, microclimate data did improve ecological models (forest plants, see Haesen, Lenoir, et al., 2023; and tundra plants see Kemppinen et al., 2021), yet, one approach is not necessarily transferable to other organisms (Lembrechts, Lenoir, et al., 2019). For instance, decade-long gridded air temperature data did outperform short-term soil temperature data in distribution models of bacterial membrane lipids with long-term stability in the soil (Halffman et al., 2022), as patterns that form over decades or centuries do not relate to short-term microclimatic fluctuations. These examples highlight that methods, including microclimate data and tools, should always be hypothesis-driven and justified by ecological and biogeographical theory. In many cases, the use of macroclimate data can be sufficient, or macroclimate data could simply be downscaled using, for example, fine-scaled topographic proxies (Kusch & Davy, 2022). Therefore, the microclimate approach is not a default answer to all ecological and biogeographical questions.

## 5 | WHAT'S NEXT?

In this perspective paper, we showcased that microclimate ecology and biogeography have evolved into a distinct, global discipline that is relevant across taxa, ecosystems and biomes. We highlighted the most substantial recent microclimate advances at the core of ecology and biogeography. Microclimate science is rooted in environmental biophysics and has recently experienced a surge of methodological progress, such as in logger autonomy, measurement accuracy and computing power allowing advancements in microclimate investigations and applications. This recent unlocking of microclimatic data and knowledge is welcomed, as microclimates are inseparable from the physiological constraints of individuals, populations, communities and ecosystems. Consequently, microclimates are also critical for understanding the influence of global change drivers, such as climate and land-use change on ecology and biogeography. As a result, microclimate science stands at the core of multiple important applications in ecosystem management, such as biodiversity conservation, forestry and urban ecology. Nevertheless, major steps are also ahead for this emerging field to have it reach its full potential.

First of all, global microclimate research should be conscious of its biases. For instance, forest and tundra biomes are well represented in the microclimate literature, while microclimates matter to many terrestrial organisms across all terrestrial biomes. Second, it is also important to note that in the English-written scientific literature,

microclimate ecology and biogeography are largely represented by studies, researchers and institutions of European, North American and Australian origin. We emphasize that these knowledge gaps and biases are important to consider in all future research that aims for a genuinely global coverage in microclimate investigations. This is key for making ecology and biogeography a more global endeavour (Nuñez et al., 2021).

### 5.1 | Knowledge gaps in microclimate investigations in ecology and biogeography

The mismatches between macroclimate and microclimate should be considered when predicting responses of organisms to climate change (Liancourt et al., 2020; Zellweger et al., 2020). It is crucial to understand the influence of microclimates on organisms under climate change, but there are many remaining unknowns. This would require measuring and modelling the effects of all different microclimatic conditions that influence a given organism and its functions (Kemppinen & Niittynen, 2022). This could, for example, be achieved by coupling observational approaches with experiments, which would allow understanding of the climatic optima and tolerance levels of the organism (Ripley et al., 2020; Vandvik et al., 2020). Also, mobile organisms can move between microclimates in search of more suitable conditions (Frey, Hadley, & Betts, 2016; Kim et al., 2022), however, more investigation is needed to understand which organisms exploit microrefugia under climate change and why.

Microclimate science is increasingly incorporated into ecological and biogeographical questions at local to regional extents (De Frenne et al., 2021), but questions of continental or global extents are rare (but see e.g. Haesen, Lenoir, et al., 2023; Risch et al., 2023). Incorporating the principles and approaches of microclimate science into studies beyond local extents would call for improved global data integration. This would also require the harmonization of measurement methods and increased monitoring of remote, undersampled areas and ecosystems, such as tropics, deserts and tundra. The first is partly hindered by the lack of standard guidelines that would increase comparability of microclimate data (Maclean et al., 2021), and the latter by the cost of microclimate sensors which is not globally accessible (Nuñez et al., 2021). However, some microclimate products, such as databases of modelled soil and near-surface temperatures, have recently become openly available at continental and global extents (Haesen et al., 2021; Lembrechts et al., 2022).

Lastly, microclimate investigations on larger organisms and above-ground systems are plentiful, whereas, more research is needed on microclimate relationships of microorganisms and below-ground organisms and ecosystem processes. However, investigations in soil ecology are partly hindered due to a lack of high-resolution data on belowground microclimates (Eisenhauer et al., 2022).

### 5.2 | Knowledge gaps in microclimate applications in ecosystem management

More evidence is needed on the outcomes of microclimate management. This evidence should show when and where microclimate management is required for promoting and protecting biodiversity (Ellis, 2020; Tinya et al., 2021). Currently, the evidence for microclimate management to build climate-resilient ecosystems is often theoretical (Hylander et al., 2022; Morelli et al., 2020), and therefore, additional data could strengthen these links.

There is a need for identifying general patterns of microclimate-organism relationships across and within ecosystems (Kemppinen et al., 2021). For example, what makes microclimates act as microrefugia varies by site, by species and potentially by life stage, each depending on different spatiotemporal factors and scales (Caron et al., 2021; Greiser et al., 2022). Thus, not all microrefugia are equally valuable for protecting biodiversity (Hylander et al., 2015).

Microclimate science can be used beyond ecology and biogeography. This could lead to new knowledge and applications in microclimate ecology and urban ecology (lungman et al., 2023; Roman et al., 2021), microclimate biogeography and agriculture (Gardner et al., 2021) and microclimate biogeography and health geography (Paijmans et al., 2010; Wimberly et al., 2020; Wong & Jim, 2017). Microclimate science can be used to address major societal challenges, such as health and well-being (Gillerot et al., 2022; Jenerette et al., 2016), green energy efficiency (Shafique et al., 2020) and socioeconomic injustice (Ghosh et al., 2022; Yin et al., 2023). By embracing interdisciplinarity, microclimate science can be exploited in solving these crucial issues for an ecologically and socioeconomically sustainable future.

### 5.3 | Knowledge gaps in methods for microclimate science

Methods for microclimate science should aim to achieve a more flexible spatio-temporal scaling of microclimate data. This entails developing a comprehensive library of gridded microclimate products that match the scale and extent required in specific research questions. However, pursuing higher resolutions is not valuable in itself in ecological and biogeographical investigations, as the inclusion of microclimate mechanisms, especially those non-linearly related to macroclimate, takes precedence over spatiotemporal resolution (Bennie et al., 2014; Bütikofer et al., 2020). Nonetheless, most existing products lack in at least one dimension, whether it be in spatial or temporal resolution, and/or mechanistic proximity. Enhancing these dimensions can be accomplished by integrating open access data platforms for in situ data, such as the SoilTemp database (Lembrechts et al., 2020b), gridded microclimate products (e.g. Haesen, Lembrechts, et al., 2023; Klimes et al., 2022) and increased efficiency and scalability of mechanistic microclimate models (Maclean & Klimes, 2021).

Importantly, microclimate data should evolve from stationary to dynamic products (Kearney et al., 2020). For instance, future microclimatic data are largely lacking, since the currently available microclimate datasets with a broad spatial extent only provide bioclimatic variables for the present (Haesen, Lembrechts, et al., 2023; Lembrechts et al., 2022). Ideally, datasets would also capture microclimates in all three dimensions of space. Ultimately, predictors used for modelling microclimates should be advanced to accommodate this progress (e.g. land-use change scenarios).

Integrating microclimate-vegetation feedback into global change biology is an important avenue (Bonan et al., 2021). This could be further developed by coupling airborne laser scanning-based single tree-delineation methods with radiative transfer and microclimate models (Webster et al., 2020). This would allow for spatially extensive and explicit simulations of microclimate dynamics under, for instance, different management regimes, natural disturbance dynamics or climate scenarios.

We have demonstrated that endeavours in microclimate ecology and biogeography are worthwhile and can provide many new avenues for future research. The constantly evolving methods for microclimate science open new possibilities in the investigations of microclimate-organism relationships that can be further applied into ecosystem management, such as biodiversity conservation. We hope to have inspired fellow ecologists and biogeographers to find more ways to increase the awareness of microclimates and their importance in our fields and beyond.

## AUTHOR CONTRIBUTIONS

Julia Kemppinen, Jonas J Lembrechts, Koenraad Van Meerbeek and Pieter De Frenne coordinated and led the writing process. Jofre Carnicer, Nathalie Isabelle Chardon, Paul Kardol, Jonathan Lenoir, Daijun Liu, Ilya Maclean, Jan Pergl, Patrick Saccone, Rebecca A. Senior, Ting Shen, Sandra Słowińska, Vigdis Vandvik and Jonathan von Oppen led the writing of different sections. Julia Kemppinen, Jonas J Lembrechts, Koenraad Van Meerbeek, Jofre Carnicer, Nathalie Isabelle Chardon, Paul Kardol, Jonathan Lenoir, Daijun Liu, Ilya Maclean, Patrick Saccone, Rebecca A. Senior, Ting Shen, Sandra Słowińska, Vigdis Vandvik, Jonathan von Oppen, Juha Aalto, Romain Bertrand, Jeremy Borderieux, Josef Brůna, Lauren Buckley, Jelena Bujan, Angelica Casanova-Katny, Ditte Marie Christiansen, Flavien Collart, Raquel Díaz Borrego, Diego Ellis-Soto, Elise Gallois, Loïc Gillerot, Caroline Greiser, Eva Gril, Per-Ola Hedwall, Gabriel Hes, Kristoffer Hylander, Borja Jiménez-Alfaro, Tommaso Jucker, David Klimes, Bence Kovács, Eduardo Eiji Maeda, Matěj Man, Corrie Mathiak, Ilona Naujokaitis-Lewis, Ivan Nijs, Martin Nuñez, Anna Orczewska, Sylvain Pincebourde, Roman Plichta, Susan Quick, David Renault, Laura Segura-Hernández, Federico Selvi, Jens-Christian Svenning, Anouch Tamian, Arno Thomaes, Brittany Trew, Liesbeth van den Brink, Pieter Vangansbeke, Maria Vives-Inglá, Loke von Schmalensee, Runxi Wang, Joseph Williamson, Florian Zellweger, Emmanuel Junior Zuza and Pieter De Frenne provided ideas. Julia Kemppinen, Jonas J Lembrechts, Koenraad Van Meerbeek, Jofre Carnicer, Nathalie Isabelle Chardon, Paul Kardol, Jonathan Lenoir,

Daijun Liu, Ilya Maclean, Jan Pergl, Patrick Saccone, Rebecca A. Senior, Ting Shen, Sandra Słowińska, Jonathan von Oppen, Juha Aalto, Rémy Beugnon, Jeremy Borderieux, Josef Brůna, Angelica Casanova-Katny, Karen De Pauw, Michele Di Musciano, Raquel Díaz Borrego, Joan Díaz-Calafat, Diego Ellis-Soto, Maria Begoña García, Eva Gril, Stef Haesen, Arndt Hampe, Gabriel Hes, Raúl Hoffrén, David Klimes, Martin Kopecký, Eduardo Eiji Maeda, František Máliš, Matěj Man, Eric Meineri, Pablo Peña-Aguilera, Roman Plichta, David Renault, Lorenzo Ricci, Laura Segura-Hernández, Federico Selvi, Jens-Christian Svenning, Arno Thomaes, Liesbeth van den Brink, Pieter Vangansbeke, Michaela Vitkova, Runxi Wang, Jan Wild, Joseph Williamson, Florian Zellweger, Emmanuel Junior Zuza and Pieter De Frenne provided text. Julia Kemppinen, Jonas J Lembrechts, Koenraad Van Meerbeek, Jofre Carnicer, Nathalie Isabelle Chardon, Paul Kardol, Jonathan Lenoir, Daijun Liu, Jan Pergl, Patrick Saccone, Rebecca A. Senior, Ting Shen, Sandra Słowińska, Vigdis Vandvik, Jonathan von Oppen, Cleo Bertelsmeier, Romain Bertrand, Rémy Beugnon, Jeremy Borderieux, Josef Brůna, Lauren Buckley, Jelena Bujan, Angelica Casanova-Katny, Ditte Marie Christiansen, Flavien Collart, Karen De Pauw, Leen Depauw, Raquel Díaz Borrego, Joan Díaz-Calafat, Diego Ellis-Soto, Raquel Esteban, Maria Begoña García, Loïc Gillerot, Caroline Greiser, Eva Gril, Stef Haesen, Arndt Hampe, Gabriel Hes, Helena Hespanhol, Raúl Hoffrén, Kristoffer Hylander, Borja Jiménez-Alfaro, Tommaso Jucker, David Klimes, Martin Kopecký, Bence Kovács, Eduardo Eiji Maeda, František Máliš, Corrie Mathiak, Eric Meineri, Ilona Naujokaitis-Lewis, Anna Orczewska, Pablo Peña-Aguilera, Sylvain Pincebourde, Susan Quick, David Renault, Lorenzo Ricci, Tuuli Rissanen, Laura Segura-Hernández, Federico Selvi, Lydia Soifer, Fabien Spicher, Jens-Christian Svenning, Anouch Tamian, Arno Thomaes, Brittany Trew, Stijn Van de Vondel, Liesbeth van den Brink, Pieter Vangansbeke, Michaela Vitkova, Maria Vives-Inglá, Loke von Schmalensee, Joseph Williamson, Florian Zellweger, Emmanuel Junior Zuza and Pieter De Frenne provided references. Julia Kemppinen, Jonas J Lembrechts, Koenraad Van Meerbeek, Jofre Carnicer, Nathalie Isabelle Chardon, Paul Kardol, Jonathan Lenoir, Daijun Liu, Ilya Maclean, Patrick Saccone, Rebecca A. Senior, Ting Shen, Sandra Słowińska, Vigdis Vandvik, Jonathan von Oppen, Juha Aalto, Biruk Ayalew, Olivia Bates, Cleo Bertelsmeier, Romain Bertrand, Rémy Beugnon, Jeremy Borderieux, Josef Brůna, Lauren Buckley, Jelena Bujan, Angelica Casanova-Katny, Ditte Marie Christiansen, Flavien Collart, Emiel De Lombaerde, Karen De Pauw, Leen Depauw, Michele Di Musciano, Raquel Díaz Borrego, Joan Díaz-Calafat, Diego Ellis-Soto, Raquel Esteban, Geerte Fálthammar de Jong, Elise Gallois, Maria Begoña García, Loïc Gillerot, Caroline Greiser, Eva Gril, Stef Haesen, Arndt Hampe, Per-Ola Hedwall, Gabriel Hes, Helena Hespanhol, Raúl Hoffrén, Kristoffer Hylander, Borja Jiménez-Alfaro, Tommaso Jucker, David Klimes, Joonas Kolstela, Martin Kopecký, Bence Kovács, Eduardo Eiji Maeda, František Máliš, Matěj Man, Corrie Mathiak, Eric Meineri, Ilona Naujokaitis-Lewis, Ivan Nijs, Signe Normand, Martin Nuñez, Anna Orczewska, Pablo Peña-Aguilera, Sylvain Pincebourde, Roman Plichta, Susan Quick, David Renault, Lorenzo Ricci, Tuuli Rissanen, Laura Segura-Hernández, Federico Selvi, Josep



M Serra-Diaz, Lydia Soifer, Fabien Spicher, Jens-Christian Svenning, Anouch Tamian, Arno Thomaes, Marijke Thoonen, Brittany Trew, Stijn Van de Vondel, Liesbeth van den Brink, Pieter Vangansbeke, Sanne Verdonck, Michaela Vitkova, Maria Vives-Inгла, Loke von Schmalensee, Runxi Wang, Jan Wild, Joseph Williamson, Florian Zellweger, Xiaqu Zhou, Emmanuel Junior Zuza and Pieter De Frenne read the manuscript. Julia Kemppinen, Jonas J Lembrechts, Koenraad Van Meerbeek, Jonathan Lenoir, Daijun Liu, Ilya Maclean, Patrick Saccone, Rebecca A. Senior, Ting Shen, Sandra Stowińska, Vigdis Vandvik, Jonathan von Oppen, Juha Aalto, Romain Bertrand, Rémy Beugnon, Jeremy Borderieux, Josef Brůna, Lauren Buckley, Jelena Bujan, Angelica Casanova-Katny, Emiel De Lombaerde, Karen De Pauw, Leen Depauw, Michele Di Musciano, Joan Díaz-Calafat, Raquel Esteban, Geerte Fálthammar de Jong, Elise Gallois, Maria Begoña Garcia, Loïc Gillerot, Eva Gril, Stef Haesen, Arndt Hampe, Per-Ola Hedwall, Gabriel Hes, Helena Hespanhol, Kristoffer Hylander, Borja Jiménez-Alfaro, Tommaso Jucker, David Klingses, Martin Kopecký, Bence Kovács, Eduardo Eiji Maeda, František Máliš, Matěj Man, Eric Meineri, Ilona Naujokaitis-Lewis, Ivan Nijs, Signe Normand, Martin Nuñez, Anna Orczewska, Pablo Peña-Aguilera, Sylvain Pincebourde, Roman Plichta, Susan Quick, David Renault, Lorenzo Ricci, Tuuli Rissanen, Laura Segura-Hernández, Federico Selvi, Lydia Soifer, Fabien Spicher, Jens-Christian Svenning, Anouch Tamian, Arno Thomaes, Stijn Van de Vondel, Liesbeth van den Brink, Pieter Vangansbeke, Sanne Verdonck, Michaela Vitkova, Maria Vives-Inгла, Loke von Schmalensee, Runxi Wang, Jan Wild and Pieter De Frenne provided comments.

## AFFILIATIONS

<sup>1</sup>Geography Research Unit, University of Oulu, Oulu, Finland

<sup>2</sup>Research Group Plants and Ecosystems (PLECO), University of Antwerp, Wilrijk, Belgium

<sup>3</sup>Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium

<sup>4</sup>Department of Evolutionary Biology, Environmental Sciences and Ecology, University of Barcelona/CREAF/IRBIO, Barcelona, Spain

<sup>5</sup>Biodiversity Research Centre, University of British Columbia, Vancouver, British Columbia, Canada

<sup>6</sup>Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Uppsala, Sweden

<sup>7</sup>UMR CNRS 7058 Ecologie et Dynamique Des systèmes anthropisés (EDYSAN), Université de Picardie Jules Verne, Amiens, France

<sup>8</sup>Department of Botany and Biodiversity Research, University of Vienna, Wien, Austria

<sup>9</sup>Environment and Sustainability Institute, University of Exeter, Penryn, UK

<sup>10</sup>Institute of Botany, Czech Academy of Sciences, Pruhonice, Czech Republic

<sup>11</sup>GLORIA Coordination Team, OeAW, IGF and BOKU, DIBB, Wien, Austria

<sup>12</sup>Conservation Ecology Group, Department of Biosciences, Durham University, Durham, UK

<sup>13</sup>Institute of Botany, University of Liège, Liège, Belgium

<sup>14</sup>Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Yunnan, China

<sup>15</sup>Climate Research Department, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Warsaw, Poland

<sup>16</sup>Department of Biological Sciences and Bjerknes Centre of Climate Research, University of Bergen, Bergen, Norway

<sup>17</sup>Section for Ecoinformatics and Biodiversity & Center for Biodiversity Dynamics in a Changing World (BIOCHANGE), Department of Biology, Aarhus University, Aarhus C, Denmark

<sup>18</sup>No departments at the Finnish Meteorological Institute, Finnish Meteorological Institute, Helsinki, Finland

<sup>19</sup>Department of Ecology, Environment and Plant Sciences, Stockholm University, Stockholm, Sweden

<sup>20</sup>Department of Ecology and Evolution, University of Lausanne, Lausanne, Switzerland

<sup>21</sup>Centre de Recherche sur la Biodiversité et l'Environnement (CRBE UMR5300), Université de Toulouse III Paul Sabatier, CNRS, IRD, Toulouse Cedex 9, France

<sup>22</sup>German Center for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany

<sup>23</sup>Leipzig Institute for Meteorology, Universität Leipzig, Leipzig, Germany

<sup>24</sup>CNRS, EPHE, IRD, CEFE, University of Montpellier, Montpellier Cedex 5, France

<sup>25</sup>AgroParisTech, INRAE, UMR Silva, Université de Lorraine, Nancy, France

<sup>26</sup>Department of Biology, University of Washington, Seattle, Washington, USA

<sup>27</sup>Laboratorio de Ecofisiología Vegetal y Cambio Climático, Departamento de Ciencias Veterinarias y Salud Pública, Facultad de Recursos Naturales, Universidad Católica de Temuco, Temuco, Chile

<sup>28</sup>Department of Plant and Environmental Sciences, University of Copenhagen, Denmark, Sweden

<sup>29</sup>Forest & Nature Lab, Department of Environment, Ghent University, Gontrode-Melle, Belgium

<sup>30</sup>Department of Life Health and Environmental Science, University of L'Aquila, L'Aquila, Italy

<sup>31</sup>CREAF, Barcelona, Spain

<sup>32</sup>Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Alnarp, Sweden

<sup>33</sup>Department of Ecology and Evolutionary Biology, Yale University, New Haven, Connecticut, USA

<sup>34</sup>Department of Plant Biology and Ecology, University of the Basque Country (UPV/EHU), Leioa, Spain

<sup>35</sup>Department of Biology and Environmental Science, University of Gothenburg, Göteborg, Sweden

<sup>36</sup>School of GeoSciences, University of Edinburgh, Edinburgh, UK

<sup>37</sup>Pyrenean Institute of Ecology (CSIC), Zaragoza, Spain

<sup>38</sup>Department of Physical Geography, Stockholm University, Stockholm, Sweden

<sup>39</sup>UMR CNRS 7058 "Ecologie et Dynamique Des Systèmes Anthropisés" (EDYSAN), Amiens, France

<sup>40</sup>INRAE, University of Bordeaux, BIOGECO, Cestas, France

<sup>41</sup>BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Vairão, Portugal

<sup>42</sup>Department of Geography and Land Management, University of Zaragoza (Spain), Zaragoza, Spain

<sup>43</sup>Biodiversity Research Institute, University of Oviedo, Mieres, Spain

<sup>44</sup>School of Biological Sciences, University of Bristol, Bristol, UK

<sup>45</sup>School of Natural Resources and Environment, University of Florida, Gainesville, Florida, USA

<sup>46</sup>Institute of Botany of the Czech Academy of Sciences, University of Life Sciences Prague, Prague, Czech Republic

<sup>47</sup>Centre for Ecological Research, Institute of Ecology and Botany, Vácrátót, Hungary

<sup>48</sup>Department of Plant Systematics, Ecology and Theoretical Biology, Eötvös Loránd University, Budapest, Hungary

<sup>49</sup>Department of Geosciences and Geography, Faculty of Science, University of Helsinki, Helsinki, Finland

<sup>50</sup>Technical University in Zvolen, Zvolen, Slovakia

<sup>51</sup>Chair of Soil Science, Geography Institute, Friedrich-Schiller-Universität Jena, Jena, Germany

<sup>52</sup>Aix-Marseille University, Marseille, France

<sup>53</sup>National Wildlife Research Centre, Environment and Climate Change Canada, Carleton University, Ottawa, Ontario, Canada

<sup>54</sup>Plants and Ecosystems, Department of Biology, University of Antwerp, Wilrijk, Belgium

<sup>55</sup>Department of Biology, Aarhus University, Aarhus C, Denmark

<sup>56</sup>Department of Biology and Biochemistry, University of Houston, Houston, Texas, USA



- <sup>57</sup>Faculty of Biology, Biotechnology and Environmental Protection, University of Silesia, Katowice, Poland
- <sup>58</sup>Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden
- <sup>59</sup>Institut de Recherche sur la Biologie de l'Insecte, UMR 7261, CNRS - Université de Tours, Tours, France
- <sup>60</sup>Department of Forest Botany, Dendrology and Geobiocoenology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic
- <sup>61</sup>Birmingham Institute of Forest Research, University of Birmingham, Birmingham, UK
- <sup>62</sup>CNRS, ECOBIO (Ecosystèmes, Biodiversité, Evolution), UMR, University of Rennes, Rennes, France
- <sup>63</sup>School of Biological Sciences, University of Nebraska-Lincoln, Lincoln, Nebraska, USA
- <sup>64</sup>Department of Agriculture, Food, Environment and Forestry, University of Firenze, Palermo, Italy
- <sup>65</sup>AgroParisTech, Silva, Université de Lorraine, Nancy, France
- <sup>66</sup>UMR CNRS 7058, Écologie et Dynamique Des Systèmes Anthropisés (EDYSAN), Amiens, France
- <sup>67</sup>Department of Biology, Center for Ecological Dynamics in a Novel Biosphere (ECONOVO) & Center for Biodiversity Dynamics in a Changing World (BIOCHANGE), Aarhus University, Aarhus, Denmark
- <sup>68</sup>IPHC CNRS UMR 7178, University of Strasbourg, Strasbourg, France
- <sup>69</sup>Research Institute for Nature and Forest (INBO), Brussels, Belgium
- <sup>70</sup>Department of Biology, University of Antwerp, Antwerp, Belgium
- <sup>71</sup>ECOBIOIS, University of Concepcion, Chile, Germany
- <sup>72</sup>Plant Ecology Group, University of Tübingen, Tübingen, Germany
- <sup>73</sup>Earth and Life Institute, Environmental Sciences, Université Catholique de Louvain, Louvain-la-Neuve, Belgium
- <sup>74</sup>Division of Forest, Nature and Landscape, KU Leuven, Leuven, Belgium
- <sup>75</sup>Department of Invasion Ecology, Institute of Botany, Czech Academy of Sciences, Průhonice, Czech Republic
- <sup>76</sup>Universitat Autònoma de Barcelona, Catalonia, Spain
- <sup>77</sup>Department of Zoology, Stockholm University, Stockholm, Sweden
- <sup>78</sup>School of Biological Sciences, The University of Hong Kong, Hong Kong SAR, China
- <sup>79</sup>Department of Genetics, Evolution and Environment, Centre for Biodiversity and Environment Research, University College London, London, UK
- <sup>80</sup>Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland
- <sup>81</sup>Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium
- <sup>82</sup>School of Environment, Earth and Ecosystem Sciences, The Open University, Milton Keynes, UK

## ACKNOWLEDGEMENTS

We thank our reviewers Janet Franklin and Michael Kearney and our editor Brian Enquist for their valuable comments. We thank Pekka Niittynen for providing a script for automating the management of author information and contributions. The Microclimate Ecology & Biogeography conference in Antwerp, Belgium in 2022 was supported by the Research Foundation Flanders (project W001919N). JK acknowledges funding from the Academy of Finland (grant no. 349606). JJJ and IN acknowledge funding from the Research Foundation Flanders (project 12P1819N) and from BiodivERsA (ASICS project (ANR-20-EBIS-0004, BiodivERsA, BiodivClim call 2019–2020)). JC acknowledges the funding from PID2020-117636GB-C21 and TED2021-132007B-I00. NIC was funded by a Swiss National Science Foundation Postdoc Mobility Fellowship (Grant ID: 194331). PK acknowledges funding from European Research Council (ERC) under the European Union's

Horizon 2020 research and innovation programme (grant agreement no. 864287 –THRESHOLD–ERC-2019-COG). JL acknowledges funding from the Agence Nationale de la Recherche (ANR), under the framework of the young investigators' funding scheme (JCJC Grant N°ANR-19-CE32-0005-01: IMPRINT project). DL is financially supported by the FWF Austrian Science Foundation (Lise Meitner Programme M2714-B29). JP and MV were supported by BiodivClim Call 2019 (TACR SS70010001; Technology Agency of the Czech Republic), the project DivLand (TACR SS02030018) and long-term research development project RVO 67985939 (Czech Academy of Sciences). SS is supported by the project no. 2022/45/B/ST10/03423 funded by the National Science Centre in Poland. VV acknowledges funding from the Research Council of Norway (grant no. 315249, 274712, 244525). SN and JvO acknowledge funding from the Independent Research Fund of Denmark (grant no. 7027-00133B to SN). JA acknowledges the Academy of Finland Flagship funding (grant no. 337552). RB acknowledges funding from the Saxon State Ministry for Science, Culture and Tourism (SMWK)–[3-7304/35/6-2021/48880]. JeBo acknowledges the funding from the AgroParisTech/ Région Grand-Est joint grant 19\_GE8\_01020p05035. JoBr was supported by the Czech Science Foundation (project 20-28119S) and the long-term research development project RVO 67985939 (Czech Academy of Sciences). ACK acknowledges funding from FOVI 210043 and ANILLO ACONCAGUA ANID ACT 210021. KDP acknowledges funding from the Research Foundation Flanders (FWO) (K.D.P. ASP035-19). LD acknowledges funding from the Research Foundation Flanders (FWO) (1221523N). DES acknowledges funding from NASA FINESST (80NSSC22K1535). RE acknowledges funding: UPV/EHU-GV IT-1648-22 and PID2020-113244GA-C22 (funded by MCIN/ AEI /10.13039/501100011033). EG is funded by the Natural Environment Research Council (NERC) NE/S007407/1. MBG acknowledges the support of the REFUGIA project (PID2021-129056OB-I00). CG received funding from FORMAS [project nr. 2021- 01993]. EG's PhD was funded by the Agence Nationale de la Recherche (ANR), under the framework of the young investigators' funding scheme (JCJC Grant N°ANR-19-CE32-0005-01: IMPRINT project). SH received funding from a FLOF fellowship of the KU Leuven (project nr. 3E190655). HH research is funded by national funds by FCT, under the transitional rule of Decree Law 57/2016–DL57/2016/CP 1334 CT0005. RH acknowledges funding from the Spanish Association of Terrestrial Ecology (AEET) through the programme 'Grants for research projects led by young researchers 2019'. The research was supported by a grant from Formas to KH [2021-00816]. BJA is funded by grant MCI-20-PID2019-108636GA-I00 of the Spanish Research Agency. TJ was supported by a NERC Independent Research Fellowship (grant code: NE/S01537X/1). MK was supported by the Czech Science Foundation (project 20-28119S) and the Czech Academy of Sciences (project RVO 67985939). BK was supported by the ÚNKP-22-4 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund (ÚNKP-22-4-II-ELTE-318).

FM was supported by Slovak Research and Development Agency project APVV-19-0319. MM was supported by the Czech Science Foundation (project 20-28119S) and the Czech Academy of Sciences (project RVO 67985939). CM acknowledges the IntegSaatprojekt and its funders (FKZ: 2220WK65X4), as well as the Honours Programme for Future Researchers at the Friedrich-Schiller-University. EM acknowledges the funding from the Région Sud Provence-Alpes-Côte d'Azur (AAP 2020 n°02697 MICROMED project). JLL and IN acknowledge funding from the Research Foundation Flanders (project 12P1819N) and from BiodivERsA (ASICS project (ANR-20-EBI5-0004, BiodivERsA, BiodivClim call 2019–2020)). DR is supported by the ASICS project (ANR-20-EBI5-0004, BiodivERsA, BiodivClim call 2019–2020), the French Polar Institute (Project 136-SUBANTECO), Zone Atelier CNRS Antarctique et Terres Australes (ZATA 'Antarctic') and CNRS (IRP PRICES). TR acknowledges funding from the Doctoral Programme in Geosciences. JMSD was supported by the ANR-JCJC (Agence Nationale de la Recherche, jeunes chercheuses et jeunes chercheurs) SEEDFOR (ANR-21-CE32-0003). JMSD acknowledges the support from NASA for UConn's Ecological Modelling Institute (#80NSSC 22K0883). JCS considers this work a contribution to the Center for Ecological Dynamics in a Novel Biosphere (ECONOVO), funded by the Danish National Research Foundation (grant DNRF173) and his VILLUM Investigator project 'Biodiversity Dynamics in a Changing World', funded by VILLUM FONDEN (grant 16549). SVDV is a PhD fellow supported by the Research Foundation Flanders (FWO; 1590923N). LvdB acknowledges Conaf, and Comunidad agrícola Quebrada de Talca, Chile. MV was supported by a research grant from the BiodivClim Call 2019 (grant nr. TACR SS70010001) and long-term research development project RVO 67985939 from the Czech Academy of Sciences. can have the same acknowledgement as Jan Pergl. MV-I was supported by the Spanish Ministry of Science and Innovation through a doctoral grant (FPU17/05869). JW was supported by the Czech Science Foundation (project 20-28119S) and the Czech Academy of Sciences (project RVO 67985939). F.Z. was funded by the Swiss National Science Foundation (project number 193645). E.Z. was funded by the Global Challenges Research Fund through the Open University and the EarthWatch Community Science Camp (NERC-UKRI Grant no. NE/S017437/1).

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

Not applicable.

## ORCID

Julia Kemppinen  <https://orcid.org/0000-0001-7521-7229>

Jonas J. Lembrechts  <https://orcid.org/0000-0002-1933-0750>

Koenraad Van Meerbeek  <https://orcid.org/0000-0002-9260-3815>

[org/0000-0002-9260-3815](https://orcid.org/0000-0002-9260-3815)

Jofre Carnicer  <https://orcid.org/0000-0001-7454-8296>

Nathalie Isabelle Chardon  <https://orcid.org/0000-0001-9120-4778>

Paul Kardol  <https://orcid.org/0000-0001-7065-3435>

Jonathan Lenoir  <https://orcid.org/0000-0003-0638-9582>

Daijun Liu  <https://orcid.org/0000-0002-0993-0832>

Ilya Maclean  <https://orcid.org/0000-0001-8030-9136>

Jan Pergl  <https://orcid.org/0000-0002-0045-1974>

Patrick Saccone  <https://orcid.org/0000-0001-8820-593X>

Rebecca A. Senior  <https://orcid.org/0000-0002-8208-736X>

Ting Shen  <https://orcid.org/0000-0002-3061-624X>

Sandra Słowińska  <https://orcid.org/0000-0003-4233-7384>

Vigdis Vandvik  <https://orcid.org/0000-0003-4651-4798>

Jonathan von Oppen  <https://orcid.org/0000-0001-6346-2964>

Juha Aalto  <https://orcid.org/0000-0001-6819-4911>

Biruk Ayalew  <https://orcid.org/0000-0002-4658-7850>

Cleo Bertelsmeier  <https://orcid.org/0000-0003-3624-1300>

Romain Bertrand  <https://orcid.org/0000-0003-2386-9174>

Rémy Beugnon  <https://orcid.org/0000-0003-2457-5688>

Jeremy Borderieux  <https://orcid.org/0000-0003-3993-1067>

Josef Brůna  <https://orcid.org/0000-0002-4839-4593>

Lauren Buckley  <https://orcid.org/0000-0003-1315-3818>

Jelena Bujan  <https://orcid.org/0000-0002-7938-0266>

Angelica Casanova-Katny  <https://orcid.org/0000-0003-3860-1445>

[org/0000-0003-3860-1445](https://orcid.org/0000-0003-3860-1445)

Ditte Marie Christiansen  <https://orcid.org/0000-0002-7020-5082>

[org/0000-0002-7020-5082](https://orcid.org/0000-0002-7020-5082)

Flavien Collart  <https://orcid.org/0000-0002-4342-5848>

Emiel De Lombaerde  <https://orcid.org/0000-0002-0050-2735>

Karen De Pauw  <https://orcid.org/0000-0001-8369-2679>

Leen Depauw  <https://orcid.org/0000-0001-5703-6811>

Michele Di Musciano  <https://orcid.org/0000-0002-3130-7270>

Raquel Díaz Borrego  <https://orcid.org/0000-0002-5957-1030>

Joan Díaz-Calafat  <https://orcid.org/0000-0002-5823-2176>

Diego Ellis-Soto  <https://orcid.org/0000-0003-4766-021X>

Raquel Esteban  <https://orcid.org/0000-0003-2560-3310>

Geerte Fäthammar de Jong  <https://orcid.org/0000-0003-3774-1059>

[org/0000-0003-3774-1059](https://orcid.org/0000-0003-3774-1059)

Elise Gallois  <https://orcid.org/0000-0002-9402-1931>

Maria Begoña García  <https://orcid.org/0000-0003-4231-6006>

Loïc Gillerot  <https://orcid.org/0000-0002-0699-4478>

Caroline Greiser  <https://orcid.org/0000-0003-4023-4402>

Eva Gril  <https://orcid.org/0000-0002-7340-8264>

Stef Haesen  <https://orcid.org/0000-0002-4491-4213>

Arndt Hampe  <https://orcid.org/0000-0003-2551-9784>

Per-Ola Hedwall  <https://orcid.org/0000-0002-0120-7420>

Gabriel Hes  <https://orcid.org/0000-0002-0408-8463>

Helena Hespanhol  <https://orcid.org/0000-0002-8109-8112>

Raúl Hoffrén  <https://orcid.org/0000-0002-9123-304X>

Kristoffer Hylander  <https://orcid.org/0000-0002-1215-2648>

Borja Jiménez-Alfaro  <https://orcid.org/0000-0001-6601-9597>

Tommaso Jucker  <https://orcid.org/0000-0002-0751-6312>

David Klings  <https://orcid.org/0000-0002-7900-9379>

Joonas Kolstela  <https://orcid.org/0000-0002-6031-5819>

- Martin Kopecký  <https://orcid.org/0000-0002-1018-9316>
- Bence Kovács  <https://orcid.org/0000-0002-8045-8489>
- Eduardo Eiji Maeda  <https://orcid.org/0000-0001-7932-1824>
- František Máliš  <https://orcid.org/0000-0003-2760-6988>
- Matěj Man  <https://orcid.org/0000-0002-4557-8768>
- Corrie Mathiak  <https://orcid.org/0000-0003-0199-7490>
- Eric Meineri  <https://orcid.org/0000-0001-8825-8986>
- Ilona Naujokaitis-Lewis  <https://orcid.org/0000-0001-9504-4484>
- Ivan Nijs  <https://orcid.org/0000-0003-3111-680X>
- Signe Normand  <https://orcid.org/0000-0002-8782-4154>
- Martin Nuñez  <https://orcid.org/0000-0003-0324-5479>
- Anna Orczewska  <https://orcid.org/0000-0002-7924-9794>
- Pablo Peña-Aguilera  <https://orcid.org/0000-0002-8999-1140>
- Sylvain Pincebourde  <https://orcid.org/0000-0001-7964-5861>
- Roman Plichta  <https://orcid.org/0000-0003-2442-8522>
- Susan Quick  <https://orcid.org/0000-0003-4239-5285>
- David Renault  <https://orcid.org/0000-0003-3644-1759>
- Lorenzo Ricci  <https://orcid.org/0000-0002-0411-2435>
- Tuuli Rissanen  <https://orcid.org/0000-0001-9912-4676>
- Laura Segura-Hernández  <https://orcid.org/0000-0002-1165-3889>
- Federico Selvi  <https://orcid.org/0000-0002-3820-125X>
- Josep M. Serra-Díaz  <https://orcid.org/0000-0003-1988-1154>
- Lydia Soifer  <https://orcid.org/0000-0002-8004-6070>
- Fabien Spicher  <https://orcid.org/0000-0002-9999-955X>
- Jens-Christian Svenning  <https://orcid.org/0000-0002-3415-0862>
- Anouch Tamian  <https://orcid.org/0000-0003-1175-3326>
- Arno Thomaes  <https://orcid.org/0000-0001-5723-5976>
- Marijke Thoonen  <https://orcid.org/0000-0002-0305-5029>
- Brittany Trew  <https://orcid.org/0000-0002-0649-828X>
- Stijn Van de Vondel  <https://orcid.org/0000-0002-0223-7330>
- Liesbeth van den Brink  <https://orcid.org/0000-0003-0313-8147>
- Pieter Vangansbeke  <https://orcid.org/0000-0002-6356-2858>
- Sanne Verdonck  <https://orcid.org/0000-0002-2503-1933>
- Michaela Vitkova  <https://orcid.org/0000-0002-2848-7725>
- Maria Vives-Ingla  <https://orcid.org/0000-0003-4887-8392>
- Loke von Schmalensee  <https://orcid.org/0000-0003-3233-4905>
- Runxi Wang  <https://orcid.org/0000-0003-4902-169X>
- Jan Wild  <https://orcid.org/0000-0003-3007-4070>
- Joseph Williamson  <https://orcid.org/0000-0003-4916-5386>
- Florian Zellweger  <https://orcid.org/0000-0003-1265-9147>
- Xiaqu Zhou  <https://orcid.org/0000-0002-2129-0209>
- Emmanuel Junior Zuza  <https://orcid.org/0000-0001-5706-8637>
- Pieter De Frenne  <https://orcid.org/0000-0002-8613-0943>

## REFERENCES

- Aalto, J., Tyystjärvi, V., Niittynen, P., Kemppinen, J., Rissanen, T., Gregow, H., & Luoto, M. (2022). Microclimate temperature variations from boreal forests to the tundra. *Agricultural and Forest Meteorology*, 323, 109037.
- Ackerly, D. D., Kling, M. M., Clark, M. L., Papper, P., Oldfather, M. F., Flint, A. L., & Flint, L. E. (2020). Topoclimate, refugia, and biotic responses to climate change. *Frontiers in Ecology and the Environment*, 18, 288–297.
- Alison, J., Payne, S., Alexander, J. M., Bjorkman, A. D., Clark, V. R., Gwate, O., Huntsaar, M., Iseli, E., Lenoir, J., Mann, H. M. R., Steenhuisen, S.-L., & Høye, T. T. (2023). Deep learning to extract the meteorological by-catch of wildlife cameras. *bioRxiv*.
- Aronson, M. F. J., La Sorte, F. A., Nilon, C. H., Katti, M., Goddard, M. A., Lepczyk, C. A., Warren, P. S., Williams, N. S. G., Cilliers, S., Clarkson, B., Dobbs, C., Dolan, R., Hedblom, M., Klotz, S., Kooijmans, J. L., Kühn, I., Macgregor-Fors, I., McDonnell, M., Mörtberg, U., ... Winter, M. (2014). A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. *Proceedings. Biological Sciences/The Royal Society*, 281, 20133330.
- Ashcroft, M. B. (2010). Identifying refugia from climate change. *Journal of Biogeography*, 37, 1413.
- Ashcroft, M. B., Chisholm, L. A., & French, K. O. (2009). Climate change at the landscape scale: Predicting fine-grained spatial heterogeneity in warming and potential refugia for vegetation. *Global Change Biology*, 15, 656–667.
- Ashcroft, M. B., Gollan, J. R., Warton, D. I., & Ramp, D. (2012). A novel approach to quantify and locate potential microrefugia using topoclimate, climate stability, and isolation from the matrix. *Global Change Biology*, 18, 1866–1879.
- Baker, E., Harper, A. B., Williamson, D., & Challenor, P. (2022). Emulation of high-resolution land surface models using sparse Gaussian processes with application to JULES. *Geoscientific Model Development*, 15, 1913–1929.
- Båserud, L., Reuder, J., Jonassen, M. O., Bonin, T. A., Chilson, P. B., Jiménez, M. A., & Durand, P. (2020). Potential and limitations in estimating sensible-heat-flux profiles from consecutive temperature profiles using remotely-piloted aircraft systems. *Boundary–Layer Meteorology*, 174, 145–177.
- Basham, E. W., Baecher, J. A., Klimes, D. H., & Scheffers, B. R. (2023). Vertical stratification patterns of tropical forest vertebrates: A meta-analysis. *Biological Reviews of the Cambridge Philosophical Society*, 98, 99–114.
- Baum, W. A., & Court, A. (1949). Research status and needs in microclimatology. *Transactions of the American Geophysical Union*, 30, 488–493.
- Beer, J., Muschler, R., Kass, D., & Somarriba, E. (1998). Shade management in coffee and cacao plantations. *Directions in Tropical Agroforestry Research*, 38, 139–164.
- Begg, G. S., Cook, S. M., Dye, R., Ferrante, M., Franck, P., Lavigne, C., Lövei, G. L., Mansion-Vaquie, A., Pell, J. K., Petit, S., Quesada, N., Ricci, B., Wratten, S. D., & Birch, A. N. E. (2017). A functional overview of conservation biological control. *Crop Protection*, 97, 145–158.
- Bennie, J., Wilson, R. J., MacLean, I. M. D., & Suggitt, A. J. (2014). Seeing the woods for the trees—When is microclimate important in species distribution models? *Global Change Biology*, 20, 2699–2700.
- Bentley, B. P., Kearney, M. R., Whiting, S. D., & Mitchell, N. J. (2020). Microclimate modelling of beach sand temperatures reveals high spatial and temporal variation at sea turtle rookeries. *Journal of Thermal Biology*, 88, 102522.
- Bert, D., Lebourgeois, F., Adib, O., Ducousso, A., Ogée, J., & Hampe, A. (2022). Past and future radial growth and water-use efficiency of *Fagus sylvatica* and *Quercus robur* in a long-term climate refugium. *Dendrochronologia*, 72, 125939.
- Bertrand, R., Riofrío-Dillon, G., Lenoir, J., Drapier, J., de Ruffray, P., Gégout, J.-C., & Loreau, M. (2016). Ecological constraints increase the climatic debt in forests. *Nature Communications*, 7, 12643.
- Besard, T., Foket, C., & De Sutter, B. (2019). Effective extensible programming: Unleashing Julia on GPUs. *IEEE Transactions on Parallel and Distributed Systems*, 30, 827–841.



- Bezanson, J., Chen, J., Chung, B., Karpinski, S., Shah, V. B., Vitek, J., & Zoubritzky, L. (2018). Julia: Dynamism and performance reconciled by design. *Proceedings of the ACM on Programming Languages*, 2, 1–23.
- Blonder, B., Both, S., Coomes, D. A., Elias, D., Jucker, T., Kvasnica, J., Majalap, N., Malhi, Y. S., Milodowski, D., Riutta, T., & Svátek, M. (2018). Extreme and highly heterogeneous microclimates in selectively logged tropical forests. *Frontiers in Forests and Global Change*, 1.
- Bonan, G. B., Patton, E. G., Finnigan, J. J., Baldocchi, D. D., & Harman, I. N. (2021). Moving beyond the incorrect but useful paradigm: Reevaluating big-leaf and multilayer plant canopies to model biosphere-atmosphere fluxes—A review. *Agricultural and Forest Meteorology*, 306, 108435.
- Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97, 147–155.
- Bramer, I., Anderson, B. J., Bennie, J., Bladon, A. J., De Frenne, P., Hemming, D., Hill, R. A., Kearney, M. R., Körner, C., Korstjens, A. H., Lenoir, J., Maclean, I. M. D., Marsh, C. D., Morecroft, M. D., Ohlemüller, R., Slater, H. D., Suggitt, A. J., Zellweger, F., & Gillingham, P. K. (2018). Advances in monitoring and modelling climate at ecologically relevant scales. In *Next generation biomonitoring: Part 1 advances in ecological research* (pp. 101–161). Elsevier.
- Brang, P., Spathelf, P., Larsen, J. B., Bauhus, J., Boncina, A., Chauvin, C., Drossler, L., Garcia-Guemes, C., Heiri, C., Kerr, G., Lexer, M. J., Mason, B., Mohren, F., Muhlethaler, U., Nocentini, S., & Svoboda, M. (2014). Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry*, 87, 492–503.
- Briscoe, N. J., McGregor, H., Roshier, D., Carter, A., Wintle, B. A., & Kearney, M. R. (2022). Too hot to hunt: Mechanistic predictions of thermal refuge from cat predation risk. *Conservation Letters*, 15, e12906.
- Briscoe, N. J., Morris, S. D., Mathewson, P. D., Buckley, L. B., Jusup, M., Levy, O., Maclean, I. M. D., Pincebourde, S., Riddell, E. A., Roberts, J. A., Schouten, R., Sears, M. W., & Kearney, M. R. (2023). Mechanistic forecasts of species responses to climate change: The promise of biophysical ecology. *Global Change Biology*, 29, 1451–1470.
- Brower, L. P., Williams, E. H., Fink, L. S., Slayback, D. A., Ramírez, M. I., García, M. V. L., Zubieta, R. R., Weiss, S. B., Calvert, W. H., & Zuchowski, W. (2011). Overwintering clusters of the monarch butterfly coincide with the least hazardous vertical temperatures in the oyamel forest. *Journal of the Lepidopterists' Society*, 65, 27–46.
- Bujan, J., Yanoviak, S. P., & Kaspari, M. (2016). Desiccation resistance in tropical insects: Causes and mechanisms underlying variability in a Panama ant community. *Ecology and Evolution*, 6, 6282–6291.
- Bütikofer, L., Anderson, K., Bebb, D. P., Bennie, J. J., Early, R. I., & Maclean, I. M. D. (2020). The problem of scale in predicting biological responses to climate. *Global Change Biology*, 26, 6657–6666.
- Cahoon, S. M. P., Sullivan, P. F., Shaver, G. R., Welker, J. M., Post, E., & Holyoak, M. (2012). Interactions among shrub cover and the soil microclimate may determine future Arctic carbon budgets. *Ecology Letters*, 15, 1415–1422.
- Calders, K., Adams, J., Armston, J., Bartholomeus, H., Bauwens, S., Bentley, L. P., Chave, J., Danson, F. M., Demol, M., Disney, M., Gaulton, R., Krishna Moorthy, S. M., Levick, S. R., Saarinen, N., Schaaf, C., Stovall, A., Terry, L., Wilkes, P., & Verbeeck, H. (2020). Terrestrial laser scanning in forest ecology: Expanding the horizon. *Remote Sensing of Environment*, 251, 112102.
- Carnicer, J., Stefanescu, C., Vives-Inglá, M., López, C., Cortizas, S., Wheat, C., Vila, R., Llusà, J., & Peñuelas, J. (2019). Phenotypic biomarkers of climatic impacts on declining insect populations: A key role for decadal drought, thermal buffering and amplification effects and host plant dynamics. *The Journal of Animal Ecology*, 88, 376–391.
- Caron, M. M., Zellweger, F., Verheyen, K., Baeten, L., Hédli, R., Bernhardt-Römermann, M., Berki, I., Brunet, J., Decocq, G., Díaz, S., Dirnböck, T., Durak, T., Heinken, T., Jaroszewicz, B., Kopecký, M., Lenoir, J., Macek, M., Malicki, M., Mäliš, F., ... De Frenne, P. (2021). Thermal differences between juveniles and adults increased over time in European forest trees. *The Journal of Ecology*, 109, 3944–3957.
- Carter, A. L., & Janzen, F. J. (2021). Predicting the effects of climate change on incubation in reptiles: Methodological advances and new directions. *The Journal of Experimental Biology*, 224.
- Cavieres, L. A., Brooker, R. W., Butterfield, B. J., Cook, B. J., Kikvidze, Z., Lortie, C. J., Michalet, R., Pugnaire, F. I., Schöb, C., Xiao, S., Anthelme, F., Björk, R. G., Dickinson, K. J. M., Cranston, B. H., Gavilán, R., Gutiérrez-Girón, A., Kanka, R., Maalouf, J.-P., Mark, A. F., ... Callaway, R. M. (2014). Facilitative plant interactions and climate simultaneously drive alpine plant diversity. *Ecology Letters*, 17, 193–202.
- Checa, M. F., Rodríguez, J., Willmott, K. R., & Liger, B. (2014). Microclimate variability significantly affects the composition, abundance and phenology of butterfly communities in a highly threatened Neotropical dry Forest. *Florida Entomologist*, 97, 1–13.
- Chen, J., Franklin, J. F., & Spies, T. A. (1993). Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. *Agricultural and Forest Meteorology*, 63, 219–237.
- Chen, Y., Liu, Y., Zhang, J., Yang, W., He, R., & Deng, C. (2018). Microclimate exerts greater control over litter decomposition and enzyme activity than litter quality in an alpine forest-tundra ecotone. *Scientific Reports*, 8, 14998.
- Christiansen, D. M., Iversen, L. L., Ehrlén, J., Hylander, K. (2022). Changes in forest structure drive temperature preferences of boreal understorey plant communities. *Journal of Ecology*, 110, 631–643. <https://doi.org/10.1111/1365-2745.13825>
- Curtis, R. J., & Isaac, N. J. B. (2015). The effect of temperature and habitat quality on abundance of the Glanville fritillary on the Isle of Wight: Implications for conservation management in a warming climate. *Journal of Insect Conservation*, 19, 217–225.
- Davis, F. W., Sweet, L. C., Serra-Diaz, J. M., Franklin, J., McCullough, I., Flint, A., Flint, L., Dingman, J. R., Regan, H. M., Syphard, A. D., Hannah, L., Redmond, K., & Moritz, M. A. (2016). Shrinking windows of opportunity for oak seedling establishment in southern California mountains. *Ecosphere*, 7, e01573.
- Davis, F. W., Synes, N. W., Fricker, G. A., McCullough, I. M., Serra-Diaz, J. M., Franklin, J., & Flint, A. L. (2019). LiDAR-derived topography and forest structure predict fine-scale variation in daily surface temperatures in oak savanna and conifer forest landscapes. *Agricultural and Forest Meteorology*, 269, 192–202.
- Davis, K. T., Dobrowski, S. Z., Holden, Z. A., Higuera, P. E., & Abatzoglou, J. T. (2019). Microclimatic buffering in forests of the future: The role of local water balance. *Ecography*, 42, 1–11.
- De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., Ashcroft, M. B., Christiansen, D. M., Decocq, G., De Pauw, K., Govaert, S., Greiser, C., Gril, E., Hampe, A., Jucker, T., Klimes, D. H., Koelemeijer, I. A., Lembrechts, J. J., Marrec, R., ... Hylander, K. (2021). Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology*, 27, 2279–2297.
- de Souza, D. O., dos Santos Alvalá, R. C., & do Nascimento, M. G. (2016). Urbanization effects on the microclimate of Manaus: A modeling study. *Atmospheric Research*, 167, 237–248.
- de Tralantes, C., Dunn, J., Martin, J. M., & Johnson, J. C. (2022). Siblingicide in the city: The urban heat Island accelerates sibling cannibalism in the black widow spider (*Latrodectus hesperus*). *Urban Ecosystems*, 25, 305–312.
- Dietze, M. C., Thomas, R. Q., Peters, J., Boettiger, C., Shiklomanov, A. N., & Ashander, J. (2021). A community convention for ecological forecasting: Output files and metadata.
- Disney, M. (2019). Terrestrial LiDAR: A three-dimensional revolution in how we look at trees. *The New Phytologist*, 222, 1736–1741.

- Dobrowski, S. Z. (2011). A climatic basis for microrefugia: The influence of terrain on climate. *Global Change Biology*, 17, 1022–1035.
- Dobrowski, S. Z., Swanson, A. K., Abatzoglou, J. T., Holden, Z. A., Safford, H. D., Schwartz, M. K., & Gavin, D. G. (2015). Forest structure and species traits mediate projected recruitment declines in western US tree species. *Global Ecology and Biogeography: A Journal of Macroecology*, 24, 917–927.
- Duffy, J. P., Anderson, K., Fawcett, D., Curtis, R. J., & Maclean, I. M. D. (2021). Drones provide spatial and volumetric data to deliver new insights into microclimate modelling. *Landscape Ecology*, 36, 685–702.
- Eisenhauer, N., Bender, S. F., Calderón-Sanou, I., de Vries, F. T., Lembrechts, J. J., Thuiller, W., Wall, D. H., Zeiss, R., Bahram, M., Beugnot, R., Burton, V. J., Crowther, T. W., Delgado-Baquerizo, M., Geisen, S., Kardol, P., Krashevska, V., Martínez-Muñoz, C. A., Patoine, G., Seeber, J., ... Potapov, A. (2022). Frontiers in soil ecology—Insights from the world biodiversity forum 2022. *Journal of Sustainable Agriculture and Environment*, 1, 245–261.
- Ellis, C. J. (2020). Microclimatic refugia in riparian woodland: A climate change adaptation strategy. *Forest Ecology and Management*, 462, 118006.
- Ellis, C. J., & Eaton, S. (2021). Climate change refugia: Landscape, stand and tree-scale microclimates in epiphyte community composition. *The Lichenologist*, 53, 135–148.
- Ellis-Soto, D., Wikelski, M., & Jetz, W. (2023). Animal-borne sensors as a biologically informed lens on a changing climate. *Nature Climate Change*, 13, 1042–1054.
- Enriquez-Urzelai, U., Kearney, M. R., Nicieza, A. G., & Tingley, R. (2019). Integrating mechanistic and correlative niche models to unravel range-limiting processes in a temperate amphibian. *Global Change Biology*, 25, 2633–2647.
- Faye, E., Rebaudo, F., Yáñez-Cajo, D., Cauvy-Fraunié, S., & Dangles, O. (2016). A toolbox for studying thermal heterogeneity across spatial scales: From unmanned aerial vehicle imagery to landscape metrics. *Methods in Ecology and Evolution/British Ecological Society*, 7, 437–446.
- Fernández-Alonso, M. J., Díaz-Pinés, E., Ortiz, C., & Rubio, A. (2018). Disentangling the effects of tree species and microclimate on heterotrophic and autotrophic soil respiration in a Mediterranean ecotone forest. *Forest Ecology and Management*, 430, 533–544.
- Filazzola, A., Shrestha, N., & MacIvor, J. S. (2019). The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta-analysis. *The Journal of Applied Ecology*, 56, 2131–2143.
- Finocchiario, M., Médail, F., Saatkamp, A., Diadema, K., Pavon, D., & Meineri, E. (2023). Bridging the gap between microclimate and microrefugia: A bottom-up approach reveals strong climatic and biological offsets. *Global Change Biology*, 29, 1024–1036.
- Frey, S. J. K., Hadley, A. S., & Betts, M. G. (2016). Microclimate predicts within-season distribution dynamics of montane forest birds. *Diversity & Distributions*, 22, 944–959.
- Frey, S. J. K., Hadley, A. S., Johnson, S. L., Schulze, M., Jones, J. A., & Betts, M. G. (2016). Spatial models reveal the microclimatic buffering capacity of old-growth forests. *Science Advances*, 2, e1501392.
- Gardner, A. S., Maclean, I. M. D., Gaston, K. J., & Bütikofer, L. (2021). Forecasting future crop suitability with microclimate data. *Agricultural Systems*, 190, 103084.
- Geiger, R. (1942). *Das Klima der bodennahen Luftschicht*. Vieweg+Teubner Verlag. <https://doi.org/10.1007/978-3-663-06924-9>
- Geiger, R., Aron, R., H., & Todhunter, P. (1995). *The climate near the ground*. Friedr Vieweg & Sohn Verlagsgesellschaft mbH, Braunschweig/Wiesbaden. <https://doi.org/10.1007/978-3-322-86582-3>
- Ghosh, S., Sathish Kumar, C. R., Gumber, S., Dobbie, S., & Yang, H. (2022). How Asian slum emissions impact local microclimates in polluted air masses. *Atmospheric Science Letters*, 23, e1124.
- Gillerot, L., Landuyt, D., Oh, R., Chow, W., Haluza, D., Ponette, Q., Jactel, H., Bruelheide, H., Jaroszewicz, B., Scherer-Lorenzen, M., De Frenne, P., Muys, B., & Verheyen, K. (2022). Forest structure and composition alleviate human thermal stress. *Global Change Biology*, 28, 7340–7352.
- Goodwin, K. J. A., & Brown, C. D. (2023). Integrating demographic niches and black spruce range expansion at subarctic treelines. *Oecologia*, 201, 19–29.
- Gora, E. M., Lucas, J. M., & Yanoviak, S. P. (2019). Microbial composition and wood decomposition rates vary with microclimate from the ground to the canopy in a tropical forest. *Ecosystems*, 22, 1206–1219.
- Gordon, C. E., Greve, M., Henley, M., Bedetti, A., Allin, P., & Svenning, J.-C. (2023). Elephant rewilding affects landscape openness and fauna habitat across a 92-year period. *Ecological Applications: A Publication of the Ecological Society of America*, 33, e2810.
- Graae, B. J., Nystuen, K. O., Vandvik, V., & Eycott, A. E. (2022). Effects of climate change on regeneration of plants from seeds in boreal, subarctic, and subalpine regions. In *Plant regeneration from seeds* (pp. 19–32). Elsevier.
- Greenwood, O., Mossman, H. L., Suggitt, A. J., Curtis, R. J., & Maclean, I. M. D. (2016). Using management to conserve biodiversity under climate change. *The Journal of Applied Ecology*, 53, 885–894.
- Greiser, C., Ehrlén, J., Luoto, M., Meineri, E., Merinero, S., Willman, B., & Hylander, K. (2021). Warm range margin of boreal bryophytes and lichens not directly limited by temperatures. *Journal of Ecology*, 109, 3724–3736.
- Greiser, C., von Schmalensee, L., Lindestad, O., Gotthard, K., & Lehmann, P. (2022). Microclimatic variation affects developmental phenology, synchrony and voltinism in an insect population. *Functional Ecology*, 36, 3036–3048.
- Haesen, S., Lembrechts, J. J., De Frenne, P., Lenoir, J., Aalto, J., Ashcroft, M. B., Kopecký, M., Luoto, M., Maclean, I., Nijs, I., Niittynen, P., van den Hoogen, J., Arriga, N., Brūna, J., Buchmann, N., Čiliak, M., Collalti, A., De Lombaerde, E., Descombes, P., ... Van Meerbeek, K. (2021). ForestTemp—Sub-canopy microclimate temperatures of European forests. *Global Change Biology*, 27, 6307–6319.
- Haesen, S., Lembrechts, J. J., De Frenne, P., Lenoir, J., Aalto, J., Ashcroft, M. B., Kopecký, M., Luoto, M., Maclean, I., Nijs, I., Niittynen, P., van den Hoogen, J., Arriga, N., Brūna, J., Buchmann, N., Čiliak, M., Collalti, A., De Lombaerde, E., Descombes, P., ... Van Meerbeek, K. (2023). ForestClim—Bioclimatic variables for microclimate temperatures of European forests. *Global Change Biology*, 29, 2886–2892.
- Haesen, S., Lenoir, J., Gril, E., De Frenne, P., Lembrechts, J. J., Kopecký, M., Macek, M., Man, M., Wild, J., & Van Meerbeek, K. (2023). Microclimate reveals the true thermal niche of forest plant species. *Ecology Letters*, 26, 2043–2055.
- Halfman, R., Lembrechts, J., Radujković, D., De Gruyter, J., Nijs, I., & De Jonge, C. (2022). Soil chemistry, temperature and bacterial community composition drive brGDGT distributions along a subarctic elevation gradient. *Organic Geochemistry*, 163, 104346.
- Hartig, T., & Kahn, P. H., Jr. (2016). Living in cities, naturally. *Science*, 352, 938–940.
- Heinonen, M., Anagnostou, M., Bartolo, J., Bell, S., Benyon, R., Bergerud, R. A., Bojkovski, J., Böse, N., Dinu, C., Smorgon, D., Flakiewicz, K., Martin, M. J., Nedialkov, S., Nielsen, M. B., Oğuz Aytikin, S., Otych, J., Pedersen, M., Rujan, M., Testa, N., ... White, M. (2014). Comparison of air temperature calibrations. *International Journal of Thermophysics*, 35, 1251–1272.
- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25, 1965–1978.
- Hoffrén, R., & García, M. B. (2023). Thermal unmanned aerial vehicles for the identification of microclimatic refugia in topographically complex areas. *Remote Sensing of Environment*, 286, 113427.



- Hylander, K., Ehrlén, J., Luoto, M., & Meineri, E. (2015). Microrefugia: Not for everyone. *Ambio*, 44(Suppl. 1), S60–S68.
- Hylander, K., Greiser, C., Christiansen, D. M., & Koelemeijer, I. A. (2022). Climate adaptation of biodiversity conservation in managed forest landscapes. *Conservation Biology: The Journal of the Society for Conservation Biology*, 36, e13847.
- Jenerette, G. D., Harlan, S. L., Buyantuev, A., Stefanov, W. L., Declet-Barreto, J., Ruddell, B. L., Myint, S. W., Kaplan, S., & Li, X. (2016). Micro-scale urban surface temperatures are related to land-cover features and residential heat related health impacts in Phoenix, AZ USA. *Landscape Ecology*, 31, 745–760.
- Jonas, T., Webster, C., Mazzotti, G., & Malle, J. (2020). HPEval: A canopy shortwave radiation transmission model using high-resolution hemispherical images. *Agricultural and Forest Meteorology*, 284, 107903.
- Jones, J. C., & Oldroyd, B. P. (2006). Nest thermoregulation in social insects. In *Advances in insect physiology advances in insect physiology* (pp. 153–191). Elsevier.
- Joseph, G. S., Seymour, C. L., Coetzee, B. W. T., Ndlovu, M., De La Torre, A., Suttle, R., Hicks, N., Oxley, S., & Foord, S. H. (2016). Microclimates mitigate against hot temperatures in dryland ecosystems: Termite mounds as an example. *Ecosphere*, 7, e01509.
- Judge, R., Choi, F., & Helmuth, B. (2018). Recent advances in data logging for intertidal ecology. *Frontiers in Ecology and Evolution*, 6.
- Kakoulaki, G., Martinez, A., & Florio, P. (2021, ISBN 978-92-76-41150-5). *Non-commercial light detection and ranging (LiDAR) data in Europe*, EUR 30817 EN. Publications Office of the European Union. <https://doi.org/10.2760/212427>, JRC126223 [https://publications.jrc.ec.europa.eu/repository/bitstream/JRC126223/jrc126223\\_jrc126223\\_lidaropen sourcedata.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC126223/jrc126223_jrc126223_lidaropen sourcedata.pdf)
- Kankaanpää, T., Skov, K., Abrego, N., Lund, M., Schmidt, N. M., & Roslin, T. (2018). Spatiotemporal snowmelt patterns within a high Arctic landscape, with implications for flora and fauna. *Arctic, Antarctic, and Alpine Research*, 50, e1415624.
- Kankaanpää, T., Vesterinen, E., Hardwick, B., Schmidt, N. M., Andersson, T., Aspholm, P. E., Barrio, I. C., Beckers, N., Bêty, J., Birkemoe, T., DeSiervo, M., Drotos, K. H. I., Ehrich, D., Gilg, O., Gilg, V., Hein, N., Høye, T. T., Jakobsen, K. M., Jodouin, C., ... Roslin, T. (2020). Parasitoids indicate major climate-induced shifts in arctic communities. *Global Change Biology*, 26, 6276–6295.
- Kašpar, V., Hederová, L., Macek, M., Müllerová, J., Prošek, J., Surový, P., Wild, J., & Kopecký, M. (2021). Temperature buffering in temperate forests: Comparing microclimate models based on ground measurements with active and passive remote sensing. *Remote Sensing of Environment*, 263, 112522.
- Kaspari, M., Clay, N. A., Lucas, J., Revzen, S., Kay, A., & Yanoviak, S. P. (2016). Thermal adaptation and phosphorus shape thermal performance in an assemblage of rainforest ants. *Ecology*, 97, 1038–1047.
- Kautz, M., Schopf, R., & Ohser, J. (2013). The 'sun-effect': Microclimatic alterations predispose forest edges to bark beetle infestations. *European Journal of Forest Research*, 132, 453–465.
- Kearney, M. R. (2019). microclimUS: Hourly estimates of historical microclimates for The United States of America with example applications. *Ecology*, 100, e02829.
- Kearney, M. R., Gillingham, P. K., Bramer, I., Duffy, J. P., & Maclean, I. M. D. (2020). A method for computing hourly, historical, terrain-corrected microclimate anywhere on earth. *Methods in Ecology and Evolution*, 11, 38–43.
- Keitt, T. H., & Abelson, E. S. (2021). Ecology in the age of automation. *Science*, 373, 858–859.
- Kemppinen, J., & Niittynen, P. (2022). Microclimate relationships of intraspecific trait variation in sub-Arctic plants. *Oikos*, 2022, e09507.
- Kemppinen, J., Niittynen, P., Aalto, J., le Roux, P. C., & Luoto, M. (2019). Water as a resource, stress and disturbance shaping tundra vegetation. *Oikos*, 128, 811–822.
- Kemppinen, J., Niittynen, P., le Roux, P. C., Momberg, M., Happonen, K., Aalto, J., Rautakoski, H., Enquist, B. J., Vandvik, V., Halbritter, A. H., Maitner, B., & Luoto, M. (2021). Consistent trait-environment relationships within and across tundra plant communities. *Nature Ecology & Evolution*, 5, 458–467.
- Keppel, G., Mokany, K., Wardell-Johnson, G. W., Phillips, B. L., Welbergen, J. A., & Reside, A. E. (2015). The capacity of refugia for conservation planning under climate change. *Frontiers in Ecology and the Environment*, 13, 106–112.
- Keppel, G., Van Niel, K. P., Wardell-Johnson, G. W., Yates, C. J., Byrne, M., Mucina, L., Schut, A. G. T., Hopper, S. D., & Franklin, S. E. (2012). Refugia: Identifying and understanding safe havens for biodiversity under climate change. *Global Ecology and Biogeography: A Journal of Macroecology*, 21, 393–404.
- Kermavnar, J., Ferlan, M., Marinšek, A., Eler, K., Kobler, A., & Kutnar, L. (2020). Effects of various cutting treatments and topographic factors on microclimatic conditions in Dinaric fir-beech forests. *Agricultural and Forest Meteorology*, 295, 108186.
- Kim, H., McComb, B. C., Frey, S. J. K., Bell, D. M., & Betts, M. G. (2022). Forest microclimate and composition mediate long-term trends of breeding bird populations. *Global Change Biology*, 28, 6180–6193.
- Klinges, D. H., Duffy, J. P., Kearney, M. R., & Maclean, I. M. D. (2022). mcera5: Driving microclimate models with ERA5 global gridded climate data. *Methods in Ecology and Evolution/British Ecological Society*, 13, 1402–1411.
- Kraus, G. (1911). *Boden und Klima auf kleinstem Raum, Versuch einer exakten Behandlung des Standorts auf dem Wellenkalk*. von Dr. Gregor Kraus.
- Kusch, E., & Davy, R. (2022). KrigR—A tool for downloading and statistically downscaling climate reanalysis data. *Environmental Research Letters* [Web Site], 17, 024005.
- Lai, D., Liu, W., Gan, T., Liu, K., & Chen, Q. (2019). A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *The Science of the Total Environment*, 661, 337–353.
- Larsen, A., Larsen, J. R., & Lane, S. N. (2021). Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. *Earth-Science Reviews*, 218, 103623.
- Law, S. J., Bishop, T. R., Eggleton, P., Griffiths, H., Ashton, L., & Parr, C. (2020). Darker ants dominate the canopy: Testing macroecological hypotheses for patterns in colour along a microclimatic gradient. *The Journal of Animal Ecology*, 89, 347–359.
- Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., van Kampenhou, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., ... Zeng, X. (2019). The community land model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Journal of Advances in Modeling Earth Systems*, 11, 4245–4287.
- le Roux, P. C., Aalto, J., & Luoto, M. (2013). Soil moisture's underestimated role in climate change impact modelling in low-energy systems. *Global Change Biology*, 19, 2965–2975.
- Lembrechts, J. J., Aalto, J., Ashcroft, M. B., De Frenne, P., Kopecký, M., Lenoir, J., Luoto, M., Maclean, I. M. D., Rouspard, O., Fuentes-Lillo, E., García, R. A., Pellissier, L., Pitteloud, C., Alatalo, J. M., Smith, S. W., Björk, R. G., Muffler, L., Ratier Backes, A., Cesarz, S., ... Nijs, I. (2020). SoilTemp: A global database of near-surface temperature. *Global Change Biology*, 26, 6616–6629.
- Lembrechts, J. J., Lenoir, J., Roth, N., Hattab, T., Milbau, A., Haider, S., Pellissier, L., Pauchard, A., Ratier Backes, A., Dimarco, R. D., Nuñez, M. A., Aalto, J., & Nijs, I. (2019). Comparing temperature data sources for use in species distribution models: From in-situ logging to remote sensing. *Global Ecology and Biogeography: A Journal of Macroecology*, 28, 1578–1596.

- Lembrechts, J. J., Lenoir, J., Scheffers, B., & De Frenne, P. (2021). Designing countrywide and regional microclimate networks. *Global Ecology and Biogeography: A Journal of Macroecology*, 30, 1168–1174.
- Lembrechts, J. J., Nijs, I., & Lenoir, J. (2019). Incorporating microclimate into species distribution models. *Ecography*, 42, 1267–1279.
- Lembrechts, J. J., van den Hoogen, J., Aalto, J., Ashcroft, M. B., De Frenne, P., Kemppinen, J., Kopecký, M., Luoto, M., Maclean, I. M. D., Crowther, T. W., Bailey, J. J., Haesen, S., Klimes, D. H., Niittynen, P., Scheffers, B. R., Van Meerbeek, K., Aartsma, P., Abdalaze, O., Abedi, M., ... Lenoir, J. (2022). Global maps of soil temperature. *Global Change Biology*, 28, 3110–3144.
- Lenoir, J., Hattab, T., & Pierre, G. (2017). Climatic microrefugia under anthropogenic climate change: Implications for species redistribution. *Ecography*, 40, 253–266.
- Levy, O., Buckley, L. B., Keitt, T. H., & Angilletta, M. J., Jr. (2016). A dynamically downscaled projection of past and future microclimates. *Ecology*, 97, 1888.
- Li, S., Xu, L. D., & Zhao, S. (2015). The internet of things: A survey. *Information Systems Frontiers*, 17, 243–259.
- Liancourt, P., Song, X., Macek, M., Santrucek, J., & Dolezal, J. (2020). Plant's-eye view of temperature governs elevational distributions. *Global Change Biology*, 26, 4094–4103.
- Lin, B. B., Perfecto, I., & Vandermeer, J. (2008). Synergies between agricultural intensification and climate change could create surprising vulnerabilities for crops. *Bioscience*, 58, 847–854.
- Lin, Y., Wang, Z., Jim, C. Y., Li, J., Deng, J., & Liu, J. (2020). Water as an urban heat sink: Blue infrastructure alleviates urban heat Island effect in mega-city agglomeration. *Journal of Cleaner Production*, 262, 121411.
- Liu, D., Ogaya, R., Barbeta, A., Yang, X., & Peñuelas, J. (2018). Long-term experimental drought combined with natural extremes accelerate vegetation shift in a Mediterranean holm oak forest. *Environmental and Experimental Botany*, 151, 1–11.
- Lloret, F., Siscart, D., & Dalmases, C. (2004). Canopy recovery after drought dieback in holm-oak Mediterranean forests of Catalonia (NE Spain). *Global Change Biology*, 10, 2092–2099.
- Lucid, M. K., Wan, H. Y., Ehlers, S., Robinson, L., Svancara, L. K., Shirk, A., & Cushman, S. (2021). Land snail microclimate niches identify suitable areas for climate refugia management on a montane landscape. *Ecological Indicators*, 129, 107885.
- Lundgren, E. J., Ramp, D., Stromberg, J. C., Wu, J., Nieto, N. C., Sluk, M., Moeller, K. T., & Wallach, A. D. (2021). Equids engineer desert water availability. *Science*, 372, 491–495.
- lungman, T., Cirach, M., Marando, F., Barboza, E. P., Khomenko, S., Masselot, P., Quijal-Zamorano, M., Mueller, N., Gasparrini, A., Urquiza, J., Heris, M., Thondoo, M., & Nieuwenhuijsen, M. (2023). Cooling cities through urban green infrastructure: A health impact assessment of European cities. *The Lancet*, 401(10376), P577–589.
- Luskin, M. S., & Potts, M. D. (2011). Microclimate and habitat heterogeneity through the oil palm lifecycle. *Basic and Applied Ecology*, 12, 540–551.
- Ma, L., Liu, L., Lu, Y., Chen, L., Zhang, Z., Zhang, H., Wang, X., Shu, L., Yang, Q., Song, Q., Peng, Q., Yu, Z., & Zhang, J. (2022). When microclimates meet soil microbes: Temperature controls soil microbial diversity along an elevational gradient in subtropical forests. *Soil Biology & Biochemistry*, 166, 108566.
- Maclean, I. M. D., Duffy, J. P., Haesen, S., Govaert, S., De Frenne, P., Vanneste, T., Lenoir, J., Lembrechts, J. J., Rhodes, M. W., & Van Meerbeek, K. (2021). On the measurement of microclimate. *Methods in Ecology and Evolution/British Ecological Society*, 12, 1397–1410.
- Maclean, I. M. D., & Early, R. (2023). Macroclimate data overestimate range shifts of plants in response to climate change. *Nature Climate Change*, 13, 484–490.
- Maclean, I. M. D., & Klimes, D. H. (2021). Microclimc: A mechanistic model of above, below and within-canopy microclimate. *Ecological Modelling*, 451, 109567.
- Malhi, Y., Lander, T., le Roux, E., Stevens, N., Macias-Fauria, M., Wedding, L., Girardin, C., Kristensen, J. Å., Sandom, C. J., Evans, T. D., Svenning, J.-C., & Canney, S. (2022). The role of large wild animals in climate change mitigation and adaptation. *Current Biology: CB*, 32, R181–R196.
- Man, M., Kalčík, V., Macek, M., Brúna, J., Hederová, L., Wild, J., & Kopecký, M. (2023). myClim: Microclimate data handling and standardised analyses in R. *Methods in ecology and evolution*, 14, 2308–2320.
- Man, M., Wild, J., Macek, M., & Kopecký, M. (2022). Can high-resolution topography and forest canopy structure substitute microclimate measurements? Bryophytes say no. *The Science of the Total Environment*, 821, 153377.
- Massimino, D., Beale, C. M., Suggitt, A. J., Crick, H. Q. P., Macgregor, N. A., Carroll, M. J., Maclean, I. M. D., & Pearce-Higgins, J. W. (2020). Can microclimate offer refuge to an upland bird species under climate change? *Landscape Ecology*, 35, 1907–1922.
- McCullough, I. M., Davis, F. W., Dingman, J. R., Flint, L. E., Flint, A. L., Serra-Diaz, J. M., Syphard, A. D., Moritz, M. A., Hannah, L., & Franklin, J. (2016). High and dry: High elevations disproportionately exposed to regional climate change in Mediterranean-climate landscapes. *Landscape Ecology*, 31, 1063–1075.
- McGlynn, T. P., Meineke, E. K., Bahlai, C. A., Li, E., Hartop, E. A., Adams, B. J., & Brown, B. V. (2019). Temperature accounts for the biodiversity of a hyperdiverse group of insects in urban Los Angeles. *Proceedings. Biological Sciences/The Royal Society*, 286, 20191818.
- McLaughlin, B. C., Ackerly, D. D., Klos, P. Z., Natali, J., Dawson, T. E., & Thompson, S. E. (2017). Hydrologic refugia, plants, and climate change. *Global Change Biology*, 23, 2941–2961.
- Meeussen, C., Govaert, S., Vanneste, T., Haesen, S., Van Meerbeek, K., Bollmann, K., Brunet, J., Calders, K., Cousins, S. A. O., Diekmann, M., Graae, B. J., Iacopetti, G., Lenoir, J., Orczewska, A., Ponette, Q., Plue, J., Selvi, F., Spicher, F., Sørensen, M. V., ... De Frenne, P. (2021). Drivers of carbon stocks in forest edges across Europe. *The Science of the Total Environment*, 759, 143497.
- Meineri, E., & Hylander, K. (2017). Fine-grain, large-domain climate models based on climate station and comprehensive topographic information improve microrefugia detection. *Ecography*, 40, 1003–1013.
- Menge, J. H., Magdon, P., Wöllauer, S., & Ehbrecht, M. (2023). Impacts of forest management on stand and landscape-level microclimate heterogeneity of European beech forests. *Landscape Ecology*, 38, 903–917.
- Meyer, A. V., Sakairi, Y., Kearney, M. R., & Buckley, L. B. (2023). A guide and tools for selecting and accessing microclimate data for mechanistic niche modeling. *Ecosphere*, 14, e4506.
- Mickley, J. G., Moore, T. E., Schlichting, C. D., DeRobertis, A., Pfisterer, E. N., & Bagchi, R. (2019). Measuring microenvironments for global change: DIY environmental microcontroller units (EMUs). *Methods in Ecology and Evolution/British Ecological Society*, 10, 578–584.
- Mollinari, M. M., Peres, C. A., & Edwards, D. P. (2019). Rapid recovery of thermal environment after selective logging in the Amazon. *Agricultural and Forest Meteorology*, 278, 107637.
- Momberg, M., Hedding, D. W., Luoto, M., & le Roux, P. C. (2021). Species differ in their responses to wind: The underexplored link between species fine-scale occurrences and variation in wind stress. *Journal of vegetation science: Official organ of the International Association for Vegetation Science*, 32, e13093.
- Momberg, M., Ryan, P. G., Hedding, D. W., Schoombie, J., Goddard, K. A., Craig, K. J., & le Roux, P. C. (2023). Factors determining nest-site selection of surface-nesting seabirds: A case study on the world's largest pelagic bird, the wandering albatross (*Diomedea exulans*). *The Ibis*, 165, 190–203.

- Morelli, T. L., Barrows, C. W., Ramirez, A. R., Cartwright, J. M., Ackerly, D. D., Eaves, T. D., Ebersole, J. L., Krawchuk, M. A., Letcher, B. H., Mahalovich, M. F., Meigs, G. W., Michalak, J. L., Millar, C. I., Quiñones, R. M., Stralberg, D., & Thorne, J. H. (2020). Climate-change refugia: Biodiversity in the slow lane. *Frontiers in Ecology and the Environment*, 18, 228–234.
- Moritz, C., & Agudo, R. (2013). The future of species under climate change: Resilience or decline? *Science*, 341, 504–508.
- Nadeau, C. P., Giacomazzo, A., & Urban, M. C. (2022). Cool microrefugia accumulate and conserve biodiversity under climate change. *Global Change Biology*, 28, 3222–3235.
- Niittynen, P., Heikkinen, R. K., Aalto, J., Guisan, A., Kemppinen, J., & Luoto, M. (2020). Fine-scale tundra vegetation patterns are strongly related to winter thermal conditions. *Nature Climate Change*, 10, 1143–1148.
- Niittynen, P., & Luoto, M. (2018). The importance of snow in species distribution models of arctic vegetation. *Ecography*, 41, 1024–1037.
- Norris, C., Hobson, P., & Ibisch, P. L. (2011). Microclimate and vegetation function as indicators of forest thermodynamic efficiency. *Journal of Applied Ecology*, 49, 570.
- Núñez, M. A., Chiuffo, M. C., Pauchard, A., & Zenni, R. D. (2021). Making ecology really global. *Trends in Ecology & Evolution*, 36, 766–769.
- Oldfather, M. F., & Ackerly, D. D. (2019). Microclimate and demography interact to shape stable population dynamics across the range of an alpine plant. *The New Phytologist*, 222, 193–205.
- Ononye, B. U., Akunne, C. E., Ogbuefi, E. O., Okeke, T. E., Okafor, K. P., Azaka, E. I., Obiyo, G. E., Aniefuna, C. O., Akwuaka, P. C., & Chidi, C. A. (2023). Effect of improved hive cover designs on internal microclimate and colony establishment of West African honeybees (*Apis mellifera adansonii* L.) in Awka, Nigeria. *Journal of Applied Life Sciences International*, 26, 1–16.
- Opedal, Ø. H., Armbruster, W. S., & Graae, B. J. (2015). Linking small-scale topography with microclimate, plant species diversity and intra-specific trait variation in an alpine landscape. *Plant Ecology & Diversity*, 8, 305–315.
- Örlander, G. (1993). Shading reduces both visible and invisible frost damage to Norway spruce seedlings in the field. *Forestry*, 66, 27–36.
- Ozanne, C. M. P., Anhuf, D., Boulter, S. L., Keller, M., Kitching, R. L., Körner, C., Meinzer, F. C., Mitchell, A. W., Nakashizuka, T., Dias, P. L. S., Stork, N. E., Wright, S. J., & Yoshimura, M. (2003). Biodiversity meets the atmosphere: A global view of forest canopies. *Science*, 301, 183–186.
- Paaijmans, K. P., Imbahale, S. S., Thomas, M. B., & Takken, W. (2010). Relevant microclimate for determining the development rate of malaria mosquitoes and possible implications of climate change. *Malaria Journal*, 9, 196.
- Pincebourde, S., & Casas, J. (2019). Narrow safety margin in the phyllosphere during thermal extremes. *Proceedings of the National Academy of Sciences of the United States of America*, 116, 5588–5596.
- Pincebourde, S., & Woods, H. A. (2020). There is plenty of room at the bottom: Microclimates drive insect vulnerability to climate change. *Current Opinion in Insect Science*, 41, 63–70.
- Playà-Montmany, N., & Tattersall, G. J. (2021). Spot size, distance and emissivity errors in field applications of infrared thermography. *Methods in Ecology and Evolution / British Ecological Society*, 12, 828–840.
- Poorter, H., Niinemets, Ü., Ntagkas, N., Siebenkäs, A., Mäenpää, M., Matsubara, S., & Pons, T. (2019). A meta-analysis of plant responses to light intensity for 70 traits ranging from molecules to whole plant performance. *The New Phytologist*, 223, 1073–1105.
- Porter, W. P., Mitchell, J. W., Beckman, W. A., & DeWitt, C. B. (1973). Behavioral implications of mechanistic ecology: Thermal and behavioral modeling of desert ectotherms and their microenvironment. *Oecologia*, 13, 1–54.
- Potter, K. A., Arthur Woods, H., & Pincebourde, S. (2013). Microclimatic challenges in global change biology. *Global Change Biology*, 19, 2932–2939.
- R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Rebaudo, F., Soulard, T., Condori, B., Quispe-Tarqui, R., Calatayud, P.-A., Chavez Vino, S., Tonnang, H. E. Z., & Bessière, L. (2023). A low-cost IoT network to monitor microclimate variables in ecosystems. *Methods in Ecology and Evolution/British Ecological Society*, 14, 1025–1034.
- Richardson, L. F. (1922). *Weather prediction by numerical process*. Cambridge University Press.
- Riddell, E. A., Iknayan, K. J., Hargrove, L., Tremor, S., Patton, J. L., Ramirez, R., Wolf, B. O., & Beissinger, S. R. (2021). Exposure to climate change drives stability or collapse of desert mammal and bird communities. *Science*, 371, 633–636.
- Ripley, B. S., Edwardes, A., Rossouw, M. W., Smith, V. R., & Midgley, G. F. (2020). Invasive grasses of sub-Antarctic Marion Island respond to increasing temperatures at the expense of chilling tolerance. *Annals of Botany*, 125, 765–773.
- Risch, A. C., Zimmermann, S., Schütz, M., Borer, E. T., Broadbent, A. A. D., Caldeira, M. C., Davies, K. F., Eisenhauer, N., Eskelinen, A., Fay, P. A., Hagedorn, F., Knops, J. M. H., Lembrechts, J. J., MacDougall, A. S., McCulley, R. L., Melbourne, B. A., Moore, J. L., Power, S. A., Seabloom, E. W., ... Ochoa-Hueso, R. (2023). Drivers of the microbial metabolic quotient across global grasslands. *Global Ecology and Biogeography: A Journal of Macroecology*, 32, 904–918.
- Robinson, D. A., Campbell, C. S., Hopmans, J. W., Hornbuckle, B. K., Jones, S. B., Knight, R., Ogden, F., Selker, J., & Wendroth, O. (2008). Soil moisture measurement for ecological and hydrological watershed-scale observatories: A review. *Vadose Zone Journal*, 7, 358–389.
- Roman, L. A., Conway, T. M., Eisenman, T. S., Koeser, A. K., Ordóñez Barona, C., Locke, D. H., Jenerette, G. D., Östberg, J., & Vogt, J. (2021). Beyond 'trees are good': Disservices, management costs, and tradeoffs in urban forestry. *Ambio*, 50, 615–630.
- Sanczuk, P., Govaert, S., Meeussen, C., De Pauw, K., Vanneste, T., Depauw, L., Moreira, X., Schoelynck, J., De Boevre, M., De Saeger, S., Bollmann, K., Brunet, J., Cousins, S. A. O., Plue, J., Diekmann, M., Graae, B. J., Hedwall, P., Iacopetti, G., Lenoir, J., ... De Frenne, P. (2021). Small scale environmental variation modulates plant defence syndromes of understorey plants in deciduous forests of Europe. *Global Ecology and Biogeography*, 30, 205–219.
- Sandom, C. J., Hughes, J., & Macdonald, D. W. (2013). Rewilding the Scottish highlands: Do wild boar, *Sus scrofa*, use a suitable foraging strategy to be effective ecosystem engineers? *Restoration Ecology*, 21, 336–343.
- Scheffers, B. R., Edwards, D. P., Diesmos, A., Williams, S. E., & Evans, T. A. (2014). Microhabitats reduce animal's exposure to climate extremes. *Global Change Biology*, 20, 495–503.
- Scheffers, B. R., Edwards, D. P., Macdonald, S. L., Senior, R. A., Andriamahohatra, L. R., Roslan, N., Rogers, A. M., Haugaasen, T., Wright, P., & Williams, S. E. (2017). Extreme thermal heterogeneity in structurally complex tropical rain forests. *Biotropica*, 49, 35–44.
- Scheffers, B. R., Phillips, B. L., Laurance, W. F., Sodhi, N. S., Diesmos, A., & Williams, S. E. (2013). Increasing arboreality with altitude: A novel biogeographic dimension. *Proceedings. Biological Sciences/The Royal Society*, 280, 20131581.
- Scherrer, D., & Körner, C. (2009). Infra-red thermometry of alpine landscapes challenges climatic warming projections. *Global Change Biology*, 16, 2602–2613.
- Schmalholz, M., & Hylander, K. (2011). Microtopography creates small-scale refugia for boreal forest floor bryophytes during clear-cut logging. *Ecography*, 34, 637–648.



- Schouten, R., Baudrot, V., Umina, P., & Maino, J. (2022). A working guide to spatial mechanistic modelling in Julia. *Methods in Ecology and Evolution/British Ecological Society*, 13, 945–954.
- Schwaab, J., Meier, R., Mussetti, G., Seneviratne, S., Bürgi, C., & Davin, E. L. (2021). The role of urban trees in reducing land surface temperatures in European cities. *Nature Communications*, 12, 6763.
- Sears, M. W., Angilletta, M. J., Jr., Schuler, M. S., Borchert, J., Dilliplane, K. F., Stegman, M., Rusch, T. W., & Mitchell, W. A. (2016). Configuration of the thermal landscape determines thermoregulatory performance of ectotherms. *Proceedings of the National Academy of Sciences of the United States of America*, 113, 10595–10600.
- Senior, R. A., Hill, J. K., Benedick, S., & Edwards, D. P. (2018). Tropical forests are thermally buffered despite intense selective logging. *Global Change Biology*, 24, 1267–1278.
- Senior, R. A., Hill, J. K., & Edwards, D. P. (2019). ThermStats: An R package for quantifying surface thermal heterogeneity in assessments of microclimates. *Methods in Ecology and Evolution/British Ecological Society*, 10, 1606–1614.
- Senior, R. A., Hill, J. K., González Del Pliego, P., Goode, L. K., & Edwards, D. P. (2017). A pantropical analysis of the impacts of forest degradation and conversion on local temperature. *Ecology and Evolution*, 7, 7897–7908.
- Shafique, M., Luo, X., & Zuo, J. (2020). Photovoltaic-green roofs: A review of benefits, limitations, and trends. *Solar Energy*, 202, 485–497.
- Shanks, R. E. (1956). Altitudinal and microclimatic relationships of soil temperature under natural vegetation. *Ecology*, 37, 1–7.
- Shen, T., Corlett, R. T., Collart, F., Kasprzyk, T., Guo, X.-L., Patiño, J., Su, Y., Hardy, O. J., Ma, W.-Z., Wang, J., Wei, Y.-M., Mouton, L., Li, Y., Song, L., & Vanderpoorten, A. (2022). Microclimatic variation in tropical canopies: A glimpse into the processes of community assembly in epiphytic bryophyte communities. *The Journal of Ecology*, 110, 3023–3038.
- Shen, T., Song, L., Collart, F., Guisan, A., Su, Y., Hu, H.-X., Wu, Y., Dong, J.-L., & Vanderpoorten, A. (2022). What makes a good phorophyte? Predicting occupancy, species richness and abundance of vascular epiphytes in a lowland seasonal tropical forest. *Frontiers in Forests and Global Change*, 5, 1007473.
- Stark, G., Ma, L., Zeng, Z.-G., Du, W.-G., & Levy, O. (2023). Cool shade and not-so-cool shade: How habitat loss may accelerate thermal stress under current and future climate. *Global Change Biology*, 29, 6201–6216.
- Stark, J. R., Fridley, J. D., & Gill, J. (2022). Microclimate-based species distribution models in complex forested terrain indicate widespread cryptic refugia under climate change. *Global Ecology and Biogeography: A Journal of Macroecology*, 31, 562–575.
- Stickley, S. F., & Fraterrigo, J. M. (2023). Microclimate species distribution models estimate lower levels of climate-related habitat loss for salamanders. *Journal of Nature Conservation*, 72, 126333.
- Suggitt, A. J., Wilson, R. J., Isaac, N. J. B., Beale, C. M., Auffret, A. G., August, T., Bennie, J. J., Crick, H. Q. P., Duffield, S., Fox, R., Hopkins, J. J., Macgregor, N. A., Morecroft, M. D., Walker, K. J., & Maclean, I. M. D. (2018). Extinction risk from climate change is reduced by microclimatic buffering. *Nature Climate Change*, 8, 713–717.
- Taleghani, M. (2018). Outdoor thermal comfort by different heat mitigation strategies—A review. *Renewable and Sustainable Energy Reviews*, 81, 2011–2018.
- Terando, A. J., Youngsteadt, E., Meineke, E. K., & Prado, S. G. (2017). Ad hoc instrumentation methods in ecological studies produce highly biased temperature measurements. *Ecology and Evolution*, 7, 9890–9904.
- Thers, H., Bøcher, P. K., & Svenning, J.-C. (2019). Using lidar to assess the development of structural diversity in forests undergoing passive rewilding in temperate northern Europe. *PeerJ*, 6, e6219.
- Thom, D., Ammer, C., Annighöfer, P., Aszalós, R., Dittrich, S., Hagge, J., Keeton, W. S., Kovacs, B., Krautkrämer, O., Müller, J., von Oheimb, G., & Seidl, R. (2022). Regeneration in European beech forests after drought: The effects of microclimate, deadwood and browsing. *European Journal of Forest Research*, 291, 1–15.
- Thom, D., Sommerfeld, A., Sebald, J., Hagge, J., Müller, J., & Seidl, R. (2020). Effects of disturbance patterns and deadwood on the microclimate in European beech forests. *Agricultural and Forest Meteorology*, 291, 108066.
- Thorne, J. H., Gogol-Prokurat, M., Hill, S., Walsh, D., Boynton, R. M., & Choe, H. (2020). Vegetation refugia can inform climate-adaptive land management under global warming. *Frontiers in Ecology and the Environment*, 18, 281–287.
- Tinya, F., Kovács, B., Bidló, A., Dima, B., Király, I., Kutszegi, G., Lakatos, F., Mag, Z., Márialigeti, S., Nascimbene, J., Samu, F., Siller, I., Szél, G., & Ódor, P. (2021). Environmental drivers of forest biodiversity in temperate mixed forests—A multi-taxon approach. *The Science of the Total Environment*, 795, 148720.
- Trew, B. T., & Maclean, I. M. D. (2021). Vulnerability of global biodiversity hotspots to climate change. *Global Ecology and Biogeography: A Journal of Macroecology*, 30, 768–783.
- Vandvik, V., Skarpaas, O., Klanderud, K., Telford, R. J., Halbritter, A. H., & Goldberg, D. E. (2020). Biotic rescaling reveals importance of species interactions for variation in biodiversity responses to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 117, 22858–22865.
- Vega-Álvarez, J., García-Rodríguez, J. A., & Cayuela, L. (2019). Facilitation beyond species richness. *The Journal of Ecology*, 107, 722–734.
- Virkkala, A.-M., Niittynen, P., Kemppinen, J., Marushchak, M. E., Voigt, C., Hensgens, G., Kerttula, J., Happonen, K., Tyystjärvi, V., Biasi, C., Hultman, J., Rinne, J., & Luoto, M. (2024). High-resolution spatial patterns and drivers of terrestrial ecosystem carbon dioxide, methane, and nitrous oxide fluxes in the tundra. *Biogeosciences*, 21, 335–355.
- Vives-Inglá, M., Sala-García, J., Stefanescu, C., Casadó-Tortosa, A., García, M., Peñuelas, J., & Carnicer, J. (2023). Interspecific differences in microhabitat use expose insects to contrasting thermal mortality. *Ecological Monographs*, 93, e1561.
- von Schmalensee, L. (2023). How to generate accurate continuous thermal regimes from sparse but regular temperature measurements. *Methods in Ecology and Evolution/British Ecological Society*, 14, 1208–1216.
- von Schmalensee, L., Hulda Gunnarsdóttir, K., Näslund, J., Gotthard, K., & Lehmann, P. (2021). Thermal performance under constant temperatures can accurately predict insect development times across naturally variable microclimates. *Ecology Letters*, 24, 1633–1645.
- Weber, N., Bouwes, N., Pollock, M. M., Volk, C., Wheaton, J. M., Wathen, G., Wirtz, J., & Jordan, C. E. (2017). Alteration of stream temperature by natural and artificial beaver dams. *PLoS One*, 12, e0176313.
- Webster, C., Mazzotti, G., Essery, R., & Jonas, T. (2020). Enhancing airborne LiDAR data for improved forest structure representation in shortwave transmission models. *Remote Sensing of the Environment*, 249, 112017.
- Welman, S., & Pichegru, L. (2023). Nest microclimate and heat stress in African Penguins *Spheniscus demersus* breeding on Bird Island, South Africa. *Bird Conservation International*, 33, 1–9.
- Wild, J., Kopecký, M., Macek, M., Šanda, M., Jankovec, J., & Haase, T. (2019). Climate at ecologically relevant scales: A new temperature and soil moisture logger for long-term microclimate measurement. *Agricultural and Forest Meteorology*, 268, 40–47.
- Willems, F. M., Scheepens, J. F., Ammer, C., Block, S., Bucharova, A., Schall, P., Sehrt, M., & Bosdorf, O. (2021). Spring understory herbs flower later in intensively managed forests. *Ecological Applications: A Publication of the Ecological Society of America*, 31, e02332.
- Williamson, J., Slade, E. M., Luke, S. H., Swinfield, T., Chung, A. Y. C., Coomes, D. A., Heroin, H., Jucker, T., Lewis, O. T., Vairappan, C. S., Rossiter, S. J., & Struebig, M. J. (2021). Riparian buffers act as

- microclimatic refugia in oil palm landscapes. *The Journal of Applied Ecology*, 58, 431–442.
- Wimberly, M. C., Davis, J. K., Evans, M. V., Hess, A., Newberry, P. M., Solano-Asamoah, N., & Murdock, C. C. (2020). Land cover affects microclimate and temperature suitability for arbovirus transmission in an urban landscape. *PLoS Neglected Tropical Diseases*, 14, e0008614.
- Wolf, C., Bell, D. M., Kim, H., Nelson, M. P., Schulze, M., & Betts, M. G. (2021). Temporal consistency of undercanopy thermal refugia in old-growth forest. *Agricultural and Forest Meteorology*, 307, 108520.
- Wong, G. K. L., & Jim, C. Y. (2017). Urban-microclimate effect on vector mosquito abundance of tropical green roofs. *Building and Environment*, 112, 63–76.
- Wurz, A., Tscharnkte, T., Martin, D. A., Osen, K., Rakotomalala, A. A. N. A., Raveloaritiana, E., Andrianisaina, F., Dröge, S., Fulgence, T. R., Soazafy, M. R., Andriafanomezantsoa, R., Andrianarimisa, A., Babarezoto, F. S., Barkmann, J., Hänke, H., Hölscher, D., Kreft, H., Rakouth, B., Guerrero-Ramírez, N. R., ... Grass, I. (2022). Win-win opportunities combining high yields with high multi-taxa biodiversity in tropical agroforestry. *Nature Communications*, 13, 4127.
- Xue, F., Gou, Z., & Lau, S. S. Y. (2017). Green open space in high-dense Asian cities: Site configurations, microclimates and users' perceptions. *Sustainable Cities and Society*, 34, 114–125.
- Yin, Y., He, L., Wennberg, P. O., & Frankenberg, C. (2023). Unequal exposure to heatwaves in Los Angeles: Impact of uneven green spaces. *Science Advances*, 9, eade8501.
- Zellweger, F., De Frenne, P., Lenoir, J., Rocchini, D., & Coomes, D. (2019). Advances in microclimate ecology arising from remote sensing. *Trends in Ecology & Evolution*, 34, 327–341.
- Zellweger, F., De Frenne, P., Lenoir, J., Vangansbeke, P., Verheyen, K., Bernhardt-Römermann, M., Baeten, L., Hédli, R., Berki, I., Brunet, J., Van Calster, H., Chudomelová, M., Decocq, G., Dirnböck, T., Durak, T., Heinken, T., Jaroszewicz, B., Kopecký, M., Máliš, F., ... Coomes, D. (2020). Forest microclimate dynamics drive plant responses to warming. *Science*, 368, 772–775.
- Zhou, W., Huang, G., & Cadenasso, M. L. (2011). Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. *Landscape and Urban Planning*, 102, 54–63.
- Zölch, T., Maderspacher, J., Wamsler, C., & Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban Forestry & Urban Greening*, 20, 305–316.

Zweifel, R., Steppe, K., & Sterck, F. J. (2007). Stomatal regulation by microclimate and tree water relations: Interpreting ecophysiological field data with a hydraulic plant model. *Journal of Experimental Botany*, 58, 2113–2131.

## BIOSKETCH

The authors are participants of the Microclimate Ecology and Biogeography conference held in Antwerp, Belgium in 2022. Together they collaboratively wrote this perspective paper that brings together 97 experts and their views on the recent advancements and knowledge gaps in terrestrial microclimates. The paper was coordinated by Julia Kemppinen, Jonas J. Lembrechts, Koenraad Van Meerbeek, and Pieter De Frenne, and writing different sections was led by Jofre Carnicer, Nathalie Isabelle Chardon, Paul Kardol, Jonathan Lenoir, Daijun Liu, Ilya Maclean, Jan Pergl, Patrick Saccone, Rebecca A. Senior, Ting Shen, Sandra Słowińska, Vigdis Vandvik, and Jonathan von Oppen. For more details on authors statistics and how the work was organised, please see Supplementary information [Figures S1](#).

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Kemppinen, J., Lembrechts, J. J., Van Meerbeek, K., Carnicer, J., Chardon, N. I., Kardol, P., Lenoir, J., Liu, D., Maclean, I., Pergl, J., Saccone, P., Senior, R. A., Shen, T., Słowińska, S., Vandvik, V., von Oppen, J., Aalto, J., Ayalew, B., Bates, O., ... De Frenne, P. (2024). Microclimate, an important part of ecology and biogeography. *Global Ecology and Biogeography*, 00, e13834. <https://doi.org/10.1111/geb.13834>