Methods of monitoring and modelling microclimate in ecological research

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## Abstract

Most ecological studies of the effects of climate on species are based on average conditions above ground level (measured by meteorological stations) averaged across 100 km2 or larger areas. However, most terrestrial organisms experience conditions in a much smaller area at the ground surface or within vegetation canopies, the climate of which can be very different to large scale averages. These microclimates are affected by the shape of the landscape, including the steepness and aspect of slopes, height above sea level, proximity to the sea or inland water, and whether a site is in a valley or at the top of a hill. Plants also modify the conditions found within or below their canopies, with the structure of vegetation playing an important role. The recent increase in availability of micro-sensors and remotely sensed data at appropriate resolutions has led some ecologists to begin to include microclimate information within a variety of contexts, however the field can be confusing and intimidating and mistakes are often made along the way. In this chapter we provide an overview of microclimatic processes, summarise the available methods of measuring and modelling microclimate data for incorporation in ecological research, highlighting pitfalls to avoid and the limitations of some techniques. We also consider future research directions and opportunities within this emerging field.

KeywordsFine resolution, habitat heterogeneity, micro-sensors, meteorological, small scale, topoclimate

## 1. Introduction

Climate is key to the physiology and development of organisms, their ecological interactions, and geographical distribution. Focus on climate in ecological studies has increased in context of anthropogenic climate change, the ecological impacts of which are becoming ever more apparent (e.g. Parmesan and Yohe, 2003; Pauli et al., 2012; Poloczanska et al., 2013; Settele et al., 2014; Thackeray et al*.*, 2016). However, the climatic conditions experienced by organisms can significantly deviate from those measured by standard meteorological stations (Potter et al., 2013).

Microscale climates, or microclimates, have been defined in various ways depending on the discipline and context (e.g. Box 1). Broadly speaking, they are fine scale climate variations which are, at least temporarily, decoupled from the background atmosphere (macroclimate, see Box 1). A wide range of variables, or combinations of variables, can be used to characterise microclimate, including temperature, precipitation, solar radiation, cloud cover, wind speed and direction, humidity, evaporation, and water availability. These are influenced by fine resolution biotic and abiotic variations, including topography, soil type, land cover (especially vegetation), and proximity to the coast. The term microclimate is sometimes used interchangeably with topoclimate, although topoclimates are variations in climate solely as a function of topographical features such as altitude, slope and aspect, and are generally considered to vary at a larger scale than microclimates, and occur higher off the ground (see Box 1; Barry and Blanken, 2016). Differences in the definition of microclimate may be a challenge in approaching microclimate research (see Box 2). Within the context of this paper we consider microclimates to typically have a spatial resolution of <100m, and to be within a few meters of the vegetation canopy. The temporal resolution may vary depending on the process or application being studied, but generally timescales of hourly (or higher frequency) are appropriate.

The ability to effectively and consistently measure and model microclimates is also important beyond ecology and climate science. Microclimates should be considered in civil applications such as architecture (Pérez et al., 2016; Terjung, 1974), in urban design (Allegrini and Carmeliet, 2017; Yuan et al., 2017), forestry (Ma et al., 2010; Mason, 2015), agriculture (Lin, 2007; Waffle et al., 2017), and pest and disease epidemiology (Baker, 1980; Haider et al., 2017; Murdock et al*.,* 2017). Although we focus here on microclimates within the context of conservation ecology, an understanding of microclimates could be vital to plant, animal and human health, food security, and sustainable development.

**Box 1: The definition of microclimate**

Climatic observations and models are often grouped into spatial and/or temporal scales, typically based on the dimensions of the climate variations or processes they aim to represent. However, these groups are not precise and are much debated, resulting in widely varying definitions of what ‘microclimate’ is.

The World Meteorological Organisation (WMO) identify the microscale as <100m spatial resolution, with temporal resolution dependent on the application: “minutes for aviation, hours for agriculture, and days for climate description” (WMO, 2014). Geiger et al. (2009) defines microclimate as describing “the climate of an individual site or station… characterised by rapid vertical and horizontal changes”, while Barry and Blanken (2016) define microclimates as “the layer of interface between the surface and atmosphere”. The tables below give the range of scales used to describe the different climatic groups by various sources.

**Microclimate:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Geiger et al., 2009** | **Barry and Blanken, 2016** | **Littmann, 2008** | **Orlanski, 1975; WMO, 2010 & 2014** |
| Horizontal scale | 0.001 to 100m | <~50m (defined by vegetation canopy height) | 10-100m2 | <100m |
| Vertical scale | -10 to 10m | < A few 100 m |  |  |
| Time scale | < 10 sec | < Min |  |  |

**Topoclimate/ local climate:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Geiger et al., 2009** | **Barry and Blanken, 2016** | **Littmann, 2008** | **Orlanski, 1975; WMO, 2010 & 2014** |
| Horizontal scale | 100m to 10km | 100m to ~10km | 100m to ~2km | 100m to 3km |
| Vertical scale | 5m to 1km | 500m to 1.5km |  |  |
| Time scale | 10 sec to hrs | Min to hrs |  |  |

**Mesoclimate:**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Geiger et al., 2009** | **Barry and Blanken, 2016** | **Orlanski, 1975; WMO, 2010 & 2014** |
| Horizontal scale | 1km to ~200km | 10km to ~50km | 3km to 100km |
| Vertical scale | 500m to 4km |  |  |
| Time scale | Hrs to days | Hrs to days |  |

**Macroclimate:**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Geiger et al., 2009** | **Barry and Blanken, 2016** | **Orlanski, 1975; WMO, 2010 & 2014** |
| Horizontal scale | > 200km | >50km | 100km – 3,000km |
| Vertical scale | 1km to 10km |  |  |
| Time scale | Days to weeks | > hrs |  |

It has been established that the seasonal mean temperatures that species experience can deviate by as much as 5 °C from the macroclimate (e.g. Scherrer and Körner, 2010; Suggitt et al., 2011), and deviations within landscapes can be as much as 20 °C at any one time (Figure 2; Scherrer and Körner, 2010). Even within a single inflorescence the temperature between the ovaries and the petals may differ by 10 °C (Dietrich and Körner, 2014). However, the climate envelope models used by ecologists often do not account for such small-scale climate variations (Slavich et al., 2014). They generally use coarse scale averages from meteorological stations with instruments sited a few metres above the earth’s surface (WMO, 2014). These spread across grid scales which can be as much as 10,000 fold the body size of the species being studied (Potter et al., 2013), and thus they are not able to capture important climate forcing factors and fine scale climate variations, as well as weather extremes, which have strong limiting forces on species (Easterling et al., 2000; Parmesan et al., 2000). What’s more, classic meteorological stations have guidance exposure criteria which are designed to limit local climate influences (WMO, 2014). Utilising such observations to assess ecological processes that have a strong microclimate influence will decrease the accuracy of predictions of species’ responses to climate change (Slavich et al., 2014), and hinder our ability to conserve biodiversity. For example, Trivedi et al. (2008) showed that taking local and microclimate variations into account gave different projections of the future survival of plants species at a site in Scotland compared to using large scale macroclimate data alone.

One of the reasons microclimates are ecologically important is that they can potentially buffer taxa against climate variability and longer-term changes, thus providing microrefugia which allow species and populations to survive in locations which may be deemed unsuitable using low resolution observations and models (De Frenne et al., 2013; Lenoir et al., 2017; Maclean et al., 2015; Slavich et al., 2014; Suggitt et al., 2015). Identifying and protecting refugia can be difficult (Ashcroft et al., 2012; Morelli et al., 2016), but it is becoming a more important aim for conservation science, and understanding the buffering role of microclimates may play a part in that.

Despite the long history of microclimatology (Geiger, 1927; Kraus, 1911), it is only more recently that consideration and understanding of microclimates has become widespread within the field of ecology. Developments in technology and advances in computing power have made taking simultaneous measurements over large areas much easier in the last two decades, and the mechanistic understanding of microclimates established in other scientific fields has begun to be considered by ecologists (Jones, 2013; Wang et al., 2013). The recent increase in expertise and subsequent research interest has resulted in the establishment of a strong knowledge base of microclimate ecology.

Topics which have been studied include the influence of terrain (Bennie et al., 2008; Finkel et al., 2001; Scherrer and Körner, 2010; Suggitt et al., 2011), forest structure (Chen et al., 1993; Pohlman et al., 2007; Pringle et al., 2003), and other vegetation types (Bauer and Kenyeres, 2007; Cavieres et al., 2007; D’Odorico et al., 2013; Suggittet al., 2011) on microclimate. In addition, the effects of microclimate on species abundance (Checa et al., 2014; Curtis and Isaac, 2015; Gillingham et al., 2012a), diversity (Gómez-Cifuentes et al., 2017; Raabe et al., 2010), phenology (Weiss et al., 1993), distribution (Kelly et al, 2004; Martin, 2001), invasion success (Lembrechts et al., 2017) and behaviour (Cunningham et al., 2015; Hutchinson and Lacki, 2001; Kelly et al., 2004; Kleckova and Klecka, 2016; Willis and Brigham, 2005) have been quantified. Finally, the effects of habitat management on microclimates (Meyer et al., 2001; Ripley and Archibold, 1999), including water temperatures (Imholt et al., 2010) have also been investigated, as well as the potential microclimate manipulation to be used as a means to offset the adverse impacts on biodiversity of climate change (Greenwood et al., 2016).

As interest in dedicated microclimate research has increased, so have attempts at microclimate modelling, with several different types of models in use (e.g. Gunton et al., 2015; Kearney et al., 2014; Maclean et al., 2017; Shi et al., 2016; see Section 5). Meanwhile new technologies are becoming available, such as the use of Unmanned Aerial Vehicles (UAVs) for remote sensing of temperature and other environmental variables, presenting novel opportunities for future research (see Section 4.3).

Perhaps because the surge in interest is relatively recent, the methods used to measure and model microclimates are varied, especially with regards to *in situ* measurement (see Section 4.2). This variability in data collection makes comparisons between datasets unreliable, the understanding of patterns in microclimate beyond individual field sites and case studies difficult, and the reliable identification of microrefugia challenging. For example, there are many types of relatively cheap miniature dataloggers and sensors available (see Table 1) but they vary widely in what they measure, their precision, reliability, and price. The World Meteorological Organisation (WMO) provides some practical guidance for observing microclimate, focussing on the siting of instruments for differing scales of representativeness (WMO, 2014 Annex 1.B). However, more broadly there is little to no guidance available as to which sensors are best for particular situations, how they should be placed and shielded, or even which factors of microclimate are important to measure.

We aim to tackle these challenges by summarising current methods in measuring and modelling microclimates, providing some guidance on the questions that should be asked when planning microclimate research, and how to go about deciding which approach to take. This should assist researchers and help to establish some consistency in the field, as well as presenting ideas for how the field may develop in coming years.

**Box 2: Monitoring, Modelling and Managing Microclimates Workshop**

An open workshop supported by the British Ecological Society’s Climate Change Ecology Special Interest Group was held in September 2017, attended by 25 microclimate scientists from 8 countries. Academics and conservation practitioners discussed the key challenges to microclimate research, and potential future directions.

Delegates were asked to first identify challenges for including microclimates in ecological research, and then from a master list choose the three that they considered to be the most challenging. These are listed below in order of identified importance:

· Investment of time and money, and challenges gaining funding.

· Lack of common data collection protocol and the resultant lack of comparability.

· Lacking knowledge of measurement methods.

· Lack of impact due to results not being generalizable to other systems.

· Lack of understanding of feedbacks e.g. vegetation-climate, snow-climate.

· Difficulty of finding biologically relevant climate data in freely available datasets (no database dedicated to microclimate data).

· Lack of collaboration between meteorologists and ecologists.

· Availability/reliability/appropriateness of equipment.

· Insufficient computer power.

· Defining microclimate, both in general and specifically for the target system/species.

· Researchers are not often confronted with microclimate, so it is not considered important.

· What spatial resolution to measure microclimates at.

· By measuring the microclimate you may change it e.g. flattening vegetation.

· Knowing which climatic variables to measure.

· It can be difficult and intimidating for people unfamiliar with the field.

· Knowing how often to measure the climatic variables.

· Balancing collecting enough data with having a manageable dataset.

[Insert Figure 1 here]

Figure 1: An illustration of climate, microclimate, and the processes driving it. Arrows indicate the general extent, and in some cases direction, of the climate forcing processes. See Section 2 for explanation of terms.

## 2. Factors leading to variable microclimates

Microclimatic variation is driven primarily by the four components to the earth’s heat budget, each representing the ways in which heat can be exchanged (Bennieet al., 2008; Geigeret al., 2009; Jones, 2013). In approximate order of importance these are (1) solar and thermal radiation, (2) latent-heat exchange, (3) sensible heat flux (heat convection), and (4) heat conduction (e.g. in soil).

**Box 3: Glossary of terms**

|  |  |
| --- | --- |
| Adiabatic processes | Process that do not involve heat or matter exchange |
| Free atmosphere | The portion of the earth's atmosphere, above the planetary boundary layer, in which the effect of surface friction on air motion is negligible, and in which the air behaves like an ideal fluid |
| Heat budget | The balance between incoming and outgoing heat |
| Hyperspectral data | Used in the context of remote-sensing to describe imagery in which reflectance is measured across a range of the electromagnetic spectrum |
| Irradiance | The flux of radiant energy per unit area |
| Katabatic wind/flow | Airflow that carries high density air from a higher elevation down a slope under the force of gravity Lapse rate - the rate at which air temperature falls with increasing altitude |
| Microrefugia | Small areas outside the core distribution area where species persist despite the surroundings being inhospitable |
| Photogrammetry | Gaining accurate measurements from photography |
| Physiographic | The physical factors of the earth |
| Refugia | An area in which a population can survive during a period of unfavourable conditions |
| Remote Sensing | Obtaining information about objects or areas from a distance, typically from aircraft or satellites |
| Shortwave radiation | Energy radiating from the sun and received by the earth in the visible, near-ultraviolet and near-infrared spectral region (~0.1 – 5 μm) |
| Thermodynamic | Of or related to the actions of heat and other types of energy |

### 2.1 Microclimatic processes

#### 2.1.1 Radiation Heat Flux

Energy is received from the sun in the form of shortwave radiation, some of which reaches the surface directly, while some is reflected, scattered and absorbed by particles in the atmosphere, to reach the ground as diffuse radiation. Small amounts of energy are also received at the ground as radiation reflected from surrounding surfaces. The local intensity of radiation received at the surface, which influences local temperatures, is influenced largely by three factors (Hay and McKay, 1985). First, by the angle between the direction of the sun's rays and the earth’s surface, and hence by latitudinal, seasonal and diurnal changes in the position of the sun, as well as the slope and aspect of the ground surface (see Figures 1). Second, the local intensity of radiation is also affected by various atmospheric constituents, namely gases, aerosols, and particularly by clouds. Under turbid atmospheric conditions direct radiation decreases, but diffuse radiation initially increases, and thus the effects of local topography on temperature are most pronounced under cloud-free conditions. Third, under vegetated canopies, canopy-transmission decreases with canopy cover, but is also affected by leaf structure: at low solar angles radiation is lower when leaves are vertically-oriented.

A considerable amount of solar radiation reaching the earth's surface is reflected. The fraction reflected is highly variable for different surfaces depending on their albedo, and may be as large as 0.95 for freshly fallen snow and as small as 0.05 for a wet bare soil (Wanneret al., 1997). The energy not reflected is absorbed by the earth and then converted to heat energy, which is later emitted as longwave radiation. However, some of this radiation is then absorbed by the atmosphere, especially during cloudy conditions, or by vegetation canopies, and then re-radiated back down to the earth’s surface. During the night time in open areas, particularly under clear sky conditions, longwave emissions from the surface are relatively high and so ground temperatures can be considerably cooler than air temperatures above the boundary layer (Körner and Hiltbrunner, 2017).

#### 2.1.2 Latent Heat Flux

Latent-heat exchange, particularly due to surface evaporation and transpiration, affects local temperatures because heat is required to evaporate water. This process thus consumes some of the energy budget and cools the surrounding air. Different land cover types influence the evapotranspiration rate, and therefore the local climate (Zeng et al., 2017). Similarly, when ice melts or undergoes sublimation, energy is required, and the converse is also true: energy is released when water condenses or undergoes deposition as frost (Lunardini, 1981).

#### 2.1.3 Sensible Heat Flux (heat convection)

Heat convection between the earth’s surface and the atmosphere is affected by boundary layer processes (Stull, 2012), particularly the degree to which heat and moisture are transported by eddy diffusion, which itself has two causes: frictional and convective exchange (Oke, 2002). The former is determined by the roughness of the ground surface, whereas the latter is a function of wind speed (see Figure 1). By day, particularly during warm weather, convective mixing also contributes to air heat transport (Geigeret al., 2009).

#### 2.1.4 Heat conduction

Heat conduction, in this case the transfer of heat from the air to the soil and vice-versa, is dependent on air-soil temperature gradients. Temperatures typically increase with soil-depth at night and in winter, but on warm, sunny days in summer, the converse is true. Conduction is also dependent on the thermal properties of soil. These in turn depend on soil moisture content, as well as on substrate type: rocks typically have a much higher thermal conductivity than clay and sand, as such animals basking on warm rocks will warm up more quickly than if basking on sand (Johansen, 1977).

[Insert Figure 2 here]

Figure 2: Temperatures experienced across a heterogenous landscape. a) Image of a hillside in Switzerland, b) Thermal infra-red image of the same hillside and c) Temperature of pixels down the transect shown in b), showing the effect of vegetation on temperature. Although there is a general decrease in temperature with elevation within habitat types, the short alpine meadow at higher elevations shows much higher temperatures than the wooded area at lower elevations. The relative frequency of pixels at given temperatures within the two habitats is summarised in a). (Körner, 2007)

### 2.2 Mesoclimatic processes

Over mesoclimatic extents, vertical temperature gradients and horizontal air movement become increasingly important. Arguably the most important effect is that of altitude. At higher altitudes, the expansion of air caused by lower atmospheric pressure consumes energy, thus reducing the heat available per unit volume. By this process, dry air cools at a predictable adiabatic lapse rate of 9.8°C per 1,000 m altitude (Barry and Blanken, 2016). With increasing moisture content the latent heat released by condensation reduces this rate of heat loss in the air, to about 5.0°C per 1,000m altitude depending on the temperature. However, the additional effects of mixing of air masses means that environmental lapse rates are often variable, and while typically around 5.0-6.0°C per 1,000m (Blandfordet al., 2008), can be hard to predict. Such lapse rates also vary seasonally (Kollas et al., 2014).

Airmass movement is particularly important in mountainous and coastal areas, or close to large water bodies. On hot sunny days in mountainous areas, greater heating over adjacent lowlands can create a horizontal pressure gradient that produces a movement of air towards the mountain. A return flow often occurs at night with the reversal of gradient. Under certain climatic conditions, katabatic flow can occur (see Figure 1). This happens when air in contact with the ground at higher elevations cools, increases in specific gravity, and therefore flows to lower elevations. The differences in density are marginal and the airflow is therefore quite weak and easily obstructed, occurring only during still nights when surface cooling has progressed for some time (Haiden and Whiteman, 2005; Manins and Sawford, 1979). The reverse happens during the day. The cold air that flows into valleys, either as a result of compensating or katabatic flow, typically escapes by funnelling down valleys. During the day, when slope flow is reversed, the direction of valley flows also reverses (Whiteman, 2000). These air flows generally reduce lapse rates, with smaller differences in temperature between the top and bottom of slopes than would otherwise be expected. During the day, the transport of air to higher elevations results in warming, reducing the temperature gradient. At night, the sinking of cold air can result in the usual decrease in temperature with height reversing, causing a temperature inversion. In extreme cases, frost hollows form in which the vegetation cover can differ substantially from surrounding areas (Davidson and Reid, 1985).

Another important landscape-scale determinant of surface temperature results from the presence of large waterbodies, particularly the sea. Water has a particularly high specific heat capacity relative to many substances, including the various compounds that comprise terrestrial landmasses, and therefore tends to heat up and cool down more slowly. During the afternoon, when land is typically warmer than water, the resulting vertical expansion of the air above land causes compensating onshore winds, while at night the air over water is warmer and the situation is reversed (Wexler, 1946). For this reason, both seasonal and daily temperature variation is often much lower near the sea, an effect noticeable even over relatively short distances of a few kilometres (Maclean et al., 2017).

### 2.3 Fine-scale variation in water availability

Hydrological conditions vary steeply in space and over time (Maclean et al., 2012), and to understand these processes it is helpful to consider a single hydrological basin. Water reaches a basin as precipitation, and then either infiltrates into the ground or runs-off and collects as surface water in low-lying areas. Infiltration rates are dependent on the physical properties of soil (Pepper and Morrissey, 1985; see Figure 1). Infiltration occurs until the soil is saturated, but thereafter any remaining water entering the basin runs-off and accumulates as surface water. Water can leave a basin at its lowest boundary and similarly can enter a basin from adjacent basins. Variations within a basin are driven predominantly by topography, with the lowest areas generally accumulating the most water, and flat areas being typically wetter than steep slopes due to lower rates of surface run-off.   
  
Water also leaves a basin as a result of evapotranspiration. Rates of evapotranspiration are strongly weather dependent and are caused by the motion of water molecules at any temperature above absolute zero (Burman et al., 1987). Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide the energy required to change the state of the molecules of water from liquid to vapour. The rate of removal of water vapour from the evaporating surface is driven by the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and stop if wet air is not transferred to the atmosphere. Consequently, evapotranspiration is higher from surfaces receiving more solar energy and from more exposed locations, where wind speeds are higher. The transpiration component of evapotranspiration is influenced by the nature of vegetation in addition to weather. Plants predominately lose their water through stomata: small openings in the leaves through which water vapour can pass. Different vegetation types have different transpiration rates, but in general transpiration increases with leaf area, the roughness of vegetated surfaces and with the size of stomatal apertures (Jarvis and McNaughton, 1986; see Figure 1).   
  
As theory suggests, dry conditions typically occur on steep slopes, particularly those that face the sun, and, rainfall aside, valley bottoms are typically wetter than mountain tops. The effects of vegetation on water availability are, however, more complex. On the one hand, greater evapotranspiration is associated with higher vegetation cover, due to the effects of leaf area. On the other hand, canopy shading can reduce evapotranspiration, leading to damper conditions in the understory. The processes are also dynamic: drought conditions can cause vegetation moisture stress and possibly die-back, which influences evapotranspiration rates and hence water availability (da Costa et al., 2010).

## 3. Organisms and their environment

### 3.1 Individuals and microclimate

The fundamental reason for the importance of microclimates to organisms is that they drive energy, mass, and momentum exchange which, in turn, set the thermodynamic bounds on life (Bird et al., 2002; Porter and Gates, 1969). For example, the temperature of a terrestrial organism at a given moment is the result of the balance of energy fluxes, from incoming and reflected solar radiation, and heat from its metabolism, as well as the heat lost or gained by the processes of convection, conduction, and evaporation, and any storage of heat in the body (Porter and Gates, 1969). All of these processes except for metabolism and storage explicitly involve one or more aspects of microclimate - radiation, air temperature, precipitation, wind speed, humidity and substrate temperature. Similarly, the mass budget of an organism in terms of water is the outcome of water gained from the environment, from its metabolism, as well as that lost by evaporation and potentially excretion/faeces. The evaporation process is microclimate-sensitive, depending on the vapour pressure difference between the relevant surfaces of the organism and the air immediately surrounding the organism, as well as the air temperature and wind speed (Gates, 1980; Tracy, 1976). Finally, movement costs for mobile organisms and mechanical stress on sessile organisms depends on the force exerted by wind or water, which itself depends on fluid temperature and speed (e.g. Denny, 1988; Telewski, 1995).

The actual microclimate experienced by an organism in a particular habitat is the outcome of the interaction between organism and environment (Lewontin, 2000). The microclimate of all organisms is in part a function of their morphology and physiology. For example, the simple change in height above the ground with growth and development can have a strong effect on microclimate exposure (e.g. Körner and Hiltbrunner, 2017). Even different parts of the same organism may be at different temperatures: tree leaf temperature is different to that of the trunk and different again to root temperature. Behaviour is an important factor for animals and, to a lesser but not unimportant degree, for plants (Huey et al., 2002). Ectotherms have long been noted for their ability to regulate body temperature precisely by behavioural means (Cowles and Bogert, 1944) but plants can also alter radiative microclimates via leaf angle (Dawin and Darwin, 1880) and their internal environment by opening and closing their stomata (Helliker and Richter, 2008; Michaletz et al., 2015), while endotherms have sophisticated behavioural and postural means for regulating the microclimates they experience (Bennett et al., 1984; Briscoe et al., 2014; Cunningham et al., 2015; Kelly et al., 2004).

The interaction between an organism and the environment can generate microclimatic effects that structure entire landscapes (D’Odorico et al., 2010; Rietkerk et al., 2002). Variations in climate at different scales can interact to give an overall impact of climate on species (Frey et al., 2016). Organisms are always subject to the influence of microclimates, but these effects can be mediated by biotic interactions that either change the microclimate where an organism occurs (e.g. plant competition for light, see Figure 1) or induce an organism to move from one microclimate to another (e.g. due to competitive or predatory interactions). Organisms can also change the microclimate of the location they occupy; for example the metabolic heat production of bats can measurably influence cave microclimates (Baudunette et al., 1994). Microclimates may also be important indirectly through their impact on resources such as food, micronutrients, water and nesting materials.

For these reasons, the way in which microclimates are studied, measured and simulated are much more organism-specific than in biological considerations of macroclimate. In different cases, different variables may assume varying degrees of importance. For example, humidity may be of far greater importance to the body temperature of a frog than to a lizard, and soil moisture may be more directly influential to the survival of a germinating seed than it is to a hatchling bird. The relevant spatial and temporal scale of microclimatic observations is also intimately connected to the biological entity or phenomenon in question. For example, fine temporal resolution may be important for assessing exposure to stress but not for assessing climatic influences on life history (Helmuth et al., 2010; Kearney et al., 2012).

## 4. Measuring microclimates

Ultimately, the question facing any ecologist interested in studying microclimates is: ‘What microclimate do I want to measure or estimate?’. This may be the actual body or organ temperature of an organism, or the microclimate of the air or soil surrounding an organism. The answer will be unique to the experiment being planned, and will lie somewhere on the spectrum between a full international standard meteorological setup (ISO, 2015) and the true set of conditions that the target organism experiences in real-time. Some consideration should also be given to if/how the sensor might affect this target organism, i.e. by changing its behaviour (Willis et al., 2009) or its body temperature. Thorough background research on a putative sensor type should reveal such issues where they occur.

As the field of microclimate science matures, it is also useful to consider whether measurements can be taken in such a way as to be more broadly useful to others, to allow sharing of data between researchers and provide ground-truthing data for modellers. In order to achieve this it is important to thoroughly record every aspect of the method used. For example, many papers do not report the model of climate sensor used, but it is vital to do so if data is to be comparable. A list of sensors which have been used in microclimate research can be seen in Table 1, while Table 2 presents some issues that may be encountered when utilising different types of sensors.

The scope of microclimate monitoring can range from the placement of portable meteorological stations in locations uncaptured by standard networks, to bespoke microsensors placed on (or even in) an individual organism of interest, to the simultaneous capture of temperature information across a landscape using remote sensing. Any measure of an atmospheric condition (temperature, moisture, or others) is an approximation of reality, including those data collected by meteorological station networks. The data that are derived are therefore a function of the physical properties of the monitoring device; its emissivity, its albedo, its mass, its susceptibility to radiation and wind, and most critically, where it is placed: the level of shade, orientation to the sun and thus exposure to direct solar radiation. Because microclimate by definition varies at small spatial scales, it is a challenge for ecologists to develop a consistent, standard methodology for measuring microclimatic variables. Slight variation in the position of sensors, in their exposure to sunlight and wind, their height above the ground or in the physical characteristics of the sensors themselves can lead to large discrepancies in measurements, but attempting to reduce these discrepancies (for example by mounting sensors in a radiation screen at a standard height), will inevitably lead to a reduction in the variability observed, including those aspects which may be of most interest.

Table 1: A summary of equipment that has been used to measure microclimates in the field, quantified during a systematic review of the literature (see Supplementary Methods for details). Please note that most of the brands produce a variety of models with varying capabilities and prices and the model used has not always been reported. Price categories: £ =~£5 to ~£100; ££=~£50 to ~£200; £££= >~£200.

|  |  |  |  |
| --- | --- | --- | --- |
| Type of equipment used | Details | Number of studies | Price |
| Onset's HOBO dataloggers | Stand-alone data loggers with internal sensors for a variety of environmental measurements. Most commonly used for temperature and humidity. Come in USB, WIFI, and Bluetooth compatible models. | 40 | ££ |
| Maxim's iButton dataloggers | Stand-alone miniature data loggers with integral monitoring of temperature and humidity. USB compatable. | 37 | £ |
| Campbell Scientific dataloggers | Dataloggers compatible with a variety of external environmental sensors which can be bought separately | 19 | £££ |
| Gemini's Tinytag dataloggers | Both stand-alone and external sensor data loggers for a variety of environmental measurements. | 7 | £££ |
| Lascar dataloggers | Stand-alone dataloggers for a variety of environmental measurements. Come in USB, WIFI, and Bluetooth compatible models. | 2 | ££ |
| Logtag dataloggers | Stand alone and external sensor dataloggers for measuring temperature. | 2 | ££ |
| LI-COR dataloggers | Dataloggers compatible with a variety of external environmental sensors which can be bought separately | 2 | £££ |
| Testo dataloggers | Both stand alone and external sensor data loggers for measuring temperature and humidity. | 1 | ££ |
| Volcraft dataloggers | Stand-alone dataloggers for a variety of environmental measurements. | 1 | ££ |
| Decagon dataloggers | Dataloggers compatible with a variety of external environmental sensors which can be bought separately | 1 | £££ |
| Kestrel handheld weather meters | Handheld instruments for a variety of environmental measurements, some with datalogger capabilities | 2 | £££ |

Table 2: A summary of the variables measured in ecological studies of microclimates in the field, quantified during a systematic review of the literature (see Supplementary Methods for details). Please note that there are a variety of types and brands available for each sensor group.

|  |  |  |
| --- | --- | --- |
| Variables measured | Number of studies | Potential problems |
| Temperature | 59 | If left unshielded, temperature sensors absorb radiation: either direct short-wave radiation from the sun, or indirect short- and long-wave radiation via other components of the local environment (e.g. trees, ground surface). This can result in recorded temperatures being higher than the (‘true’) air temperature, particularly in clear-sky conditions in unshaded locations. Sensors also emit long-wave radiation, so under conditions where the net radiation balance of the device is negative- such as at night, or in shady habitats in daytime- they can also be warmer than the environment (Unwin 1980). The size of any radiation effect varies based on the sensor design (see Section 4.2.1). If the aim is to measure the ‘true’ air temperature then the use of professional shielding is a must. |
| Combined temperature and humidity | 79 | Humidity sensors are vulnerable to getting wet. If water gets on the sensor it results in inaccurate humidity readings (see Section 4.2.2). The use of a rain shelter is essential. |
| PAR/LUX | 31 | There are dataloggers available which measure both light and temperature; however this presents the problem of radiative warming of the sensor discussed above. In these cases one logger should be used to record light, and a shielded logger should be used to record temperature. |
| Wind speed/direction | 11 | There has been a lack of small self-contained anemometers which can be left in situ. Some models are now available which can be left logging for three days. |
| Soil moisture | 28 | Soil moisture sensors need to be calibrated for the soil texture and organic matter concentration that determines the electric conductivity, otherwise the results are uncertain. |

### 4.1 Measuring microclimate *in situ*

The *in situ* study of microclimates has a long history that can broadly be divided into two eras: before and after automation. Prior to automation, most instruments would take instantaneous measurements of the microclimate (see Monteith, 1972; Unwin, 1980 for useful guides). Although the level of replication in these experiments was limited by obvious practical considerations, such as the numbers of instruments to be employed, and the number of personnel available to attend them, the pre-automation era led to much of the fundamental physics of boundary layer climatology being resolved (e.g. Geiger, 1927; Homén, 1897; Kraus, 1911). Because the sensor technology behind early, analogue instruments and their modern, digital equivalents has changed little, this early microclimatological work has continued relevance today.

The falling price of the microchip during the 1980s and 1990s heralded a new wave of instruments that could autonomously collect and store microclimate measurements in the field (see Table 1). Large levels of replication and intensity of study design became available to scientists interested in how microclimates vary across space and through time. This technology has improved our understanding of how and when the boundary layer microclimate differs from measurements derived from meteorological station networks, such as the difference between recording at screen or other sensor heights (1.5 – 2.0 m) and close to the ground (e.g. Suggitt et al., 2011), how vegetation types differ in their microclimate (e.g. Morecroft et al., 1998), or even the contexts in which simplifying assumptions, such as lapse rate adjustments, break down (e.g. Bennie et al., 2010; Pepin et al., 1999).

The WMO provides guidance on the desirable characteristics, standards and uncertainties of standard meteorological instruments (WMO, 2014), some of which are applicable for micrometeorological observations. However, some of these instruments and standards will only be applicable for studying regional and synoptic processes, so although this guidance is very helpful for meteorological instruments in general, careful consideration of their suitability for micrometeorological studies should be made before they are applied.

The below subsections briefly describe what we consider to be the more important considerations when choosing and using each type of *in situ* sensor.

#### 4.1.1 Temperature

Numerous sensor types have been used to measure temperature (Table 1), and the merits and draw-backs of each are typically associated with cost and accuracy: more expensive devices record temperatures more accurately. However, by far the greatest consideration for accurate temperature recording is what temperature is actually of interest. This will dictate where sensors should be placed and how measurements should be taken. Aerodynamically well-coupled organisms such trees and bushes are likely to experience temperatures close to those represented by standard meteorological station data obtained two metres above the ground. Where finer spatial-scale data are needed, sensors appropriately shaded from solar radiation will likely provide a reasonable proxy. In other circumstances obtaining measurements 1-2 cm below the ground, where many smaller plants have their meristems, or 5 cm below the ground, where microbial activity peaks, may be desirable. To obtain such measurements burying sensors with appropriate damp-proofing is likely to be the most sensible option. It is when trying to measure the temperature experienced by small organisms close to the ground that temperature measurement becomes most problematic. Here, the temperature of an organism is not only influenced by solar radiation, but by the temperature of the ambient air with which it exchanges heat. Air temperatures close to the earth’s surface, even when shaded from direct sunlight, can often differ substantially from that within the free atmosphere due to convective heating or cooling from the ground. It is thus necessary to approximate the effects of both higher ambient air temperature and of radiative heating.

In an attempt to approximate near-ground air temperatures, many ecologists have opted to shield their sensors with a radiation shield (or even two), electing for either a ‘homemade’ or ‘off the shelf’ version (e.g. De Frenne et al., 2011; Holden et al., 2013; Lundquist and Huggett, 2008). However, we caution against doing so without rigorous testing. Different types of shield result in substantially different measurements of temperature (see Figure 3), and low-cost screens reduce ventilation and result in over-estimation of the temperatures in comparison to expensive purpose-built screens (Hubbart et al., 2005, Figure 3). Mechanical ventilation (‘aspiration’), ensuring a unit flow of air passes the sensor per unit time, can minimise this effect, but the power required to implement it limits its use in most field ecology contexts. Indeed measuring temperatures under 100% natural vegetative shading may in many circumstances may provide more reliable results (Körner and Paulsen, 2004; Lundquist and Huggett, 2008). Furthermore, shielding the device at all may mask the very component of microclimate that is of interest.

A simple solution to this would seem to be to leave a device unshielded. However, temperature sensors themselves are often housed in weather-proof casing, and are thus essentially shielded to some degree, although the surface albedo of the device and degree of ventilation the sensors experience may be quite different to those experienced by an organism in its environment. There are several possible ways forward for measuring air temperature close to the ground:

1. Use dataloggers installed close to the ground within a professionally designed radiation shield. While a full Stevenson screen is impractical for microclimate work, many operating meteteorological stations (e.g. Campbell Scientific) use radiation shelters that are 15 to 20 cm in height/diameter, and these can simply be installed close to the ground.
2. Use very small external sensors, which due to their low surface area/volume ratio are closely coupled to air temperature. Simple thermocouples or small thermistors are usually too small to heat up much above the air temperature, so if they are exposed to the air, with some simple shading, they can give an accurate measure of air temperature.
3. Use improvised shading methods, with extreme caution, and only if the design is fully tested against a meteorological station and the errors present in strong radiation have been assessed.
4. Use sensor/shield combinations that have similar physical properties (size, thermal capacity, albedo) to the organism of interest, and measure a standardised effective organism temperature (operative temperature, see below) rather than air temperature.
5. Consider the use of thermal imagery obtained under varying radiation heat flux conditions (see section 4.1), coupled with mechanistic models that permit temperature to be predicted from radiation (see section 5.2).

Above all, it is important to remember that the temperature of the sensor is measured, not directly that of the air or the organism, so any assumptions about the strength of coupling to air temperature/organism temperature must be carefully considered and whenever possible tested.

[Insert Figure 3 here]

Figure 3: The effect of different shielding methods (inverted funnels covered in tinfoil, painted white or red) on in situ temperature measurements (see Supplementary Methods)-iButtons in custom-made shields were on average warmer and experienced more extreme temperatures, particularly higher temperatures, than standard sensors and compared to the iButton in the Stevenson Screen (A). However, this was very dependent on radiative warming. Measurements taken during the two hottest hours of the day (14:00 – 16:00) tended to be more extreme (B) with the biggest difference being driven by colour (red funnels vs everything else). In comparison measurements taken between midnight and 02:00 showed little discernible difference between treatments or from the standard sensors (C). Tinfoil-wrapped ibuttons slightly underestimate temperature at night possibly due to cooling from wetting or condensation (C).

##### **4.1.1.1 Operative temperature models**

The most organism-specific empirical microclimatic measurements are made using ‘operative environmental temperature’ thermometers, which approximate the steady state temperature an organism would come to given its size, shape, and radiative thermal properties if it had zero thermal mass (Bakken, 1981, 1992; Bakken and Angilletta, 2014). For ectotherms, these are typically made out of copper (for rapid heat transfer), often by making a mould of the specimen (Hertz, 1992; Porter et al., 1973) but also by simply using hollow copper tubes (Shine and Kearney, 2001). For endotherms, heating elements inside taxidermic mounts can be used to estimate metabolic heating requirements to maintain a constant body temperature, or to include basal metabolic heat generation for estimating heat loads (Bakken, 1981; Bakken et al., 1983; for a critical review see Walsberg and Wolf, 1996). Bakken and Angilletta (2014) provide a useful overview of the use of operative temperatures in thermal ecological studies.

#### 4.1.2 Humidity

Atmospheric humidity is critical to organisms as, along with temperature, wind speed, and the radiation balance, determines the potential rate of water loss from a surface. Relative humidity (RH) and VPD vary rapidly over small distances, but temperature-independent measures such as specific or absolute humidity do not, so it is often better to measure these and interpolate (in time/space), rather than attempting to interpolate temperature-dependent measures. Several different types of hygrometer, employing different physical approaches, are used to measure humidity. The most widespread in meteorological stations is the psychometric method. A psychrometer consists of two thermometers exposed side by side, with the sensing surface of one covered by a film of water (the wet bulb), and the other dry (the dry bulb). The cooling effect of evaporation from the wet surface is used to estimate humidity. Although accurate, this method has several drawbacks for measuring fine-scale humidity, particularly for automated measurements in remote areas. The size of standard psychrometer units is often fairly large, making it difficult to make measurements in confined spaces or close to the ground, near to an organism or micro-environment of interest. Also, regular maintenance is needed to ensure that water reservoirs are kept topped up.

Electrical (capacitive or resistive) humidity sensors are increasingly used to provide a cheap, lightweight and flexible alternative to traditional methods, particularly for remote applications (Table 2). Electrical sensors exploit the properties of hygroscopic materials that change their electrical properties (resistance or capacitance) with a change in the ambient relative humidity, with a small temperature dependence. Several manufacturers produce electrical relative humidity sensors with miniature dataloggers, designed to be deployed outdoors and subsequently downloaded to a PC or laptop.

One frequently encountered problem with electronic humidity data sensors is the trade-off between exposing the sensor to freely circulating air and reducing the probability that moisture condenses on the sensor itself (or gets wet from rainfall or spray in damp environments), typically leading to false measurements of 100% relative humidity or even damage to their circuitry. While 100% RH is frequently observed in many environments, particularly at night when the atmosphere cools below the dew point and the air is saturated, if liquid water remains on the sensor then erroneous measurements at 100% humidity are likely to persist after the atmospheric humidity is reduced. Radiation shielding may reduce the radiative cooling effects at night, lowering the potential for condensation, but this must be carefully balanced by good ventilation to allow the sensor to dry after any condensation occurs.

An alternative or complementary approach to humidity sensors in sporadically damp environments are leaf wetness sensors, which measure the dielectric constant of the surface of the sensor itself (usually shaped like a leaf), and can detect small amounts of water or ice on the “leaf” surface.

#### 4.1.3 Radiation

*This subsection refers to those parts of the electromagnetic spectrum which are biologically relevant and measureable- note that visible light / photosynthetically active radiation (wavelength 400 – 700 nm) are dealt with separately below, although some of the sensors described here capture these wavelengths too.*

Total irradiance (per unit area) is typically measured by a solarimeter, and modern devices will also separate the direct and diffuse components (by shading the sensor in some way). Because irradiance can vary considerably over short scales, some solarimeters will feature a number of sensors along a length (a ‘tube’, ‘bar’ or ‘wand’) to take a more representative sample. As its name suggests, a ‘net’ radiometer will additionally capture outgoing long-wave radiation, and thus the overall radiation budget can be discerned.

Although in theory quite possible to design, a battery-integrated radiation sensor with full spectral response would in practice suffer from a short battery life due to the power required to operate the sensor(s). The power requirement is increased for deployments where the weather conditions (snow, ice, dew) might obscure the path of radiation to the sensor, necessitating the use of a preventative heater.

Separate monitoring of radiation (in addition to temperature) may be required to understand the thermal opportunities available to organisms in situations where the timing of a change in the radiation budget may not be apparent in recorded temperatures, but could easily be apparent in ecological findings (such as activity levels or metabolic processes). Similarly, the coupling between the temperature measured by an *in situ* sensor and the surface temperature of the target organism may break down at certain (high) levels of irradiance (even in plants, Barozzi et al., 2016), and such cases may necessitate further monitoring of the radiation itself.

#### 4.1.4 Visible light and Photosynthetically Active Radiation (PAR)

Visible light meters fall into two categories: reflected-light and incident-light. A reflected-light meter measures light reflected from the scene it is pointed at (luminance), while an incident-light meter measures light coming from a source (illumination)- this latter type feature a translucent ‘dome’ to better capture the ambient light conditions. In many cases, the spectral response of both types of sensor will be calibrated to the response of the human eye in well-lit conditions (photopic vision, Sharpe et al., 2005), and the target organism may or may not exhibit the same response in such conditions. A spectroradiometer is therefore preferable for studies of animal vision as it can measure the quantity of light arriving in particular wavelength bands (the spectral power distribution); readings can thus be tailored to the organism of interest.

Although the wavelength range of ‘visible’ light and of PAR is roughly the same, the typical photosynthetic response to radiation within these bounds (McCree, 1971) is quite different to that of the human eye. PAR sensors are therefore calibrated to a different power distribution, although in practice integrated sensing units are available that will report PAR, visible light and total radiation (including direct and diffuse) simultaneously. As with all radiation measurements, PAR readings can be highly variable under a vegetation canopy, and as before, a number of sensors will be deployed over a long ‘bar’ to ensure consistency of measurement (and also reduce the number of replicate measurements required). Most radiation sensors report energy fluxes, typically W m-2 but PAR sensors may alternatively measure quanta of photons: mol m2 s-1, while visible light is measured in lux. Field of view and/or cosine-correction is important – many PAR or lux meters measure on a plane (and thus require cosine correction) rather than from all directions, as an organism would experience.

Other, more cost-effective means of quantifying the coverage of a canopy can also be employed as a proxy for radiation reaching the earth’s surface. A densiometer or hemispherical photographs can both provide a rough estimate of the percentage tree cover at a point. Hemispherical photographs also offer an alternative means of calculating the Leaf Area Index (LAI), the ratio of leaf area to ground area, and surprisingly accurate estimates (R2 0.95 vs. LAI sensor) of this variable are possible if exposure levels are correctly set to maximise the contrast between the vegetation and the sky (Zhang et al., 2005).

#### 4.1.5 Wind

Anemometers, devices used to measure wind speed, generally fall into three categories. The cheapest and most widely used in ecological studies are cup or propeller anemometers, in which rotating cups or a propeller are driven by the wind. In the latter case, the device must either be held perpendicular to the direction of the wind, or be mounted on a vane; for automated measurements such devices typically measure direction as well as speed. While mechanical anemometers are standard on meteorological stations, and handheld versions are frequently used by ecologists for single measurements, they are less often installed with dataloggers to measure microclimate (see Table 2). In part this is due to the relatively large size of many units making it difficult to measure within 1-2m of the ground, where the wind is decoupled from the background atmosphere. However, miniature propeller anemometers with integral dataloggers and the ability to measure temperature and humidity as well, are now available at a relatively low cost (e.g. Samson and Hunt, 2012) and may be appropriate for some microclimate applications.

The second form of anemometers used in ecological studies are hot-wire anemometers, in which an electrically heated wire element is cooled by the wind, and the wind speed calculated by the rate of heat loss. Unlike mechanical anemometers, these devices have a rapid response time and the lack of moving parts allows them to be installed close to the ground or within vegetation, so they have potential for measuring small-scale eddies and microclimatic effects. However, the relative expense of the units is prohibitive for many ecological applications.

Finally, ultrasonic anemometers use ultrasonic sound waves to measure wind speed and direction (in 1, 2 or 3 dimensions) based on the time of flight of sonic pulses between pairs of transducers. While expensive, sonic anemometers are suitable for measuring turbulent air flow in three dimensions with a very high temporal resolution, and are typically used in conjunction with infrared or laser-based gas analysers to measure ecosystem fluxes using the eddy covariance method (Burba and Anderson, 2007). The eddy covariance micrometeorological technique, which involves high-speed measurements of fluxes of water, gas, heat, and momentum within the atmospheric boundary layer, is widely used by micrometeorologists across the globe.

#### 4.1.6 Soil moisture

Soil moisture is a key component of microclimate that affects both water availability to plants, and indirectly influences the temperature and humidity close to the ground, via its effect on the surface water and energy balance. While measurements can be made by extracting soil cores, drying and weighing them, this form of measurement is destructive and not suitable for long-term monitoring. Automated in-situ measurements can be made by tensiometers, by electrical resistance blocks, which measure the electrical resistance within a gypsum block or granules within a metal probe, or by Time Domain Reflectometry (TDR). TDR sensors send an electrical signal via metal rods into the soil and measure the signal return. This has potential for spatial surveys of soil moisture as the probe does not need to equilibrate with the soil, readings are fast and accurate, and many readings can be taken using a single probe within a short space of time. However, the calibration of TDR probes is sensitive to soil characteristics, and so may need separate calibrations for different soil types (see Table 2). All three probe types can be connected to loggers where a network of probes collecting time-series data is required.

As below-ground microclimates (such as soil moisture or temperature) typically change on a slower timescale than those above ground (which are more subject to rapid changes in the radiation balance and air movement) for many applications it may be possible to sample them less frequently, or to take measurements across a spatial domain using a single sensor within a specified time period. However, soil moisture can change rapidly during and following precipitation events, particularly near the soil surface, so care must be taken when planning spatial sampling strategies.

The above sensors typically measure soil moisture in the close vicinity of the probe itself (within centimetres), making them suitable for high spatial-resolution measurement or investigating fine-scale variation. However, as soil moisture varies over fine scales (see Section 3.3), many point-based measurements may be needed to characterise a domain if measurements representative of a wider area are needed. In this case, another technique, cosmic ray soil neutron sensing, can be used to measure integrated soil moisture over a footprint with a diameter of up to 600m (IAEA, 2017). However, for most studies with a focus on microclimate, this technique is likely to integrate over too large an area to be useful.

### 4.1.7 Ground truthing and sensor calibration

An important consideration when planning a project is the need to ensure that the data collected by each of the numerous sensors and / or dataloggers required is truly comparable. Most units come with a guaranteed degree of accuracy, but this will vary between designs, and there can be differences between units. A simple solution is to calibrate the units, by deploying them together in the same environment for a few days prior to use in the field. The recorded values can be modelled as a function of unit and time, and the deviation of each unit from the mean calculated. This offers a simple but effective “correction value” which can be applied to the field data collected on each unit. The process can be repeated following fieldwork in order to test for changes in relative measurement accuracy over time. For long term studies ongoing cross checks to a reference weather station that is subject to regular calibration checks is valuable.

### 4.1.8 Sampling design

Whether placing sensors to allow statistical interpolation of microclimates or to provide ground-truthing data for models or remotely sensed data, it is necessary to carefully consider the sampling design. The level of replication will depend to some extent on the number of loggers available and the heterogeneity and extent of the area to be sampled. Care should be taken to sample entire gradients of microclimatic conditions prevailing in a study system. For example, Suggitt at al. (2011) used a Digital Elevation Model (DEM) to categorise a topographically heterogeneous landscape into categories of slope steepness, aspect and elevation, then within a GIS generated an equal number of random sample locations within each category to ensure the whole range of these drivers were sampled at the earth’s surface. In addition, measurements should be taken for a sufficient amount of time to capture the full range of weather conditions at a site, including unusual situations such as those that drive cold-air drainage (see section 3). The level of replication should represent the spatial and temporal heterogeneity of the environment and/or the scale relevant to the target organisms, while keeping the dataset manageable. In some cases experimental manipulations of the factors driving microclimates have been used, such as removal of vegetation to examine effects of the interactions between slope aspect and vegetation cover (Lembrechts et al., 2017).

Other applications may require sampling below the soil surface (e.g. Edwards et al., 2017), or within vegetation canopies (e.g. Graae et al., 2012). In these cases it is necessary to consider whether absolute height or depth is important, or distance from a feature of interest (e.g. distance from the top of the canopy). This is likely to depend on the target organism and should approximate the location of their behaviour or life-stage of interest. For example, to measure the climatic experiences of tree-dwellers (like primates or tree frogs, e.g. Scheffers et al., 2013) it is important to capture variation of climatic conditions within the canopy, close to the ground and above the canopy where direct sunlight greatly increases experienced temperatures but where the animals often have to go for food.

### 4.2 Ex situ sensing of microclimate

Satellite remote sensing (RS), although not traditionally available at resolutions suitable for monitoring microclimate, has advanced rapidly and is now providing products at spatial and temporal resolutions that are useful for some microclimate-related applications. Over the last 50 years, satellite RS has played a major role in the monitoring and understanding of large-scale (global and regional) environmental changes (Pettorelli et al., 2014), including land cover (Elias et al., 2015), crop condition (Atzberger, 2013), land and marine productivity (Myneni et al., 1997; Brewington et al., 2014; Guay et al., 2014), phenology (Parmesan and Yohe, 2003), desertification (Ibrahim et al., 2015), and forest fires (Cuomo et al., 2001). During this time advances in satellite and sensor technologies have enabled considerable improvements in the spatial, temporal, spectral and radiometric resolution of the products available. Moderate to very high resolution satellite imagery is now routinely used to monitor and assess relatively small-scale (<100m) or rapid (<1 day) processes relevant to, e.g. operational meteorology (Søraas et al., 2017), soil moisture/drought (Mishra et al., 2017), forest fires (Wooster et al. 2013), pest outbreaks (Hicke and Logan, 2009), permafrost layer dynamics (National Research Council, 2014), and species/wildlife tracking (Yang et al., 2014).

The spatial and temporal coverage of satellite sensors and their resultant datasets varies considerably, mainly due to the application for which the data are to be used and technical limitations of the satellites and sensors. Geostationary satellites have the advantage of high temporal resolution coverage over a large area of the earth’s surface. However, polar orbiting (sun synchronous) satellites, being at lower altitudes, are generally able to sense higher spatial resolutions. Figure 4 highlights some of the applications and sensors available for satellite RS across a range of spatial and temporal scales.

The term “micro” suggests that the magnitude of the synergies between RS and microclimate research are constrained by the level of detail, i.e. the spatial resolution or grain size, of the RS data. The greatest potential lies in very high-resolution (VHR) RS instrumentation providing environmental data at a level of detail that matches the scale at which the focal species experiences its environment or habitat.

#### 4.2.1 Remote sensing of microclimate variables

One option for taking temperature measurements simultaneously across a landscape is to take thermal infra-red images using a specialised camera (e.g. Scherrer and Körner, 2010, who took images every minute for 24 hours of an opposing hillside). This is becoming more affordable with the advent of devices that can be attached to mobile phones, although care must be taken to correctly calibrate and ground truth the data. Many of these devices are point and click and appear easy to use for the novice, but parameters like emissivity and distance to target can affect the readings obtained (Vollmer and Möllman, 2017). Consideration also must be given to the wavelengths measured: for different applications different parts of the infra-red spectrum might be appropriate.

Thermal imagers can also be mounted to Unmanned Aerial Vehicles (UAVs) to give a ‘bird’s-eye view’ data layer for the top of a vegetation canopy which can be imported for use in Geographic Information Systems (GIS) for subsequent analysis (e.g. Zarco-Tejada et al., 2012). To use these data with distribution records or field observations it is necessary to measure the location of ground control points with a Global Navigational Satellite System (GNSS) to ‘tie’ the image to the correct part of the earth’s surface (Greenwood, 2015). The type of GNSS should be selected based on the spatial accuracy required for the application. Handheld devices have a spatial accuracy of 3-5m at best, so for fine spatial resolution data layers (e.g. < 5m) a differential GNSS should be used. However, some UAVs have inbuilt navigational GNSS devices for navigation that outperform handheld GNSS (Turner et al. 2014; Greenwood, 2015).

Thermal images have been available from satellites at a moderate resolution of 60 x 60 m since 1999 (ETM+ on LANDSAT 7). For finer resolution images, aircraft with thermal imagers attached can capture thermal images at resolutions < 5 x 5 m, depending on the height of the flight above the earth’s surface. These have already been used in studies of urban heat islands (Zhao and Wentz, 2016) and their increased availability could represent an opportunity for microclimate research in non-urban areas in future.

There are caveats when using thermal images, in that what is measured is the temperature of the surface itself, not the atmospheric conditions that many would consider to be the microclimate. However, thermal imagers can directly measure organism temperatures, which could be useful for some applications (e.g. Dietrich and Körner, 2014; Töpfer and Gedeon, 2014). In addition, thermal images provide a snapshot of temperature at the time recorded and do not necessarily represent microclimatic conditions as a whole. Indeed, mean, minimum and maximum temperatures within landscapes do not necessarily correlate, the warmest places on average may not experience the hottest maximum temperatures and the coolest places on average may not experience the coldest minimum temperatures (Suggitt et al., 2011; see section 2). In order to fully represent microclimates, images should be recorded at different times of day and night, across seasons and the full range of mesoclimatic conditions experienced at a site.

#### 4.2.2 Remote sensing of proxy variables

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[Insert Figure 4 here]

Figure 4: Temporal and spatial resolutions of primary data available from selected satellites used for environmental monitoring. Polar orbiting (hashed background), geostationary (grey background). Coloured boxes highlight various environmental applications utilising satellite RS data, superscript numbers refer to publications as follows:

1 Tsendbazar et al. (2017) and Russell et al. (2014); 2 Myneni et al. (1997); 3 Sun et al. (2017); 4 Eldering et al. (2017); 5 Søraas et al. (2017); 6 Mishra et al. (2017); 7 Wooster et al. (2013); 8 Atzberger. (2013); 9 Hicke and Logan. (2009); 10 National Research Council (2014); 11 Yang et al. (2014); Satellite details are as follows:

|  |  |  |  |
| --- | --- | --- | --- |
| Acronym | Name | Organisation | Website |
| OCO-2 | Orbiting Carbon Observatory | NASA/JPL, USA | <https://oco.jpl.nasa.gov/> |
| AVHRR | Advanced Very High Resolution Radiometer | NOAA, USA | <http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html> |
| MODIS | Moderate Resolution Imaging Spectroradiometer | NASA, USA | <https://modis.gsfc.nasa.gov/> |
| VIIRS | Visible Infrared Imaging Radiometer Suite | NASA, USA | <https://ncc.nesdis.noaa.gov/VIIRS/> |
|  | Landsat-8 | NASA/USGS, USA | <https://landsat.usgs.gov/landsat-8> |
| GOME-2 | Global Ozone Monitoring Experiment -2 | ESA, Europe | <http://gome.aeronomie.be/> |
|  | Sentinel 1 and 2 | ESA, Europe | <https://sentinel.esa.int/web/sentinel/missions/sentinel-1>  <https://sentinel.esa.int/web/sentinel/missions/sentinel-2> |
| SMAP | Soil Moisture Active/Passive | NASA, USA | <https://smap.jpl.nasa.gov/> |
|  | METEOSAT | EUMETSAT, Europe | <https://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Meteosat/index.html> |
| GOES | Geostationary Operational Environmental Satellites | NOAA, USA | <https://www.nasa.gov/content/goes> |
|  | IKONOS | DigitalGlobe, USA | <https://www.satimagingcorp.com/satellite-sensors/ikonos/> |
| SPOT-5 | Satellite Pour l’Observation de la Terre – 5 | CNES, France | <https://spot.cnes.fr/en/SPOT/index.htm> |
|  | MetOp | EUMETSAT/ESA, Europe | <https://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/index.html> |
| POES | Polar Operational Satellites | NOAA, USA | <https://poes.gsfc.nasa.gov/index.html> |
|  | GeoEye-1 | DigitalGlobe, USA | <https://www.satimagingcorp.com/satellite-sensors/geoeye-1/> |

Microclimatic gradients and the associated availability of ecological micro-niches are to a large extent determined by three-dimensional (3D) structure, e.g. micro-topography and/or horizontal and vertical vegetation structure (Section 2, Bazzaz and Wayne, 1994; Scherrer and Körner 2010). Thus, RS data that accurately assess the 3D structure of natural or human made systems are expected to benefit microclimate research the most. In this respect, the recent surge of airborne RS generates many useful datasets and tools. Full-waveform Airborne Laser Scanning (ALS or airborne Light Detection and Ranging LiDAR), for example, provides contiguous and highly detailed information about the 3D structure of the land surface environment, which allows the derivation of high-end Digital Terrain Models (DTMs) as well as detailed data on horizontal and vertical vegetation structure, including Canopy Height Models (CHMs, Lefskyet al., 2002; Morsdorfet al., 2006). ALS data is thus suited to parameterise and map principle ecological phenomena, such as small-scale variations of temperature due to micro-topographic variability, as well as temperature buffering mediated by canopy structure, providing crucial input data to microclimate modelling (see Section 5.2, Leempoel et al., 2015; Freyet al., 2016; Lenoir et al., 2017).

As an alternative to ALS, detailed landscape and vegetation structure data can also be derived from airborne radar or photogrammetry and image matching (i.e. structure from motion, Gruen, 2012; Ginzler and Hobi, 2015). However, photogrammetry suffers from a number of limitations such as difficulties with deriving accurate terrain and detailed vertical vegetation structure information beneath tree canopies due to occlusion effects, as well as insufficient handling of shadow areas and cloud effects (Gruen, 2012). Detailed data across large areas is normally recorded from airplanes or helicopters, whereas UAVs, such as drones, are increasingly used to map smaller areas, with the advantage of increased spatial and temporal resolutions (Anderson and Gaston, 2013). Terrestrial Laser Scanning (TLS) constitutes a further promising data source, as it provides 3D environmental data at an even higher level of detail than UAVs and ALS, but not contiguously across landscapes, as TLS data availability is spatially restricted to sample plots (Lianget al., 2016; Tellinget al., 2017). However, an advantage of TLS is that it reliably depicts understorey vegetation and within-canopy structure, which can complement ALS structure data in landscape scale analysis (Hancocket al., 2017). A promising ecological application of detailed 3D vegetation structure data is to approximate below-canopy light regimes and associated microclimatic conditions prevailing across horizontal and vertical forest structure gradients (e.g. Moeseret al., 2014).

Air- and space-bourne systems recording hyperspectral data provide information that is complementary to vegetation structure measurements because such data reveals insights into vegetation functional trait composition that may affect microclimatic gradients, e.g. via effects of leaf traits on the light regime beneath forest canopies (Kimmins, 2004; Asner et al., 2015). In addition, measuring surface albedo can be important for microclimate research as it affects the radiation balance (see section 2) and using remotely sensed data to assess cloud cover could greatly help in downscaling radiation. As with directly measured microclimate variables, there must be accurate spatial co-registration of *in-situ* measurements and the RS-derived environmental data.

[Insert Figures 5a. and 5b. here]

Figure 5a: The spatial resolution of climate/ecological models. Refs: 1 (Kriticos et al., 2012); 2 (Kriticos et al., 2004); 3 (Sutherst and Bourne, 2009); 4 (Pearson et al., 2014); 5 (Bennie et al., 2013); 6 (Gillingham et al., 2012a); 7 (Kearney, 2013); 8 (Meineri and Hylander, 2017); 9 (Huntley et al., 2017); 10 (Slavich et al., 2014 ); 11 (Seo et al., 2009); 12 (Buckley et al., 2011); 13 (Graae et al., 2012); 14 (De Frenne et al., 2013); 15 (Lenoir et al., 2017); 16 (Ashcroft and Gollan, 2012); 17 (Frey et al., 2016); 18 (Flint and Flint, 2012)

Figure 5b: The temporal scale of climate/ecological models and field studies. Refs: 1 (Boyles et al., 2017); 2 (Carrol et al., 2017); 3 (Agosta et al., 2017); 4 (Tampucci et al., 2017); 5 (Scheffers et al., 2013); 6 (Rodhouse et al., 2017); 7 (Sporn et al., 2009); 8 (Graae et al., 2012); 9 (De Frenne et al., 2013); 10 (Lenoir et al., 2017); 11 (Ashcroft and Gollan, 2011); 12 (Frey et al., 2016)

## 

**Box 4: Acronyms Explained**

|  |  |  |
| --- | --- | --- |
| DEM | Digital Elevation Model | Encompasses both DTMs and DSMs |
| DGVM | Dynamic Global Vegetation Model | Shifts in global vegetation and associated processes |
| DSM | Digital Surface Model | The elevation of the land surface plus surface features such as vegetation and buildings |
| DTM | Digital Terrain Model | The elevation of a land surface, typically above sea level |
| GDD5 | Growing Degree Days above 5 degrees | Essentially the amount of time available for most plants to grow |
| GNSS | Global Navigation Satellite System | Satellite navigation systems that provide autonomous geo-spatial positioning with global coverage |
| GPS | Global Positioning System | A type of GNSS using the US constellation of satellites |
| IBM | Individual Based Model | Simulation models that describe autonomous individual organisms |
| LAI | Leaf Area Index | The one-sided green leaf area per unit ground surface area |
| LiDAR | Light Detection and Ranging | A remote sensing method utilising a pulsed laser to measure variable distances to the Earth |
| PAR | Photosynthetically Active Radiation | The light available for photosynthesis, in the 400 to 700 nanometer wavelength range |
| SDM | Species Distribution Model | Species occurrence or abundance in response to environmental factors |
| TDR | Time Domain Reflectometry | A measurement technique used to determine the characteristics of electrical lines by observing reflected waveforms |
| TLS | Terrestrial Laser Scanning | A ground-based, active imaging method that acquires 3D point clouds of object surfaces by laser range finding |
| UAV | Unmanned Arial Vehicles | Aircraft without a pilot aboard, aka drones |

## 5. Modelling microclimates

### 5.1 Why model microclimates?

Modelling allows the different factors which affect microclimate to be explored and the relative sensitivities within the study system to factors such as aspect, altitude and canopy cover (see Section 3), to be tested. It also allows a scaling up from measurements at a network of locations to larger scales, for example to predict variations in temperature over a heterogeneous landscape. In turn it allows relationships with organisms’ distribution (Gillingham et al. 2012a), characteristics and behaviour to be identified. Modelling also allows predictions and projections of ecological impacts, including projection of the impacts of climate change on species distributions (Gillingham et al., 2012b). There are a wide range of approaches, which incorporate a variety of the factors and processes that influence microclimates and result in a variety of predicted variables (Lenoir et al., 2017, and see table 3 for an overview). Model spatial resolution is driven by a trade-off between the availability of fine-resolution DEMs and available computing power to run the model for the extent of interest. Figure 5a shows the spatial resolution of a variety of models examining microclimate ecology, while Figure 5b shows the temporal scale of models and studies on the same subject, which may be useful as a reference to assist in deciding the appropriate resolution and scales to model at. In some cases such as the direct computation of heat, mass and momentum budgets, one needs estimates of actual microclimatic conditions (e.g. Porter and Gates, 1969) whereas in correlative models, proxies such as topographic indices or radiation metrics may suffice (e.g. Gillingham et al. 2012a, 2012b, see Figure 5).

Table 3: A summary of models utilised in microclimate research

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Model type | Climate Data Input | Other predictors | Processes modelled | Response Variables | Reference |
| Interpolated | Micro-sensors | Topographic from DEM, Canopy cover | Radiation, cold air drainage | Temperature | Ashcroft et al. (2012) |
| Interpolated | Micro-sensors | Topographic from DEM, Canopy cover (remotely sensed), distance from coast | Radiation, cold air drainage, distance to coast, latent heat | Temperature, Humidity (if recorded by sensors) | Ashcroft and Gollan (2012); Ashcroft and Gollan (2013), Gollan et al. (2014), Slavich et al. (2014) |
| Interpolated | Micro-sensors | Topographic and vegetation structure both from LiDAR | Radiation | Temperature | Frey et al. (2016) |
| Interpolated | Weather stations and Micro-sensors | Topographic from DEM | Radiation, cold air drainage, soil moisture | Temperature | Fridley (2009) |
| Interpolated | Micro-sensors | Topographic, distance from coast | Radiation, topographic wetness index | Temperature | Vanwalleghem and Meentemeyer (2009) |
| Interpolated | Weather stations with satellite data to ground-truth | Topographic | Radiation, cold air drainage | Temperature (note this is ‘free air’ at 2m temperature, not near the ground) | Dobrowski et al. (2009) |
| Downscaled | Macroclimatic grid with micro-sensors to ground-truth | Topographic from DEM | Radiation, cold air drainage, PET (driven by radiation) | Temperature, rainfall, climate water deficit | Flint and Flint (2012), Dingman et al. (2013), McCullough et al (2016) |
| Downscaled | Weather stations | Topographic | Radiation, cool air drainage, topographic wetness index, distance to water bodies | Temperature | Meineri and Hylander (2017) |
| Mechanistic | Weather station or macroclimatic grids with micro-sensors to ground-truth | Topographic from DEM | Radiation, local wind speed | Temperature | Bennie et al. (2008, 2013), Gillingham et al. (2012a,b) |
| Mechanistic | Weather station or macroclimatic grid | Topographic, soil properties, vegetation shading | Radiation, convection, conduction, evaporation, latent heat (of soil) | Air and soil temperature, air humidity, wind velocity | Kearney et al. (2014), 2017) |
| Mechanistic | Weather station or macroclimatic grids with micro-sensors to ground-truth | Topographic from DEM, sea-surface temperatures, albedo from aerial imagery | Radiation, local wind speed, coastal effects, elevation, cold air drainage, latent heat exchange | Temperature | Maclean et al. (2017) |
| Mechanistic | Weather station or macroclimatic grids with field measurements to ground-truth | Topographic from DEM | Soil and surface water conditions | Surface water depth, soil moisture fraction | Maclean et al. (2012) |

### 5.2 Statistical models

Two main types of statistical approaches have been used in the scientific literature to model microclimate in a spatially-explicit manner: directly through spatial interpolations of microclimatic measurements from georeferenced microsensors, (e.g. Ashcroft et al., 2012; Suggitt et al., 2011) or indirectly by downscaling macroclimate from georeferenced synoptic weather stations or coarse-grained climatic grids (e.g. WorldClim or CHELSA data: Hijmans et al., 2005; Karger et al., 2016). Whatever the overall statistical approach used (interpolating microclimate or downscaling macroclimate), high-resolution digital elevation models (DEMs) are needed to generate meaningful predictor variables that are subsequently linked to micro- (interpolation) or macroclimate (downscaling) measurements for mapping climatic conditions at very fine spatial resolutions. The resolution of the output, and thus the accuracy that factors such as solar radiation load can be represented with is thus dependent on the available resolution of the DEM for the area in question as well as available computing power. For instance, Ashcroft and Gollan (2013) used physiographic variables, such as topographic exposure, relative slope position and distance to the coast, derived from a 25 m DEM, to interpolate daily maximum air temperature at 5 cm height from a network of microsensors.

The only difference between the two above-listed approaches is that one directly models microclimate based on true microclimatic measurements whereas the other relies on macroclimate data only, thus assuming that the set of predictor variables used to model climatic conditions at finer spatial resolutions will capture microclimatic processes. For example, Dobrowski et al. (2009) used a 30 m DEM to generate physiographically informed variables accounting for processes such as elevation-based lapse rates, solar insolation and cold-air drainage effects. This set of topographic variables were then used as predictors and regressed against the residuals of a model relating free-air temperature measurements from synoptic weather stations to remotely-sensed free-air temperature estimates from radiosondes and satellites that provide high temporal (3 h) and coarse spatial (32 km) resolution data on macroclimate (cf. regional free-air temperature conditions). This two-step statistical approach based on the general model of Lundquistet al. (2008) does not require any microclimatic measurements to model temperature conditions at reasonably fine (30 m) spatial resolution. Although very appealing, this indirect approach has strong limitations since it still represents free-air temperature conditions, and cannot be extrapolated to habitat types other than the ones equipped with weather stations. Unfortunately, most weather stations to date are installed in open habitats: standard meteorological recording protocols standardise measures above closely cut grass and thus (deliberately) fail to capture the impact of vegetation on the microclimate near the ground. Others are installed for very specific purposes, such as on mountain tops in ski resorts, which are also unlikely to capture the impacts of vegetation. Very few long-term weather stations have been installed within forest habitats (De Frenne and Verheyen, 2016) although forest microclimate has often been monitored as part of studies of forest ecophysiology, carbon and water fluxes.

Statistical approaches have a drawback in that relationships are established over a relatively short period. It is well appreciated that models based on statistical methods can be unreliable when used to predict beyond the realm of existing data ([e.g. Rice, 2004](#_ENREF_37)).

### 5.3 Mechanistic models

Models that are based on the physical processes underpinning local climatic variation are more likely to provide reliable predictions under novel conditions ([Evans and Westra, 2012](#_ENREF_9)). Mechanistic models seek to model microclimate using a mathematical representation of the processes involved in determining it. For example, the spatially explicit grid-based model of Bennie et al. (2008) calculates direct and indirect solar radiation from the slope and aspect of a location (themselves calculated from a DEM), given the average conditions experienced at a weather station. Porter et al. (1973) and Kearney et al. (2017) have developed a point-based model that makes hourly calculations of solar and infrared radiation intensities, above-ground profiles of air temperature, wind velocity and relative humidity at user-defined heights, and soil temperature and moisture profiles at 10 depths from the surface down to a maximum depth specified by the user. The fractional shade, slope and aspect, and horizon angles can be specified to capture topographic effects, and depth-specific soil thermal and hydraulic properties can also be user-defined. Mechanistic models still require inputs from weather stations or climate models (such as total radiation, wind speed and temperature) but crucially the downscaling process is based on known mechanisms rather than being statistical or using interpolation algorithms.

## 6. Opportunities and unanswered questions

There are currently some clear gaps in microclimate research within Ecology, due to trends in research focus or lack of technological or computer capabilities. For example, there is a lack of small scale, self-contained wind speed sensors which can be left in situ alongside temperature and moisture data loggers, resulting in this important factor being under-studied. Also, there are currently large geographical gaps, particularly in Africa, Asia and the Polar regions.

It is understood that microclimates are important to species distributions (Kelly et al., 2004; Briscoe et al., 2014), however there has been little research into the effects of microclimate on phenology, and how important it is in influencing phenological responses to climate change. It is also vital to understand how species use microclimates, and what factors influence their ability to fully utilise potential microclimatic niches. There has been a focus on thermal microclimates, driven by the fact that these appear easier to measure. However, for many species and in many ecosystems, hydro- and hygro-microclimates might be more relevant. Increasing our efforts in measuring and modelling water- and humidity-driven variation in microclimates will offer new opportunities in terrestrial ecological research.

It would be useful to understand to what extent habitats and species are buffered by and reliant upon microclimates (Wakelin et al., 2013). For this it is important to have long term datasets. At present microclimate research is generally done on the short term, with measurements being taken for a few months to a year at a time. In order to understand the decoupling of microclimates from macroclimate we need multiple year studies. This will allow us to better understand and model how that decoupling is affected by climate change (for example, does the difference in temperature increase or decrease with climate change?). There is also the potential for changes in vegetation structure and species composition caused by climate change to modify microclimate. The most obvious effect would be at treelines, where a taller canopy has major impacts on surface and soil temperatures, however the extent to which canopy height is limited by temperature or windspeeds will modify this.

As yet there has been little consideration of climatic extremes in microclimate research. As it has been established that extremes are important limiting factors to organisms (Cunningham et al., 2013) this is a topic that cannot be overlooked if microclimate research is to be useful in protecting species. Relevant to this is the understanding of how microclimates buffer not just against general climate change, but against extreme events such as heat waves and droughts. Morecroft et al. (1998) found that in one winter, the presence of a tree canopy at one site in Britain prevented the incidence of ground frost which was frequently experienced at a grassland site nearby. It would be useful to gain a good understanding of how habitat management practises influence microclimates, in order to establish the best ways to manage habitats for the protection and creation of microclimatic refuges. There will hopefully be opportunities to work with conservation practitioners in order to increase awareness of the importance of microclimates to species and allow them to integrate awareness of microclimates into their management practises.

In order to achieve these goals and develop an understanding of microclimates which is widely applicable and useful to conservationists, it is necessary to have data widely available to researchers and the resulting information available to practitioners. An online global dataset where microclimate data is freely available would make comparisons between studies for the establishment of patterns in microclimates around the world far easier. In order for the data on such a dataset to be comparable it is necessary to have some level of standardisation in data collection methods and a high level of metadata describing the methods of measurement and study sites.

Recent developments in technology and data availability present interesting opportunities for future microclimate research. One field which is developing rapidly is remotely sensed data, which is becoming more widely available online. Ongoing plans for satellite RS, particularly through the recent EU/ESA Copernicus programme (Sentinel satellites), as well as continued high resolution monitoring programmes e.g. the NASA/USGS Landsat programme, will ensure the quality and availability of high resolution satellite RS data continues to improve, providing new and improved opportunities for studying microclimate from space. An increasing number of apps which may be of use in microclimate research are also being developed, such as thermal cameras which can be used on a smartphone, and apps which capture canopy cover measurements.

Considering these developments, strengthening the cooperation between RS experts and ecologists is likely to reveal mutual benefits (Turner et al., 2003) and constitutes an important way forward to advance in microclimate research. This is a subject where new researchers could greatly benefit from supervisors and mentors in a variety of fields, so that they may have access to the necessary knowledge to work with varied methods early in their career. This would also reduce the intimidation factor of these methods which can seem overwhelming.

## 7. Conclusions

While it is important to consider the potential influence of microclimates when considering climatic interactions with ecology, and conservation efforts such as the protection of microrefugia, it is a complex topic with many different potential methods available. There are a variety of questions that need to be asked at the very beginning of research planning, and which need to continue to be checked through the design process. Box 5 provides a quick reference of some of the most important questions in order to design an effective, appropriate, replicable study of microclimate ecology.

### 

**Box 5: Summary of important points**

When planning microclimate research there are a variety of questions that should be asked in order to develop an appropriate methodology.

**Before designing methods, consider:**

* Does the coarse scale climate account for the most important variation?
* How might microclimate influence your species/community? (see Section 3)
* Which microclimatic factors are the most biologically relevant to your species/community, and which are the most important for you to measure/model? E.g. air temperature or operative temperature, extremes or averages.
* Which processes are most important in influencing the microclimate your study species/community experiences? (See Section 2)
* At what scales does your study species/community experience microclimate?
* Does *in situ* measurement or modelling make more sense for your research question? (see Sections 4 and 5)
* How much data do you need vs how much you can manage

**When designing methods, consider:**

*In situ* measurement –

· Do you want to measure the environment or what the individual's experience?

· What equipment should you use for that purpose?

· What could go wrong with that equipment? Do you need to consider shielding?

· What calibrations do you need to do?

Modelling –

· Do you want to be spatially implicit or explicit?

· Do you want to be temporally implicit or explicit?

· What input data is best for your research question?

· Do you need ground-truth data?

## References

Agosta, S.J., Hulshof, C.M., Staats, E.G., 2017. Organismal responses to habitat change: herbivore performance, climate and leaf traits in regenerating tropical dry forests. Journal of Animal Ecology, 86(3).

Allegrini, J., Carmeliet, J., 2017. Coupled CFD and building energy simulations for studying the impacts of building height topology and buoyancy on local urban microclimates. Urban Climate, 21, pp. 278–305.

Anderson, K., Gaston, K. J., 2013. Lightweight unmanned aerial vehicles will revolutionize spatial ecology. Frontiers in Ecology and the Environment, 11(3), pp. 138–146.

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(6), pp. 1866–1879.

Ashcroft, M.B., Gollan, J.R., 2012. Fine‐resolution (25 m) topoclimatic grids of near‐surface (5 cm) extreme temperatures and humidities across various habitats in a large (200 × 300 km) and diverse region. International Journal of Climatology. John Wiley & Sons, Ltd., 32(14), pp. 2134–2148.

Ashcroft, M., Gollan, J., 2013. Moisture, thermal inertia, and the spatial distributions of near-surface soil and air temperatures: Understanding factors that promote microrefugia. Agricultural and Forest Meteorology, 176, pp.77-89.

Asner, G.P., Martin, R.E., Anderson, C.B., Knapp, D.E. 2015., Quantifying forest canopy traits: Imaging spectroscopy versus field survey. Remote Sensing of Environment, 158(0), pp. 15–27.

Atzberger, C., 2013. Advances in remote sensing of agriculture: Context description, existing operational monitoring systems and major information needs. Remote Sensing, 5(2), pp. 949–981.

Baker, C.R.B., 1980. Some Problems in Using Meteorological Data to Forecast the Timing of Insect Life Cycles. EPPO Bulletin. Blackwell Publishing Ltd, 10(2), pp. 83–91.

Bakken, G.S., 1981. How many equivalent black-body temperatures are there?. Journal of Thermal Biology, 6(1), pp. 59–60.

Bakken, G.S., 1992. Measurement and application of operative and standard operative temperatures in ecology. American Zoologist, 32(2), pp. 194–216.

Bakken, G.S., Angilletta, M.J., 2014. How to avoid errors when quantifying thermal environments. Functional Ecology. Edited by M. Konarzewski, 28(1), pp. 96–107.

Bakken, G.S., Erskine, D.J., Santee, W.R., 1983. Construction and Operation of Heated Taxidermic Mounts Used to Measure Standard Operative Temperature. Ecology. Ecological Society of America, 64(6), pp. 1658–1662.

Barozzi, B., Bellazzi, A., Pollastro, M. C., 2016. The Energy Impact in Buildings of Vegetative Solutions for Extensive Green Roofs in Temperate Climates. Buildings, 6(3), p. 33.

Barry, R.G., Blanken, P.D., 2016. Microclimate and local climate. Cambridge University Press.

Baudunette, R.V., Wells, R.T., Sanderson, K.J., Clark, B., 1994. Microclimatic conditions in maternity caves of the bent-wing bat, Miniopterus schreibersii: an attempted restoration of a former maternity site. Wildlife Research, 21, pp. 607-619.

Bauer, N., Kenyeres, Z., 2007. Seasonal changes of microclimatic conditions in grasslands and its influence on orthopteran assemblages. Biologia - Section Botany, 62(6), pp. 742–748.

Bazzaz, F.A., Wayne, P.M., 1994. Coping with environmental heterogeneity: the physiological ecology of tree seedling regen- eration across the gap–understory continuum. in Caldwell, M. M., Pearcy, R. W. (eds). Exploitation of environmental heterogeneity by plants; ecophysiological processes above and below ground. New York: Academic Press, pp. 349–390.

Bennett, A F., Huey, R.B., John-Alder, H., Nagy, K.A., 1984. The parasol tail and thermoregulatory behavior of the Cape ground squirrel Xerus inauris. Physiological Zoology, 57(1), pp. 57–62.

Bennie, J.J., Wiltshire, A.J., Joyce, A.N., Clark, D., Lloyd, A.R., Adamson, J., Parr, T., Baxter, R., Huntley, B., 2010. Characterising inter-annual variation in the spatial pattern of thermal microclimate in a UK upland using a combined empirical–physical model. Agricultural and Forest Meteorology, 150(1), pp. 12–19.

Bennie, J., Hodgson, J.A., Lawson, C.R., Holloway, C.T., Roy, D.B., Brereton, T., Thomas, C.D., Wilson, R.J., 2013. Range expansion through fragmented landscapes under a variable climate. Ecology Letters. Edited by N. Haddad, 16(7), pp. 921–929.

Bennie, J., Huntley, B., Wiltshire, A., Hill, M.O., Baxter, R., 2008. Slope, aspect and climate: spatially explicit and implicit models of topographic microclimate in chalk grassland. Ecological modelling, 216(1), pp. 47–59.

Bird, R. B., Stewart, W. E., Lightfoot, E. N., 2002. Transport Phenomena. 2nd edn. New York: Wiley and Sons.

Blandford, T.R., Humes, K.S., Harshburger, B.J., Moore, B.C., Walden, V.P., Ye, H., 2008. Seasonal and synoptic variations in near-surface air temperature lapse rates in a mountainous basin. Journal of Applied Meteorology and Climatology, 47(1), pp. 249–261.

Boyles, J.G., Boyles, E., Dunlap, R.K., Johnson, S.A.. Brack, V., 2017. Long-term microclimate measurements add further evidence that there is no “optimal” temperature for bat hibernation. Mammalian Biology, 86.

Brewington, L., Frizzelle, B.G., Walsh, S.J., Mena, C.F., Sampedro, C., 2014. Remote Sensing of the Marine Environment: Challenges and Opportunities in the Galapagos Islands of Ecuador. in The Galapagos Marine Reserve. Springer, pp. 109–136.

Briscoe, N.J., Handasyde, K.A., Griffiths, S.R., Porter, W.P., Krockenberger, A., Kearney, M.R., 2014. Tree-hugging koalas demonstrate a novel thermoregulatory mechanism for arboreal mammals. Biology letters, 10(6), p.20140235.

Briscoe, N.J., Handasyde, K.A., Griffiths, S.R., Porter, W.P., Krockenberger, A., Kearney, M.R., 2014. Tree-hugging koalas demonstrate a novel thermoregulatory mechanism for arboreal mammals Ecology. Ecological Society of America, 92(12), pp. 2214–2221.

Burba, G., Anderson, D., 2007. Introduction to the eddy covariance method: General guidelines and conventional workflow. Li-Cor Biosciences, 141.

Burman, R. D., Jensen, M., Allen, R. G., 1987. Thermodynamic factors in evapotranspiration. in Irrigation Systems for the 21st Century. ASCE, pp. 140–148.

Carroll, J.M., Davis, C.A., Elmore, R.D., Fuhlendorf, S.D., 2017. Using a historic drought and high‐heat event to validate thermal exposure predictions for ground‐dwelling birds. Ecology and Evolution, 7(16).

Cavieres, L.A., Badano, E.I., Sierra-Almeida, A., Molina-Montenegro, M.A., 2007. Microclimatic modifications of cushion plants and their consequences for seedling survival of native and non-native herbaceous species in the high Andes of central Chile.Arctic, Antarctic & Alpine Research. Allen Press Publishing Services Inc., 39(2), pp. 229–236.

Checa, M.F., Rodriguez, 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), pp. 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(3–4), pp. 219–237.

Cowles, R. B., Bogert, C. M., 1944. A preliminary study of the thermal requirements of desert reptiles. Bulletin of the AMNH; v. 83, article 5’.

Cunningham, S.J., Kruger, A.C., Nxumalo, M.P., Hockey, P.A., 2013. Identifying biologically meaningful hot-weather events using threshold temperatures that affect life-history. Plos One. Public Library of Science, 8(12), p. 1.

Cunningham, S. J., Martin, R. O., Hockey, P. A. R., 2015. Can behaviour buffer the impacts of climate change on an arid-zone bird?. Ostrich. Taylor & Francis, 86(1–2), pp. 119–126.

Cuomo, V., Lasaponara, R., Tramutoli, V., 2001. Evaluation of a new satellite-based method for forest fire detection. International Journal of Remote Sensing, 22(9), pp. 1799–1826.

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(2), pp. 217–225.

da Costa, A.C.L., Galbraith, D., Almeida, S., Portela, B.T.T., da Costa, M., de Athaydes Silva Junior, J., Braga, A.P., de Gonçalves, P.H., de Oliveira, A.A., Fisher, R., Phillips, O.L., 2010. Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest.New Phytologist, 187(3), pp. 579–591.

Darwin, C., Darwin, F., 1880. The power of movement in plants. London: John Murray.

Davidson, N.J., Reid, J.B., 1985. Frost as a factor influencing the growth and distribution of subalpine eucalypts. Australian Journal of Botany, 33(6), pp. 657–667.

De Frenne, P., Brunet, J., Shevtsova, A., Kolb, A., Graae, B.J., Chabrerie, O., Cousins, S.A., Decocq, G., De Schrijver, A.N., Diekmann, M., Gruwez, R., 2011. Temperature effects on forest herbs assessed by warming and transplant experiments along a latitudinal gradient. Global Change Biology, 17(10), pp. 3240–3253.

De Frenne, P., Rodríguez-Sánchez, F., Coomes, D.A., Baeten, L., Verstraeten, G., Vellend, M., Bernhardt-Römermann, M., Brown, C.D., Brunet, J., Cornelis, J., Decocq, G.M., 2013. Microclimate moderates plant responses to macroclimate warming. Proceedings of the National Academy of Sciences, 110(46), pp. 18561–18565.

De Frenne, P., Verheyen, K., 2016. Weather stations lack forest data. Science, 351(6270), p. 234.

Denny, M., 2014. Biology and the mechanics of the wave-swept environment. Princeton University Press.

Dietrich, L., Körner, C., 2014. Thermal imaging reveals massive heat accumulation in flowers across a broad spectrum of alpine taxa. Alpine botany, 124(1), pp.27-35.

Dingman, J.R., Sweet, L.C., McCullough, I., Davis, F.W., Flint, A., Franklin, J., Flint, L.E., 2013. Cross-scale modeling of surface temperature and tree seedling establishment in mountain landscapes. Ecological Processes, 2(1), p. 30.

Dobrowski, S.Z., Abatzoglou, J.T., Greenberg, J.A., Schladow, S.G., 2009. How much influence does landscape-scale physiography have on air temperature in a mountain environment?. Agricultural and Forest Meteorology, 149(10), pp. 1751–1758.

D'odorico, P., He, Y., Collins, S., De Wekker, S.F., Engel, V., Fuentes, J.D., 2013. Vegetation–microclimate feedbacks in woodland–grassland ecotones. Global Ecology and Biogeography, 22(4), pp. 364–379.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. Science, 289(5487), pp. 2068–2074.

Edwards, F.A., Finan, J., Graham, L.K., Larsen, T.H., Wilcove, D.S., Hsu, W.W., Chey, V.K., Hamer, K.C., 2017. The impact of logging roads on dung beetle assemblages in a tropical rainforest reserve. Biological Conservation, 205, pp. 85–92.

Eldering, A., Wennberg, P.O., Crisp, D., Schimel, D.S., Gunson, M.R., Chatterjee, A., Liu, J., Schwandner, F.M., Sun, Y., O’dell, C.W., Frankenberg, C., 2017. The Orbiting Carbon Observatory-2 early science investigations of regional carbon dioxide fluxes. Science, 358(6360), p. eaam5745.

Elias, M., Hensel, O., Richter, U., Hülsebusch, C., Kaufmann, B., Wasonga, O., 2015. Land conversion dynamics in the Borana rangelands of Southern Ethiopia: an integrated assessment using remote sensing techniques and field survey data. Environments, 2(1), pp. 1–31.

Evans, J.P., Westra, S., 2012. Investigating the mechanisms of diurnal rainfall variability using a regional climate model. Journal of Climate, 25(20), pp. 7232–7247.

Finkel, M., Fragman, O., Nevo, E., 2001. Biodiversity and interslope divergence of vascular plants caused by sharp microclimatic differences at “Evolution Canyon II”, Lower Nahal Keziv, Upper Galilee, Israel. Israel Journal of Plant Sciences, 49(4), pp. 285–295.

Flint, L.E., Flint, A.L., 2012. Downscaling future climate scenarios to fine scales for hydrologic and ecological modeling and analysis. Ecological Processes, 1(1), p. 2.

Frey, S.J., 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(4), p. e1501392.

Fridley, J.D., 2009. Downscaling climate over complex terrain: high finescale (< 1000 m) spatial variation of near-ground temperatures in a montane forested landscape (Great Smoky Mountains). Journal of Applied Meteorology and Climatology, 48(5), pp. 1033–1049.

Gates, D.M., 1980. Biophysical Ecology. Edited by D. E. Reichle. New York: Springer Verlag.

Geiger, R., 1927. Das Klima der bodennahen Luftschicht. Brunswick: Vieweg & Sohn.

Geiger, R., Aron, R.H., Todhunter, P., 2009. The climate near the ground. Rowman & Littlefield.

Gillingham, P.K., Huntley, B., Kunin, W.E., Thomas, C.D., 2012. The effect of spatial resolution on projected responses to climate warming. Diversity and Distributions, 18(10), pp. 990–1000.

Gillingham, P.K., Palmer, S.C., Huntley, B., Kunin, W.E., Chipperfield, J.D., Thomas, C.D., 2012. The relative importance of climate and habitat in determining the distributions of species at different spatial scales: a case study with ground beetles in Great Britain. Ecography, 35(9), pp. 831–838.

Ginzler, C., Hobi, M., 2015. Countrywide Stereo-Image Matching for Updating Digital Surface Models in the Framework of the Swiss National Forest Inventory. Remote Sensing, 7(4), pp. 4343–4370.

Gollan, J. R., Ramp, D., Ashcroft, M.B., 2014. Assessing the distribution and protection status of two types of cool environment to facilitate their conservation under climate change. Conservation Biology, 28(2), pp. 456–466.

Gómez-Cifuentes, A., Munevar, A., Gimenez, V.C., Gatti, M.G., Zurita, G.A., 2017. Influence of land use on the taxonomic and functional diversity of dung beetles (Coleoptera: Scarabaeinae) in the southern Atlantic forest of Argentina.Journal of Insect Conservation, 21(1), pp. 147–156.

Graae, B.J., De Frenne, P., Kolb, A., Brunet, J., Chabrerie, O., Verheyen, K., Pepin, N., Heinken, T., Zobel, M., Shevtsova, A., Nijs, I., 2012. On the use of weather data in ecological studies along altitudinal and latitudinal gradients. Oikos. Blackwell Publishing Ltd, 121(1), pp. 3–19.

Greenwood, F., 2015. How to make maps with drones. in Drones and Aerial Observation: New Technologies for Property Rights, Human Rights, and Global Development. New America, pp. 35–47.

Greenwood, O., Mossman, H.L., Suggitt, A.J., Curtis, R.J., Maclean, I., 2016. Using in situ management to conserve biodiversity under climate change. Journal of Applied Ecology, 53(3), pp. 885–894.

Gruen, A., 2012. Development and Status of Image Matching in Photogrammetry’. The Photogrammetric Record, 27(137), pp. 36–57.

Guay, K.C., Beck, P.S., Berner, L.T., Goetz, S.J., Baccini, A., Buermann, W., 2014. Vegetation productivity patterns at high northern latitudes: a multi‐sensor satellite data assessment. Global Change Biology, 20(10), pp. 3147–3158.

Gunton, R.M., Polce, C., Kunin, W.E,. 2015. Predicting ground temperatures across European landscapes. Methods in Ecology and Evolution, 6(5), pp. 532–542.

Haiden, T., Whiteman, C.D., 2005. Katabatic flow mechanisms on a low-angle slope. Journal of applied meteorology, 44(1), pp. 113–126.

Haider, N., Kirkeby, C., Kristensen, B., Kjær, L.J., Sørensen, J.H., Bødker, R., 2017. Microclimatic temperatures increase the potential for vector-borne disease transmission in the Scandinavian climate. Scientific Reports, 7(1).

Hancock, S., Anderson, K., Disney, M., Gaston, K.J., 2017. Measurement of fine-spatial-resolution 3D vegetation structure with airborne waveform lidar: Calibration and validation with voxelised terrestrial lidar. Remote Sensing of Environment, 188, pp. 37–50.

Hay, J.E., McKay, D.C.,1985. Estimating solar irradiance on inclined surfaces: a review and assessment of methodologies. International Journal of Solar Energy, 3(4–5), pp. 203–240.

Helliker, B.R., Richter, S.L., 2008. Subtropical to boreal convergence of tree-leaf temperatures. Nature, 454(7203), pp. 511–514.

Helmuth, B., Broitman, B.R., Yamane, L., Gilman, S.E., Mach, K., Mislan, K.A.S., Denny, M.W., 2010. Organismal climatology: analyzing environmental variability at scales relevant to physiological stress. The Journal of Experimental Biology, 213(6), p. 995.

Hertz, P.E., 1992. Temperature regulation in Puerto Rican Anolis lizards: a field test using null hypotheses. Ecology, 73(4), pp. 1405–1417.

Hicke, J.A., Logan, J., 2009. Mapping whitebark pine mortality caused by a mountain pine beetle outbreak with high spatial resolution satellite imagery. International Journal of Remote Sensing, 30(17), pp. 4427–4441.

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. John Wiley & Sons, Ltd., 25(15), pp. 1965–1978.

Holden, Z.A., Klene, A.E., Keefe, R.F., Moisen, G.G., 2013. Design and evaluation of an inexpensive radiation shield for monitoring surface air temperatures. Agricultural and Forest Meteorology, 180, pp. 281–286.

Homén, T., 1897. Der tägliche Wärmeumsatz im Boden und die Wärmestrahlung zwischen Himmel und Erde. Leipzig: Engelmann.

Hubbart, J., Link, T., Campbell, C., Cobos, D., 2005. Evaluation of a low‐cost temperature measurement system for environmental applications. Hydrological Processes. John Wiley & Sons, Ltd., 19(7), pp. 1517–1523.

Huey, R.B., Carlson, M., Crozier, L., Frazier, M., Hamilton, H., Harley, C., Hoang, A., Kingsolver, J.G., 2002. Plants versus animals: do they deal with stress in different ways?. Integrative and Comparative Biology, 42(3), pp.415-423.

Huntley, B., Allen, J.R., Bennie, J., Collingham, Y.C., Miller, P.A., Suggitt, A.J., 2017. Climatic disequilibrium threatens conservation priority forests. Conservation Letters.

Hutchinson, J.T., Lacki, M.J., 2001. Possible microclimate benefits of roost site selection in the Red Bat, Lasiurus borealis, in mixed mesophytic forests of Kentucky. Canadian Field-Naturalist, 115(2), pp. 205–209.

IAEA. 2017. Cosmic Ray Neutron Sensing: Use, Calibration and Validation for Soil Moisture Estimation. IAEA-TECDOC-1809. Vienna: IAEA.

Ibrahim, Y.Z., Balzter, H., Kaduk, J and Tucker, C. J. 2015 Land degradation assessment using residual trend analysis of GIMMS NDVI3g, soil moisture and rainfall in Sub-Saharan West Africa from 1982 to 2012. Remote Sensing, 7(5), pp. 5471–5494.

Imholt, C., Gibbins, C.N., Malcolm, I.A., Langan, S., Soulsby, C., 2010. Influence of riparian cover on stream temperatures and the growth of the mayfly Baetis rhodani in an upland stream. Aquatic Ecology, 44(4), pp. 669–678.

ISO. 2015. Siting classifications for surface observing stations on land (ISO 19289:2015). Geneva: ISO.

Jarvis, P.G., McNaughton, K.G., 1986. Stomatal control of transpiration: scaling up from leaf to region. Advances in ecological research, 15, pp. 1–49.

Johansen, O., 1977. Thermal conductivity of soils. Cold Regions Research and Engineering Lab Hanover NH.

Jones, H.G., 2013. Plants and microclimate: a quantitative approach to environmental plant physiology. Cambridge university press.

Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E., Linder, H.P., Kessler, M., 2017. Climatologies at high resolution for the earth’s land surface areas. Scientific Data, 4.

Kearney, M.R., Shamakhy, A., Tingley, R., Karoly, D.J., Hoffmann, A.A., Briggs, P.R., Porter, W.P., 2014. Microclimate modelling at macro scales: a test of a general microclimate model integrated with gridded continental‐scale soil and weather data. Methods in Ecology and Evolution, 5(3), pp. 273–286.

Kearney, M.R., Matzelle, A., Helmuth, B., 2012. Biomechanics meets the ecological niche: the importance of temporal data resolution. The Journal of Experimental Biology, 215(6), p. 922.

Kearney, M., 2013. Activity restriction and the mechanistic basis for extinctions under climate warming. Ecology Letters. Edited by L. Buckley, 16(12), pp. 1470–1479.

Kearney, M.R., Porter, W.P., 2017. NicheMapR – an R package for biophysical modelling: the microclimate model. Ecography, 40(5), pp. 664–674.

Kelly, A., Godley, B.J., Furness, R.W., 2004. Magpies, Pica pica, at the southern limit of their range actively select their thermal environment at high ambient temperatures. Zoology in the Middle East. Taylor & Francis, 32(1), pp. 13–26.

Kimmins, J.P., 2004. Forest Ecology - A Foundation for Sustainable Forest Management and Environmental Ethics in Forestry. Prentice Hall, Upper Saddle River, New Jersey.

Kleckova, I., Klecka, J., 2016. Facing the Heat: Thermoregulation and Behaviour of Lowland Species of a Cold-Dwelling Butterfly Genus, Erebia. Plos One, 11(3).

Kollas, C., Randin, C.F., Vitasse, Y., Körner, C., 2014. How accurately can minimum temperatures at the cold limits of tree species be extrapolated from weather station data?. Agricultural and forest meteorology, 184, pp.257-266.

Körner, C., 2007. Climatic treelines: conventions, global patterns, causes (Klimatische Baumgrenzen: Konventionen, globale Muster, Ursachen). Erdkunde, pp. 316–324.

Körner, C., Hiltbrunner, E., 2017. The 90 ways to describe plant temperature. In Perspectives in Plant Ecology, Evolution and Systematics.

Körner, C., Paulsen, J., 2004. A world‐wide study of high altitude treeline temperatures. Journal of Biogeography, 31(5), pp. 713–732.

Kraus, G.C.M., 1911. Boden und Klima auf kleinstem raum. Jena: Gustav Fischer.

Kriticos, D.J., Lamoureaux, S., Bourdôt, G.W., Pettit, W., 2004. Nassella tussock: current and potential distributions in New Zealand. New Zealand Plant Protection, 57, p. 81.

Kriticos, D.J., Webber, B.L., Leriche, A., Ota, N., Macadam, I., Bathols, J., Scott, J.K., 2012. CliMond: global high‐resolution historical and future scenario climate surfaces for bioclimatic modelling. Methods in Ecology and Evolution. Blackwell Publishing Ltd, 3(1), pp. 53–64.

Leempoel, K., Parisod, C., Geiser, C., Daprà, L., Vittoz, P., Joost, S., 2015. Very high‐resolution digital elevation models: are multi‐scale derived variables ecologically relevant?. Methods in Ecology and Evolution, 6(12), pp. 1373–1383.

Lefsky, M.A., Cohen, W.B., Parker, G.B., Harding, D.J., 2002. Lidar remote sensing for ecosystem studies. Bioscience, 52(1), pp. 19–30.

Lembrechts, J.J., Lenoir, J., Nuñez, M.A., Pauchard, A., Geron, C., Bussé, G., Milbau, A., Nijs, I., 2017. Microclimate variability in alpine ecosystems as stepping stones for non‐native plant establishment above their current elevational limit. Ecography.

Lenoir, J., Hattab, T., Pierre, G., 2017. Climatic microrefugia under anthropogenic climate change: implications for species redistribution. Ecography. Blackwell Publishing Ltd, 40(2), pp. 253–266.

Lewontin, R.C., 2000. The triple helix: genes, organism and environment. Cambridge, MA: Harvard University Press.

Liang, X., Kankare, V., Hyyppä, J., Wang, Y., Kukko, A., Haggrén, H., Yu, X., Kaartinen, H., Jaakkola, A., Guan, F., Holopainen, M., 2016. Terrestrial laser scanning in forest inventories. ISPRS Journal of Photogrammetry and Remote Sensing, 115, pp. 63–77.

Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agricultural and Forest Meteorology, 144(1–2), pp. 85–94.

Littmann, T., 2008. Topoclimate and microclimate. Arid Dune Ecosystems, pp. 175–182.

Lunardini, V.J., 1981. Heat transfer in cold climates. Van Nostrand Reinhold Company.

Lundquist, J.D., Huggett, B., 2008, Evergreen trees as inexpensive radiation shields for temperature sensors. Water Resources Research, 44(4).

Lundquist, J. D., Pepin, N., Rochford, C., 2008. Automated algorithm for mapping regions of cold-air pooling in complex terrain. Journal of Geophysical Research, 113(D22), p. D22107.

Ma, S., [Concilio](http://www.sciencedirect.com/science/article/pii/S0378112709008615" \l "%21), A., [Oakley](http://www.sciencedirect.com/science/article/pii/S0378112709008615#%21), B., [North](http://www.sciencedirect.com/science/article/pii/S0378112709008615#%21), M., [Chen](http://www.sciencedirect.com/science/article/pii/S0378112709008615#%21), J., 2010. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. Forest Ecology and Management, 259(5), pp. 904–915.

Maclean, I., Hopkins, J.J., Bennie, J., Lawson, C.R., Wilson, R.J., 2015. Microclimates buffer the responses of plant communities to climate change. Global Ecology and Biogeography, 24(11), pp. 1340–1350.

Maclean, I., Suggitt, A.J., Wilson, R.J., Duffy, J.P., Bennie, J.J., 2017. Fine‐scale climate change: modelling spatial variation in biologically meaningful rates of warming. Global Change Biology, 23(1), pp. 256–268.

Maclean, I.M., Bennie, J.J., Scott, A.J., Wilson, R.J., 2012. A high-resolution model of soil and surface water conditions. Ecological Modelling, 237, pp. 109–119.

Manins, P.C., Sawford, B.L., 1979. A model of katabatic winds. Journal of the Atmospheric Sciences, 36(4), pp. 619–630.

Martin, T.E., 2001. Abiotic vs. biotic influences on habitat selection of coexisting species: Climate change impacts?. Ecology, 82(1), pp. 175–188.

Mason, W.L., 2015. Implementing continuous cover forestry in planted forests: Experience with sitka spruce (Picea sitchensis) in the British Isles. Forests, 6(4), pp. 879–902.

McCree, K.J., 1971. The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agricultural Meteorology, 9(Supplement C), pp. 191–216.

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(5), pp. 1063–1075.

Meineri, E, Hylander, K., 2017. Fine‐grain, large‐domain climate models based on climate station and comprehensive topographic information improve microrefugia detection. Ecography, 40(8), pp. 1003–1013.

Meyer, C.L., Sisk, T.D., Wallace Covington, W., 2001. Microclimatic changes induced by ecological restoration of ponderosa pine forests in Northern Arizona. Restoration Ecology, 9(4), pp. 443–452.

Michaletz, S.T., Weiser, M.D., Zhou, J., Kaspari, M., Helliker, B.R. Enquist, B.J., 2015. Plant thermoregulation: energetics, trait–environment interactions, and carbon economics. Trends in Ecology & Evolution, 30(12), pp. 714–724.

Mishra, A., Vu, T., Veettil, A.V., Entekhabi, D., 2017. Drought monitoring with soil moisture active passive (SMAP) measurements. Journal of Hydrology, 552, pp. 620–632.

Moeser, D., Roubinek, J., Schleppi, P., Morsdorf, F., Jonas, T., 2014. Canopy closure, LAI and radiation transfer from airborne LiDAR synthetic images. Agricultural and Forest Meteorology, 197, pp. 158–168.

Monteith J.L., 1972, Survey of instruments for micrometeorology. London: Blackwell Scientific.

Morecroft, M.D., Taylor, M.E., Oliver, H R., 1998. Air and soil microclimates of deciduous woodland compared to an open site. Agricultural and Forest Meteorology, 90(1), pp. 141–156.

Morelli, T.L., Daly, C., Dobrowski, S.Z., Dulen, D.M., Ebersole, J.L., Jackson, S.T., Lundquist, J.D., Millar, C.I., Maher, S.P., Monahan, W.B., Nydick, K.R., 2016. Managing climate change refugia for climate adaptation. Plos One, 11(8), p. e0159909.

Morsdorf, F., Kötz, B., Meier, E., Itten, K.I., Allgöwer, B., 2006. Estimation of LAI and fractional cover from small footprint airborne laser scanning data based on gap fraction. Remote Sensing of Environment, 104(1), pp. 50–61.

Murdock, C.C., Evans, M.V., McClanahan, T.D., Miazgowicz, K.L., Tesla, B., 2017. Fine-scale variation in microclimate across an urban landscape shapes variation in mosquito population dynamics and the potential of Aedes albopictus to transmit arboviral disease. PLoS Neglected Tropical Diseases, 11(5).

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., Nemani, R.R., 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature, 386(6626), pp. 698–702.

Nakamura, R., Mahrt, L., 2005. Air Temperature Measurement Errors in Naturally Ventilated Radiation Shields. Journal of Atmospheric and Oceanic Technology. American Meteorological Society, 22(7), pp. 1046–1058.

National Research Council. 2014. Opportunities to Use Remote Sensing in Understanding Permafrost and Related Ecological Characteristics: Report of a Workshop. National Academies Press.

Oke, T.R., 2002. Boundary layer climates. Routledge.

Orlanski, I., 1975. A rational subdivision of scales for atmospheric processes. Bulletin of the American Meteorological Society, 56, pp. 527–530.

Parmesan, C., Root, T.L., Willig, M.R., 2000. Impacts of extreme weather and climate on terrestrial biota. Bulletin of the American Meteorological Society, 81(3), pp. 443–450.

Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature, 421(6918), pp. 37–42.

Pauli, H., Gottfried, M., Dullinger, S., Abdaladze, O., Akhalkatsi, M., Alonso, J.L.B., Coldea, G., Dick, J., Erschbamer, B., Calzado, R.F., Ghosn, D., 2012. Recent plant diversity changes on Europe’s mountain summits. Science, 336(6079), pp. 353–355.

Pearson, R.G., Stanton, J.C., Shoemaker, K.T., Aiello-Lammens, M.E., Ersts, P.J., Horning, N., Fordham, D.A., Raxworthy, C.J., Ryu, H.Y., McNees, J., Akçakaya, H.R., 2014. Life history and spatial traits predict extinction risk due to climate change. Nature Climate Change. Nature Publishing Group, 4(3), pp. 217–221.

Pepin, N., Benham, D., Taylor, K., 1999. Modeling Lapse Rates in the Maritime Uplands of Northern England: Implications for Climate Change. Arctic, Antarctic, and Alpine Research, pp.151-164.

Pepper, R.G., Morrissey, J.G., 1985. Soil properties affecting runoff. Journal of hydrology, 79(3–4), pp. 301–310.

Pérez Galaso, J.L., Ladrón de Guevara López, I., Boned Purkiss, J., 2016. The influence of microclimate on architectural projects: a bioclimatic analysis of the single-family detached house in Spain’s Mediterranean climate. Energy Efficiency, 9(3), pp. 621–645.

Pettorelli, N., Laurance, W.F., O'Brien, T.G., Wegmann, M., Nagendra, H., Turner, W., 2014. Satellite remote sensing for applied ecologists: opportunities and challenges. Journal of Applied Ecology, 51(4), pp. 839–848.

Pohlman, C.L., Turton, S.M., Goosem, M., 2007. Edge effects of linear canopy openings on tropical rain forest understory microclimate. Biotropica, 39(1), pp. 62–71.

Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., 2013. Global imprint of climate change on marine life. Nature Climate Change, 3(10), pp. 919–925. doi: 10.1038/nclimate1958.

Porter, W.P., Mitchell, J.W., Beckman, W.A., DeWitt, C.B., 1973. Behavioural implications of mechanistic ecology. Oecologia, 13(1), pp. 1–54.

Porter, W.P., Gates, D.M., 1969. Thermodynamic Equilibria of Animals with Environment’, Ecological Monographs. Ecological Society of America, 39(3), pp. 227–244.

Potter, K.A., Arthur Woods, H., Pincebourde, S., 2013. Microclimatic challenges in global change biology. Global Change Biology, 19(10), pp. 2932–2939.

Pringle, R.M., Webb, J.K., Shine, R., 2003. Canopy structure, microclimate, and habitat selection by a nocturnal snake, Hoplocephalus bungaroides. Ecology. Ecological Society of America, 84(10), pp. 2668–2679.

Raabe, S., Müller, J., Manthey, M., Dürhammer, O., Teuber, U., Göttlein, A., Förster, B., Brandl, R., Bässler, C., 2010. Drivers of bryophyte diversity allow implications for forest management with a focus on climate change. Forest Ecology and Management, 260(11), pp. 1956–1964.

Rice, K., 2004. Sprint research runs into a credibility gap. Nature, 432(7014), p. 147.

Rietkerk, M., Boerlijst, M.C., van Langevelde, F., HilleRisLambers, R., de Koppel, J.V., Kumar, L., Prins, H.H., de Roos, A.M., 2002. Self-organization of vegetation in arid ecosystems. The American Naturalist. The University of Chicago Press, 160(4), pp. 524–530.

Ripley, E.A., Archibold, O.W., 1999. Effects of burning on prairie aspen grove microclimate. Agriculture, Ecosystems and Environment, 72(3), pp. 227–237.

Rodhouse, T.J., Hovland, M., Jeffress, M.R., 2017. Variation in subsurface thermal characteristics of microrefuges used by range core and peripheral populations of the American pika ( Ochotona princeps ). Ecology and Evolution, 7(5), pp. 1514–1526.

Samson, D.R., Hunt, K.D., 2012. A Thermodynamic Comparison of Arboreal and Terrestrial Sleeping Sites for Dry-Habitat Chimpanzees (Pan troglodytes schweinfurthii) at the Toro-Semliki Wildlife Reserve, Uganda. American Journal of Primatology, 74(9), pp. 811–818.

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 of the Royal Society of London B: Biological Sciences, 280(1770), p.20131581.

Scherrer, D., Körner, C., 2010. Infra-red thermometry of alpine landscapes challenges climatic warming projections. Global Change Biology. Blackwell Publishing Ltd, 16(9), pp. 2602–2613.

Seo, C., Thorne, J.H., Hannah, L., Thuiller, W., 2009. Scale effects in species distribution models: implications for conservation planning under climate change. Biology Letters, 5(1), p. 39.

Settele, J., Scholes, R., Betts, R.A., Bunn, S., Leadley, P., Nepstad, D., Overpeck, J.T., Taboada, M.A., Fischlin, A., Moreno, J.M., Root, T., 2015. Terrestrial and inland water systems. in Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects. Cambridge University Press.

Sharpe, L.T., Stockman, A., Jagla, W., Jägle, H., 2005. A luminous efficiency function, V\*(λ), for daylight adaptation.Journal of Vision, 5(11), p. 3.

Shi, H.J., Paull, D., Rayburg, S., 2016 Spatial heterogeneity of temperature across alpine boulder fields in New South Wales, Australia: multilevel modelling of drivers of microhabitat climate. International Journal of Biometeorology, 60(7), pp. 965–976.

Shine, R., Kearney, M., 2001. Field studies of reptile thermoregulation: how well do physical models predict operative temperatures?. Functional Ecology, 15(2), pp. 282–288.

Slavich, E., Warton, D.I., Ashcroft, M.B., Gollan, J.R., Ramp, D., 2014. Topoclimate versus macroclimate: how does climate mapping methodology affect species distribution models and climate change projections?. Diversity and Distributions, 20(8), pp. 952–963

Søraas, F., Sandanger, M.I, Smith-Johnsen, C., 2017. NOAA POES and MetOp particle observations during the 17 March 2013 storm. Journal of Atmospheric and Solar-Terrestrial Physics.

Sporn, S.G., Bos, M.M., Hoffstätter-Müncheberg, M., Kessler, M., Gradstein, S.R., 2009. Microclimate determines community composition but not richness of epiphytic understory bryophytes of rainforest and cacao agroforests in Indonesia. Functional Plant Biology, 36(2).

Stull, R.B., 2012. An introduction to boundary layer meteorology. Springer Science & Business Media.

Suggitt, A.J., Wilson, R.J., August, T.A., Fox, R., Isaac, N.J., Macgregor, N.A., Morecroft, M.D., Maclean, I.M., 2015. Microclimate affects landscape level persistence in the British Lepidoptera. Journal of Insect Conservation, 19(2), pp. 237–253.

Suggitt, A.J., Gillingham, P.K., Hill, J.K., Huntley, B., Kunin, W.E., Roy, D.B., Thomas, C.D., 2011. Habitat microclimates drive fine‐scale variation in extreme temperatures. Oikos, 120(1), pp. 1–8.

Sun, Y., Frankenberg, C., Wood, J.D., Schimel, D.S., Jung, M., Guanter, L., Drewry, D.T., Verma, M., Porcar-Castell, A., Griffis, T.J., Gu, L., 2017. OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence. Science, 358(6360), p. eaam5747.

Sutherst, R.W., Bourne, A.S., 2009. Modelling non-equilibrium distributions of invasive species: a tale of two modelling paradigms. Biological Invasions, 11(6), pp. 1231–1237.

Tampucci, D., Gobbi, M., Marano, G., Boracchi, P., Boffa, G., Ballarin, F., Pantini, P., Seppi, R., Compostella, C., Caccianiga, M., 2017. Ecology of active rock glaciers and surrounding landforms: climate, soil, plants and arthropods., Boreas, 46(2).

Telewski, F.W., 1995. Wind-induced physiological and developmental responses in trees. in Coutts, M. P. and Grace, J. E. (eds) Wind and Trees. Cambridge University Press, pp. 237–263.

Telling, J., Lyda, A., Hartzell, P., Glennie, C., 2017. Review of earth science research using terrestrial laser scanning. Earth-Science Reviews, 169, pp. 35–68.

Terjung, W.H., 1974. Urban climatology (with reference to the interrelationship between external weather and the microclimate in houses and buildings). Progress in biometeorology. Division A: Progress in human biometeorology, 1(1 A), p. 168–"180, 624".

Thackeray, S.J., Henrys, P.A., Hemming, D., Bell, J.R., Botham, M.S., Burthe, S., Helaouet, P., Johns, D.G., Jones, I.D., Leech, D.I., Mackay, E.B., 2016. Phenological sensitivity to climate across taxa and trophic levels. Nature.

Töpfer, T., Gedeon, K., 2014. Facial skin provides thermoregulation in Stresemann’s Bush-crow Zavattariornis stresemanni. in Presented at the 26th Internafional Ornithological Congress, p. 24.

Tracy, C.R., 1976. A Model of the Dynamic Exchanges of Water and Energy between a Terrestrial Amphibian and Its Environment. Ecological Monographs. Ecological Society of America, 46(3), pp. 293–326.

Trivedi, M.R., Berry, P.M., Morecroft, M.D., Dawson, T.P., 2008. Spatial scale affects bioclimate model projections of climate change impacts on mountain plants. Global Change Biology, 14(5), pp. 1089–1103.

Tsendbazar, N.-E., de Bruin, S., Herold, M., 2017. Integrating global land cover datasets for deriving user-specific maps. International Journal of Digital Earth, 10(3), pp. 219–237.

Turner, D., Lucieer, A., Malenovský, Z., King, D.H., Robinson, S.A., 2014. Spatial co-registration of ultra-high resolution visible, multispectral and thermal images acquired with a micro-UAV over Antarctic moss beds. Remote Sensing, 6(5), p. 4003.

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., Steininger, M., 2003. Remote sensing for biodiversity science and conservation. Trends in Ecology & Evolution, 18(6), pp. 306–314.

Unwin, D. M., 1980. Microclimate measurement for ecologists. Cambridge: Cambridge University Press.

Uvarov, B. P., 1931. Insects and Climate. Transactions of the Royal Entomological Society of London, 79(1), pp. 1–232.

Vanwalleghem, T., Meentemeyer, R.K., 2009. Predicting forest microclimate in heterogeneous landscapes, Ecosystems, 12(7), pp. 1158–1172.

Vollmer, M., Möllmann, K.-P., 2017. Infrared thermal imaging: fundamentals, research and applications. John Wiley & Sons.

Waffle, A. D., Corry, R. C., Gillespie, T. J., Brown. R. D., 2017 Urban heat islands as agricultural opportunities: An innovative approach. Landscape and Urban Planning, 161, pp. 103–114.

Wakelin, J., Wilson, A.-L., Downs, C.T., 2013. Ground cavity nest temperatures and their relevance to Blue Swallow Hirundo atrocaerulea conservation, Ostrich 84(3), pp. 221–226.

Walsberg, G. E., Wolf, B.O., 1996. An Appraisal of Operative Temperature Mounts as Tools for Studies of Ecological Energetics, Physiological Zoology, 69(3), pp. 658–681.

Wang, C. Jones, R., Perry, M., Johnson, C., Clark, P., 2013. Using an ultrahigh-resolution regional climate model to predict local climatology, Quarterly Journal of the Royal Meteorological Society. 139(677), pp. 1964–1976.

Wanner, W., Strahler, A. H., Hu, B., Lewis, P., Muller, J.-P., Li, X., Schaaf, C.L.B. m Barnsley M. J., 1997. Global retrieval of bidirectional reflectance and albedo over land from EOS MODIS and MISR data: Theory and algorithm. Journal of Geophysical Research: Atmospheres, 102(D14), pp. 17143–17161.

Weiss, S. B., Murphy, D. D., Ehrlich, P. R., Metzler, C .F., 1993. Adult emergence phenology in checkerspot butterflies: the effects of macroclimate, topoclimate, and population history. Oecologia, 96(2), pp. 261–270.

Wexler, R., 1946. Theory and observations of land and sea breezes. Bull. Amer. Meteor. Soc, 27, pp. 272–287.

Whiteman, C.D., 2000. Mountain meteorology: fundamentals and applications. Pacific Northwest National Laboratory, Richland, WA (US).

Willis, C.K.R., Brigham, R.M.. 2005. Physiological and ecological aspects of roost selection by reproductive female hoary bats (Lasiurus cinereus). Journal of Mammalogy, 86(1), pp. 85–94.

Willis, C.K R. Jameson, J.W., Faure, P.A., Boyles, J.G., Brack, V.Jr., Cervone, T.H., 2009. Thermocron iButton and iBBat temperature dataloggers emit ultrasound, Journal of Comparative Physiology B, 179(7), pp. 867–874.

Wooster, M. J., Roberts, G., Smith, A. M. S., Johnston, J., Freeborn, P., Amici, S., Hudak. A. T., 2013. Thermal remote sensing of active vegetation fires and biomass burning events. pp. 347–390. In: Kuenzer C., Dech S. (eds) Thermal Infrared Remote Sensing. Remote Sensing and Digital Image Processing, vol 17. Springer, Dordrecht.

World Meteorological Organisation (WMO) . 2010. Manual on the Global Observing System. WMO-No. 544. Geneva.

World Meteorological Organisation (WMO) . 2014. Guide to Meteorological Instruments and Methods of Observation. WMO-No.8. Geneva.

Yang, Z., Wang, T., Skidmore, A.K., de Leeuw, J., Said, M.Y., Freer, J., 2014. Spotting East African Mammals in Open Savannah from Space. PLoS ONE, 9(12): e115989.

Yuan, J., Emura, K., Farnham, C., 2017. Is urban albedo or urban green covering more effective for urban microclimate improvement?. A simulation for Osaka. Sustainable Cities and Society, 32, pp. 78–86.

Zeng, Z., Piao,S., Li, L.Z.X., Zhou, L., Ciais, P., Wang, T., Li, Y. Lian, X., Wood, E. F., Friedlingstein, P., Mao, J., Estes, L. D., Myneni, R. B., Peng, S., Shi, X., Seneviratne S. I., Wang, Y., 2017. Climate mitigation from vegetation biophysical feedbacks during the past three decades. Nature Climate Change 7, pp. 432-436.

Zhang, Y., Chen, J. M., Miller, J. R., 2005. Determining digital hemispherical photograph exposure for leaf area index estimation. Agricultural and Forest Meteorology, 133(1), pp. 166–181.

Zhao, Q., Wentz, E., 2016. A MODIS/ASTER Airborne Simulator (MASTER) Imagery for Urban Heat Island Research. Data, 1(1), 7.

Zarco- Tajeda, P.J., V.González-Dugo, V., Berni, J.A.J., 2012. Fluorescence, temperature and narrow-band indices acquired from a UAV platform for water stress detection using a micro-hyperspectral imager and a thermal camera. Remote Sensing of Environment, 117, pp. 322–337.