Agricultural and Forest Meteorology 355 (2024) 110105

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Review

The contributions of microclimatic information in advancing ecosystem science

Jiquan Chen[a,*], Kyaw Tha Paw U[b], Malcolm North[c], Jerry F. Franklin[d]

[a] *Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI 48823, USA*
[b] *Department of Land, Air and Water Resources, University of California, Davis, CA 95618, USA*
[c] *USFS PSW Research Station and Department of Plant Sciences, University of California, Davis, CA 95618, USA*
[d] *College of Forest Resources, University of Washington, Seattle, WA, USA*

ARTICLE INFO

Keywords:
Microclimate
Measurements
QA/QC
VPD
Ecosystem Processes

ABSTRACT

Drawing upon over 100 years of scholarly work on microclimate, we first present an overview of the history, key references, and critical issues surrounding the collection and utilization of microclimate records in ecosystem studies. We place particular emphasis on addressing specific and pressing issues related to the applications of microclimate at the community-ecosystem-landscape level, excluding those of controlled experiment such as growth chambers and greenhouses. Specifically, we: (1) highlight some key issues concerning the collection, quality assurance/quality control (QA/QC), and utilization of microclimatic data in ecosystem studies; (2) revisit microclimatic responses to the structural changes of ecosystems and landscapes; and (3) emphasize the significance of microclimate in understanding major ecosystem/landscape processes and functions. Vapor pressure deficit (VPD) is particularly emphasized for its calculation and use because of its burgeoning applications in the literature. Case studies for each of the three thematic topics are provided with selected references to demonstrate challenges and solutions. As the scientific community gears up to enhance microclimatic stations, we envision significant increases in the use of smart sensors, wireless access, networking, open databases, and computational capabilities. Understanding and addressing some of the issues raised in this synthesis paper may help advance microclimate research and foster collaboration with other relevant disciplines, such as ecosystem science.

1. Introduction

Microclimate, also referred to as micro-climate, is generally defined as the climate near the Earth's surface (Geiger, 1965). Although the origin of this term is unknown, our search across many available databases (January 18, 2024) found the earliest documented use of the term in research presented by Roussakov (1924) in the proceedings of an annual meeting held in Russia (Fig. 1a). Geiger (1965) also notes that "directed attention, as long ago as 1929, to a need for inquiring whether in judging microclimate...." (p. 249). Wolfe (1951) delved into the study of microclimate and macroclimate in central Ohio, building upon earlier work documented in Wolfe et al. (1943, 1949), where these authors employed the term as if it were already an established concept. Evidently, the term microclimate was introduced around the 1920s, gained widespread acceptance by the late 1940s (e.g., Matthews, 1937), and became prominently utilized in the 1950s and thereafter (Shanks and Norris, 1950; Franklin, 1955).

Scientific progress in the study of microclimates has been propelled by scholars across diverse disciplines, including ecology, meteorology, plant science, agriculture, and forestry, with these disciplines being prominent in the application of the term (Fig. 1). The terms 'microclimate' and 'micro-climate' were used in 9117 titles in the publications indexed in the Web of Science Core Collection, spanning 291 subdisciplines. A search for these terms as keywords in the body of research papers, we found that they were used in a total of 43,188 publications, including books, proceedings, meetings, graduate theses, and patents. If related keywords, such as 'temperature' and 'soil moisture' were added to our search, both the publication count and citation rates would likely be substantially higher. Since Geiger's seminal work in 1965, several key publications have significantly contributed to advancing the field. Notable among these are works by Fritschen and Gay (1979); Rosenberg et al. (1983); Jones (1985); Camuffo (1998); Chen et al. (1999); Harlan et al. (2006); Erell et al. (2012); Potter et al. (2013); Campbell and Norman (2000); Barry and Blanken (2016); Bramer et al. (2018); Chen

* Corresponding author: Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI 48823, USA.
E-mail address: jqchen@msu.edu (J. Chen).

https://doi.org/10.1016/j.agrformet.2024.110105
Received 14 March 2024; Received in revised form 2 June 2024; Accepted 3 June 2024

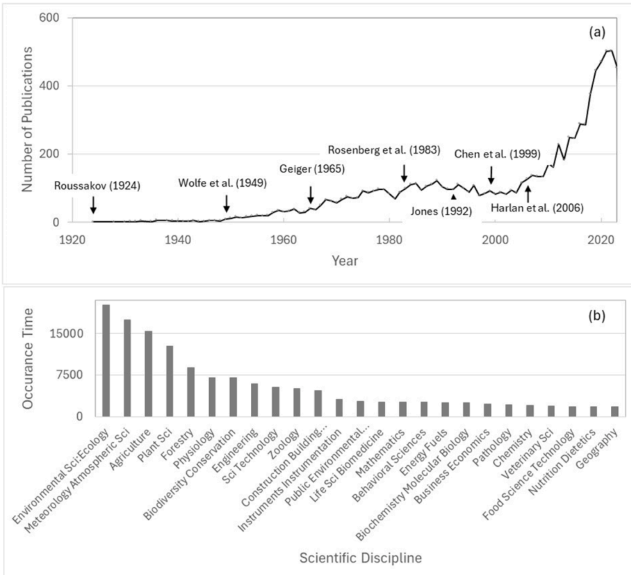

Fig. 1. (a) Changes in the number of occasions during 1637–2024 when the terms ‘microclimate’ and ‘micro-climate’ were used in publication titles based on a search of the Web of Science Core Collections on 18 January 2024. Selected milestone publications are highlighted. (b) The number of times of these terms appeared in publications in 25 top-ranked subdisciplines (of 291).

(2021), and Kemppinen et al. (2024).

The impact of the physical environment, encompassing both climate and microclimate, on nature and humans has been acknowledged since the inception of human civilization (National Research Council, 2010) and the advent of modern science (Heymann, 2010). Eratosthenes (276 BCE - 194 BCE), a Greek mathematician, astronomer, geographer, and librarian in ancient Alexandria, is credited as one of the earliest scholars to coin the term ‘climate’ for the purpose of differentiating global regions based on solar radiation (Altmann, 2005). In his influential book, *On Airs, Waters, and Places*, Eratosthenes explored the impact of climate on human health, cultural disparities, and natural landscapes in Europe and Asia. The societal structure formed in the Fertile Crescent, serving as a habitation 8000 years ago for migrants emerging from arid regions in northern Africa, was partially influenced by its favorable climate adjacent to the Mediterranean Sea (Diamond, 1997). Similarly, centrally located countries like Greece thrived due to their favorable climate, as noted by Hippocrates (Heymann, 2010). In China, the climate throughout a year was officially divided into “24 Solar Terms” in 110 BCE to guide farming activities in the Yellow River Basin. Since the eighteenth century, as the scientific community progressed towards a mechanistic understanding of natural processes, the spatial and temporal characteristics of microclimates became integral components in observational, experimental, and modeling studies in the natural sciences.

In the realm of ecosystem studies, microclimatic measurements have found widespread utility in predicting various phenomena and processes. Examples include modeling photosynthesis from light, specifically photosynthetically-active radiation (PAR) (Michaelis and Menten, 1913) and forecasting soil respiration based on temperature using the Q10 model (Van’t Holf, 1884). Significant scientific initiatives involving microclimate were championed by the Food and Agriculture Organization (FAO), particularly in modeling water loss as evapotranspiration (ET) to schedule irrigations in agriculture (Monteith, 1965). The Penman-Monteith model, which abstracts ecosystems as a single “big leaf,” is a product of these efforts and is now extensively utilized in contemporary ecosystem studies. For carbon assimilation, microclimatic variables such as PAR, temperature, vapor pressure deficit (VPD), and CO_2 concentration serve as essential drivers in modeling photosynthesis (Farquhar et al., 1980; Ball et al., 1987; Chen, 2021). Similarly, widely applied models in water evaporation within natural ecosystems feature microclimatic variables as major drivers (Penman, 1948; Thornthwaite, 1948; Priestley and Taylor, 1972; Jarvis, 1976). As the climate has undergone rapid changes and the necessity has arisen to model its impact on ecosystems, coupled with advancements in sensors, microclimatic observation networks, satellites, computational technology, and data availability, microclimate has become increasingly integrated into the understanding and modeling of ecosystem processes across various spatial and temporal scales (Norman, 1979; Farquhar et al., 1980; Chen et al., 1993b; Brosofske et al., 1997; Saunders et al., 1998 & 1999; Chen, 2021; Zou et al., 2024). The “climatic determinism” paradigm introduced by Eratosthenes, as highlighted by Heymann (2010), has proven to be remarkably useful throughout scientific history and continues to hold significance in contemporary ecosystem studies. We will use this as our basic set of assessments here. Other perspectives on environmental sciences, including those involving microclimatology, exist amongst various cultures, including indigenous peoples (Hernandez, 2022).

This article does not aim to provide a comprehensive, detailed, or exhaustive review of microclimatic research in ecology. Instead, our focus is on addressing a few specific and pressing issues related to the applications of microclimate at the community-ecosystem-landscape level, excluding considerations within enclosed environments (e.g., growth chamber, greenhouse, lab incubation, and indoor climate). Our specific objectives are: (1) highlighting key issues concerning the collection, quality assurance/quality control (QA/QC), and utilization of microclimatic data in ecosystem studies; (2) revisiting microclimatic responses to the structural changes of ecosystems and landscapes; and (3) emphasizing the significance of microclimate in modeling major ecosystem/landscape processes and functions. Our intention is to selectively include only key references in our introduction and subsequent discussions, acknowledging that this work is not a comprehensive listing of the vast existing literature on this subject (e.g., Fig. 1).

1.1. *Microclimate: measurements, data, and applications*

Microclimate research focuses on studying the climate in close proximity to a specific object of analysis, such as a cell, leaf, organism, community of plants or animals, or landscape. The nature of this research is contingent upon the questions posed and the targeted processes under investigation. While microclimate predominantly pertains to atmospheric properties like light, air temperature and humidity, carbon dioxide and other trace gas concentrations, pressure, precipitation, wind speed and direction, cloud cover, and pollution, it also encompasses the physical properties of soil, water, and the objects being studied. This includes aspects such as soil temperature and moisture, fuel moisture, turbidity of water, etc., as often documented in microclimatic studies in the existing literature (Unwin, 1980). However, there are notable variations in the definition and interpretation of microclimate. According to Rotach and Calanca (2003), the microclimate of a specific location can be defined as “the statistical state of the atmosphere in the layer directly influenced by the characteristics of the underlying surface.” This definition underscores the significance of land surface properties in shaping microclimatic conditions but technically would include the climate of the planetary boundary layer (i.e., the lowest part of the atmosphere that is directly influenced by its contact with the Earth’s surface, ranging from a few hundred meters to about 2 km). However, certain microclimatic characteristics and dynamics may depend significantly on regional conditions, irrespective of land surface characteristics. For instance, aerosols that alter the total amount and distribution of solar radiation in urban settings may have originated from nearby or distant emissions (i.e., spillover effects) (Chen et al., 2016). Such climatic conditions, resulting from human activities or natural disturbances and large-scale advections, are common subjects of investigation in ecosystem and landscape research.

With the increasing number of microclimatic stations worldwide, improvements in automated sensors, dataloggers and networking systems, and open access to a large amount of station data, ecosystem studies have escalated their use of microclimatic records. 'Surface' weather stations that are used for synoptic scale weather forecasting have historically been used in ecosystem studies because of their prevalence and long historical records. Ecosystem modeling at community-global scales has been eased by long-term global flux network monitoring that includes microclimatic variables for their varied landscapes (Baldocchi et al., 2001).

Because of the substantial contributions and irreplaceable roles of microclimatic input in promoting ecosystem science, critical attention is needed for using these data by following essential steps. Networks and even individual local stations must follow specific procedures to prepare data for use in ecosystem research. The steps for these are outlined well in Figure 2.1 of the World Meteorological Organization's *Instruments and Observing Methods* (WMO, 1993). A variable must be measured (with potentials for inaccuracy, etc.); the transduced variable created by the sensors must be recorded or logged; the logged data must be gathered or transmitted; the data must be checked; and the data must be corrected, for example calibrated and gap filled when there is missing data and complete datasets are needed. Then an ecosystem researcher may need to orchestrate additional corrections, processing and storage of the data as the analysis proceeds. Each of these steps is generally affected by researcher perspective and assumptions, as well as differences between research labs, government agencies and individual researchers (Fee, 1982; Imber and Tuana, 1988; Crasnow, 2009). Given these issues, each researcher should scrutinize their own perspectives when utilizing microclimatic data and be especially aware of such issues when combining data from different networks and stations.

Depending on the network or research team, global weather and microclimatic stations are not all installed and maintained using the same standards for where they were established, including height, local landscape conditions, sensor types, calibration protocols, etc. The sensors of a standard synoptic scale weather station are typically mounted at a height of 2 m above the ground to measure air temperature, humidity, wind speed, and other parameters, with the station located in an open area, though synoptic weather stations may have wind speed measured at a higher level, such as 10 m, for World Meteorological Organization (WMO) surface stations. Recognizing that various networks and research teams design their weather stations to meet specific objectives, users need to review station and network designs to ensure microclimatic data capability. Stations from different network programs and countries are not all the same, even the stations of the WMO. For example, it is not unusual to see stations on roadsides, airports, building rooftops, etc. The magnitude and dynamics of some microclimatic variables (e.g., temperature, wind speed) from these stations are significantly affected by the surrounding landscape structure and, thus, cannot be directly compared or used in the same way for modeling an ecosystem process. Where such features influence data, constructed empirical (or mechanistic) models will find limited applicable cases across a landscape, or even yield false predictions and high uncertainty.

For example, the Q10 model has been widely used to predict ecosystem respiration using air temperature at eddy-covariance flux towers (Black et al., 1996). In an idealized Q10 model the biota's temperature is assumed to control respiration, but normally only air temperatures are available from weather stations, rather than the biotic and soil temperature. There is the additional complication that air temperatures may be recorded at different heights, with sensors of varied frequency response, accuracy, and precision, suggesting that the residuals for best fit of respiration to a Q10 model will be large, and estimated coefficients among the sites (e.g., the Q10 values) could be difficult to compare. Recording intervals can vary from less than 30 min to 6–24 h or even longer. Measurements taken at coarser temporal resolutions (e.g., 3+ hours) will not reflect extremes, whereas high-frequency records produce large datasets and may include rare events that skew mean and variation of a microclimatic variable when data are presented at diurnal-monthly-yearly scales. Models constructed using these microclimatic data could carry large uncertainties and should only be applied in different locations and times, even when assuming the sensors are reliable and have similar precisions, by accounting and correcting for these other complicating factors. Reporting the uncertainties associated with microclimate means (e.g., variations, minimum, maximum, median, etc.) is highly recommended. Here, it is worth mentioning that some microclimatic variables are less sensitive to station height (e.g., incoming solar radiation) or logging intervals and sensor frequency response (e.g., ground water table and soil moisture). Clearly, careful examinations of microclimatic locality of stations, sensors, and sampling protocols are needed prior to any applications. One simple but important precaution is examination of the time stamping of records – that is, does it record local time, daylight savings time, UTC, or other time protocols, and does it represent the beginning, middle, or end of the measurement period?

Weather station location and the local microclimate and landscape type can strongly influence measurements. Network station protocols (WMO, 1993, 2021) recognize that all weather stations and their sensors experience their own microclimate, and their data can be influenced by local landscape features such as well-watered lawns, bare soil, asphalt, buildings structures close to the station, and location within or above canopy. Closely linked to this is the fetch effects of landscape type for the sensors, meaning a station should be situated within a landscape type in such a way as to avoid influences caused by other landscape types surrounding the station (WMO 1993, 2021).

Data collected from microclimatic stations might not consistently meet high-quality standards for immediate use and, in certain circumstances, could be erroneous (Fritschen and Gay, 1979; Maclean et al., 2021). For example, Saunders et al. (1998) used E-type fine wire thermocouples to measure air temperature, instead of conventional T-type wires, so that the effects from direct radiation and heat capacity can be reduced. The reliability of such data hinges largely on factors like station upkeep, sensor functionality, power continuity, and unforeseen disruptions. To ensure the dependable application of microclimatic measurements in ecosystem studies, rigorous QA/QC (Quality Assurance/Quality Control) protocols are imperative (e.g., Maclean et al., 2021). Regrettably, even seemingly plausible values recorded at a station can be misleading, as illustrated in Fig. 2, showing both a pyranometer and a rain gauge obscured by snow on January 22, 2024. Consequently, it becomes challenging to ascertain the accuracy of recorded precipitation and short-wave radiation. Implementing heated tubing for rain gauges during snowfall periods is strongly recommended, although this practice is not widely adopted. Through our microclimatic investigations, numerous undocumented events have been observed, leading to inaccurate measurement records. Instances such as bird and insect dwellings (e.g., spider webs) on radiometers, litterfall blockages in rain gauges, and misalignment of radiometers are common disturbances that can cause false recordings at microclimatic stations.

Fig. 2. Snow blanketed the rain gauge and pyranometer on January 22, 2024, at a microclimatic station in East Lansing, Michigan, during a week-long snowfall period.

The microclimates of the soil, the sub-canopy space, and the canopy vary greatly with height in plant ecosystems. Such variations can make observations especially challenging, because sensors may have to be located at poorly accessible heights in forests, for example, and the number of sensors is multiplied by the number of measurement heights, creating higher costs and complexities. One way to address the height dependence of microclimatic variables is to use vertically layered soil-plant-atmosphere models (also called land surface models). These models can simulate both ecosystem fluxes and the microclimate as a function of height, within and above ecosystems, which can be critical when considering species that may be confined to certain canopy layers and locations. The first of these models were based on resistance/flux-gradient type modelling (Waggoner and Reifsnyder, 1968; Norman 1979), and since then they have become far more sophisticated in their biotic physiological and turbulent transport parameterization (Meyers and Paw U, 1987; Pyles et al., 2000, 2004; Paw U, 2002; Staudt et al., 2010; Chang et al., 2018). These soil-plant-atmosphere models can be linked to regional scale models to simulate regional microclimate-ecosystem interactions (Xu et al., 2014; 2017).

Microclimatic variables undergo significant fluctuations over time, with varying rates of change observed among them. For instance, both incoming and outgoing radiation can plummet by over 90 % within mere minutes as clouds develop on an otherwise clear day (Chen et al., 1993a). Similarly, air temperature and relative humidity can exhibit marked disparities within just 1–2 h, in stark contrast to the more gradual alterations seen in soil microclimate parameters such as soil temperature and moisture levels. Accounting for these distinctions is paramount in ecological research, as field data collected at different intervals (e.g., hours or days apart) should not be directly juxtaposed. For example, due to equipment constraints, microclimatic conditions often are gauged and compared across multiple locations using portable thermometers at varying times. Despite efforts to standardize measurement windows (e.g., 10:00 – 14:00 h) in soil respiration studies, exercising caution is imperative when juxtaposing data without proper temporal calibration. This vigilance is particularly pertinent in microclimatic studies spanning gradients, such as transitions from forest edges to interiors or from streams/roads to remote landscapes (Chen et al., 1993a; Matlack, 1993; Brosofske et al., 1999; Saunders et al., 1999; Baker et al., 2014; Hofmeister et al., 2019). Ideally, comparisons of microclimatic conditions should rely on data collected simultaneously. Furthermore, owing to temporal variability, reliance solely on mean values from finely grained temporal data to characterize microclimate over broader time scales (e.g., hourly data into daily averages) may be inadequate. Instead, it is prudent to generate other statistical measures such as maximum, minimum, range, cumulative totals, and extreme values (a.k.a. anomalies) to comprehensively grasp microclimate dynamics across various temporal scales. These challenges are exacerbated by non-linear physical and ecosystem processes that result in mean values of the biotic processes not matching calculations of those biotic processes from mean microclimatic variables. For example, the monthly ecosystem respiration calculated from mean monthly temperatures using Q10 models will usually not match the mean values calculated on an hourly basis, from hourly temperatures.

Across horizontal spatial scales, similar attention is imperative due to the considerable variation in land surface properties such as microtopography, vegetation, and soil composition. As illustrated in Fig. 3, the land surface temperature of an experimental switchgrass plot ranged from 20.9 °C to 29.4 °C on July 19, 2021, despite the seemingly homogeneous planting of switchgrass across the eddy-covariance measurement footprint of 500 m (Zenone et al., 2011). These substantial spatial temperature discrepancies, along with variations in other microclimatic variables, are frequently observed in diverse ecosystems and landscapes, including the spatiotemporal dynamics of urban heat islands (Myint et al., 2015; Shiflet et al., 2017). In the Pacific Northwest, notable disparities in air temperature, soil temperature, relative humidity, and incoming short-wave radiation were recorded in a relatively

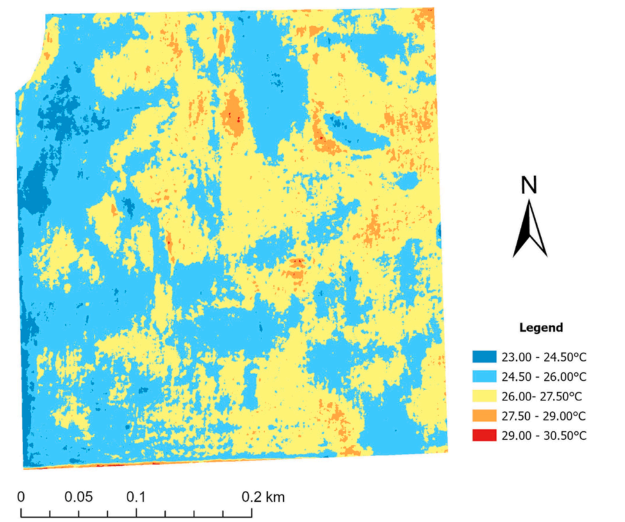

Fig. 3. Land surface temperature at an eddy-covariance flux tower site of the Kellogg Biological Station with switchgrass plantation on July 19, 2021. Data courtesy of Bruno Basso, Michigan State University.

uniform old-growth forest during the growing season (Chen and Franklin, 1997), attributable in part to the forest's mosaic of successional patches (e.g., canopy gaps) and species composition (Gray et al., 2002). Comparable findings have been documented in other forests (Chazdon et al., 1988; Ma et al., 2010) and ecosystem types such as croplands and grasslands (Saunders et al., 1998; Shao et al., 2017). Moreover, significant microclimatic variations along vertical profiles of plant communities and soil have been observed (Rambo and North, 2009; Yan et al., 2018). It is evident that measurements taken at specific heights or depths cannot be extrapolated to other vertical positions without meticulous calibration. For example, soil and ecosystem respiration rates are frequently predicted using the Q10 model, which relies on soil or air temperatures, or their combination (Chen, 2021). However, it is crucial to note that not all reported models are based on temperature measurements taken at the same position and time within the plant-atmosphere-soil column (Reichstein et al., 2023; Zou et al., 2022). Consequently, predicted respiration rates may be constrained to the study site and entail considerable uncertainty when extrapolated temporally and spatially, impeding their applicability to other ecosystems and forecasting efforts.

The magnitude and temporal-spatial dynamics of multiple microclimatic variables often exhibit strong correlations, underscoring the importance of considering multiple variables as fundamental drivers of ecosystem processes. As demonstrated by Chen et al. (1996), the spatial changes of different microclimatic variables within an isolated forest patch showed contrasting patterns and were dependent on time (hours of a day, days of a year). In ecosystem studies, there is a growing trend towards integrating multiple microclimatic variables into ecosystem modeling endeavors (e.g., Xia et al., 2023). Some well-documented interdependent changes include the synchronized variations in diel temperature and relative humidity, as well as seasonal temperature patterns correlating with precipitation in continental climate regions. Notably, high relative humidity, increased soil moisture, and reduced VPD following precipitation events are among the most prevalent microclimatic phenomena in terrestrial landscapes. However, these intuitive relationships may not always hold true or be readily apparent. For instance, forests with dense canopy cover may experience a reduced increase in soil moisture after light rains due to high canopy interception (Yu et al., 2022; Skhosana et al., 2023). Nevertheless, grasping the intricate interplay among microclimatic variables is vital for understanding the biophysical drivers of ecosystem processes and functions.

Some microclimatic variables utilized in ecological research are not directly measured but rather estimated or calculated from indirect observations. Growing degree days, growing season length, frost-free period, snow accumulation (either within the year or from previous seasons), daily-to-annual precipitation, total solar hours, drought occurrences, and heatwaves, are among the common microclimatic measures applied in ecological studies, including modeling. It is important to note the methodological definitions and discrepancies in delineating these metrics. Traditionally, climatologists have defined the growing season based on temperature, precipitation, and sunlight availability (Körner et al., 2023), primarily for agricultural management, where higher temperatures and sufficient moisture support longer growing seasons. The start and end of the growing season, for instance, have been extensively used in remote sensing of phenology for ecosystem production, often coupled with ground measurements of net ecosystem exchange of CO_2 from eddy-covariance flux towers. However, remote sensing researchers typically employ a threshold value of vegetation index (e.g., EVI or NDVI) to determine the beginning and end of the growing season (Yuan et al., 2024), whereas flux scholars define the period as when detectable gross primary productivity (GPP) exceeds 3 continuous days. Consequently, the growing season length derived from these approaches can yield vastly different results, leading to considerable uncertainty in model predictions of ecosystem functions or impeding comparisons among models or between research findings in different ecosystems. Similar challenges can be found in delineating drought and heatwaves (Qu et al., 2023).

1.2. Changes in microclimate within and across ecosystems

In Rotach and Calanca's definition (2003), the emphasis on microclimate centers around surface properties that determine the magnitude and dynamics of microclimate. Since the pioneering works of Wolfe and colleagues in the 1940s and 1950s on topographic influences on microclimate (Wolfe et al., 1943, 1949, 1950) considerable attention has been directed towards understanding how overstory canopies, litter layers, and soils shape microclimate conditions. Generally, air and soil temperatures within vegetated areas exhibit greater stability compared to open areas (Chen et al., 1993a; 1999; De Frenne et al., 2019; Meeussen et al., 2021), although, depending on season, they may be either lower (e.g., daytime in summer months) or higher (e.g., nighttime in winter months). Light distribution, including PAR, within canopies varies significantly and depends on factors such as leaf density and architecture, and their horizontal and vertical distribution (Chen and Black, 1992; Chen et al., 1993a; Canham et al., 1990, 1994; Leuchner et al., 2011; Matsuo et al., 2021). The pioneering research of Norman et al. (1971) on light distribution under forest canopies revealed substantial differences in light levels within a few centimeters at a given time (Chazdon et al., 1988; Chen and Franklin, 1997), suggesting the need for numerous radiometers or instruments with multiple sensors to accurately quantify radiation mean and variation under forest canopies (Chadson et al., 1988; Webster et al., 2016). Relative humidity within forests is typically higher than that in open areas but can also be lower or similar during precipitation events. Consequently, VPD within forests is generally lower than that in adjacent open areas (e.g., after forest clearing). These differences are commonly attributed to the "buffering effects" of overstory canopies, which have been widely demonstrated to contribute to more stable and less extreme climates in urban landscapes through the expansion of greenspaces (Erell et al., 2012), in agroecosystems through the establishment of tree/shrub covers (including corridors) (Cleugh, 1998; Lin, 2007), and in forests by retaining some trees during harvesting (Xu et al., 1997; Chen et al., 1999; Zheng et al., 2000; Heithecker and Halpern, 2006).

Litter layers in natural ecosystems serve as another buffering structure mediating soil microclimate and albedo – a phenomenon long observed (MacKinney, 1929; Sayer, 2006). Similar to the buffering functions of canopies, litter layers shield the soil by reducing soil heat flux and evaporative water loss. Consequently, soils with high litter cover exhibit more stable temperatures and higher moisture levels (Ogée and Brunet, 2002; Iqbal et al., 2020; Ma et al., 2010). These attributes are why mulches are incorporated into cover crops (Hartwig and Ammon, 2002) and urban lawns (Jabran and Jabran, 2019), woody debris is retained during forest harvesting (Heithecker and Halpern, 2006; Harmon and Hua 1991; Innes et al., 2006; Dhar et al., 2022), grazing is reduced in grasslands (Odriozola et al., 2014; Yan et al., 2018), and stover is preserved in cover crop management (O'Brien et al., 2020). Therefore, it is necessary to include litter depth and coverage when predicting ecosystem processes such as soil respiration (DeForest et al., 2009; Ryu et al., 2009), decomposition, and nutrient availability. Litter cover also has an important role in reducing radiation reflectance compared to bare ground. Increasingly, studies have demonstrated that the albedo of altered land surfaces can significantly differ from undisturbed ecosystems (e.g., >10 %). This disparity, if sustained throughout the year, is equivalent to >0.5 Mg CO_2 ha^{-1} $year^{-1}$ in warming (lowered albedo) or cooling (elevated albedo) benefits provided by the ecosystem (Abraha et al., 2021; Chen, 2021; Sieber et al., 2022; Lei et al., 2023; Zhu et al., 2024). For instance, litter layers on forest floors (Melloh et al., 2001) and croplands (e.g., stover, Kim et al., 2009) have been found to have substantially lower albedo. During snow-covered periods, litter's high absorption of incoming radiation results in faster snow melting, which, in turn, alters soil water content and temperature. The reduced reflectance due to litter cover is particularly pronounced in ecosystems with sparse overstory cover (e.g., drylands, Shao et al., 2017).

Soil microclimate exhibits greater stability compared to near-surface microclimate, although spatial and temporal variations can be significant for physical and ecological processes, such as nutrient leaching into deep soils, microbial activities, and litter decomposition (Waring and Running, 2010). Soil temperature and moisture, along with their variations across a stand and over vertical profiles, as well as over time, require careful examination. Microtopography, for instance, serves as the primary driver for horizontal water movement in soils, resulting in substantial soil moisture accumulation in concave positions across stands (e.g., Bogner et al., 2013) (Fig. 4). Within the soil, factors such as texture, density, organic content, root distribution, and soil fauna contribute to varying magnitudes and dynamics of soil temperature and moisture holding capacity (Meyer et al., 2007).

Microclimatic conditions and dynamics at landscape levels (spanning a few kilometers) also depend on landscape structure, regardless of similar regional climates (Chen et al., 1999; Vanwalleghem and

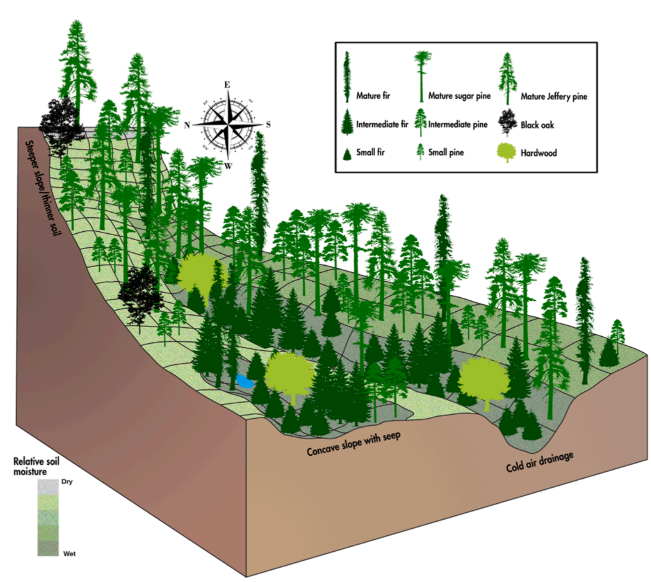

Fig. 4. An illustration of microtopographic influences on soil moisture which, in turn, affect species composition and density.

Meentemeyer, 2009). Across a 10-km landscape in Missouri's Ozarks, Xu et al. (2002) reported significant variations in microclimate due to topographic features, overstory and understory cover, and landscape patch types. Seasonal mean air temperatures ranged from 19.6 °C to 22.7 °C, with volumetric soil moisture varying from 3.5 % to 28.6 %. In northern Wisconsin, where the landscape is flat, Saunders et al. (1998) also observed considerable soil temperature fluctuations along a ~4 km transect, ranging from 14.23 °C to 27.31 °C. Similar findings have been reported in other landscapes as well (e.g., Townsend and Fuhlendorf, 2010). Apart from these ecosystem-type differences, extensive literature has accumulated on microclimates resulting from landscape features such as edges, roads, streams, corridors, and remnant forest patches in agricultural landscapes or small openings in forested landscapes (Chen et al., 1993a; Brosofske et al., 1999; Rambo and North, 2008). These structures not only create unique microclimates (Chen et al., 1993a) but also induce horizontal changes in adjacent ecosystems. Across clearcuts and forest edges, such influences can extend to more than 240 m in old-growth Douglas-fir forests in the Pacific Northwest (Chen et al., 1995), although the depth-of-edge influences vary by variable of the interest. Similar edge influences on microclimate have been widely reported in fragmented tropical rainforests (Laurance, 1991), regenerated hardwood landscapes in New England (Matlack, 1993), and other contexts (Meeussen et al., 2021). Streams and roads are also prominent landscape features in terrestrial ecosystems. Their unique microclimates play fundamental roles in affecting various ecological processes, such as species distribution, plant growth and mortality (Chen et al., 1992), seed dispersal (Warneke et al., 2022), animal movement (Haynes and T. Cronin, 2006), carbon and water fluxes, and nutrient cycling (Weathers et al., 2001).

More importantly, these features can exert extensive influences on adjacent ecosystems – commonly referred to as edge effects (Harper et al., 2005; Chen et al., 1995), which are anisotropic and time-dependent. As demonstrated in Chen et al. (1993), edge orientation is a fundamental variable determining the magnitude and dynamics of all microclimatic variables. At a south-facing edge, incoming solar radiation exhibits similar diurnal changes to that in the adjacent clearcut, whereas at a north-facing edge, shadowing effects from overstory trees produce diurnal changes in incoming radiation similar to those inside the forest. Consequently, the depth-of-edge influence much less from a north-facing edge into the forest. Due to these direction-dependent edge effects, edge influences from multiple directions are much stronger than those from a single direction (Chen et al., 1996; Zheng and Chen, 2000; Fletcher, 2005; Li et al., 2007). Additionally, these differences due to edge orientation extend to other microclimatic variables such as temperature and moisture (Chen et al., 1995). For microclimates associated with other linear structures (e.g., roads, streams), corridor orientation also remains a critical factor when assessing edge effects, particularly in the context of developing management plans (e.g., designing riparian buffer zones; Van de Water and North, 2011).

Spatial variations in canopies and soil properties strongly influence the unique local microclimate within forest stands, which, in turn, is further influenced by landscape structure across ecosystems (Fig. 5). As microclimatic information is increasingly used to interpret and model

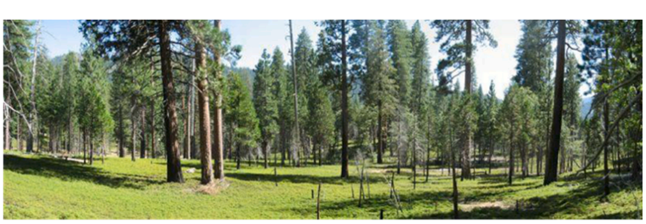

Fig. 5. An old-growth, mixed-conifer stand in Yosemite National Park with a restored fire regime. Note the tree spatial distribution consisting of individual trees, clumps of tree and openings that provide heterogeneous microclimate.

ecosystem/landscape processes, managing and predicting microclimate from structural features is becoming an important research component to create an optimum microclimate that promotes ecosystem-landscape functions. Various harvesting methods in forestry (North et al., 2009; Ma et al., 2010; Knapp et al., 2021), grazing intensities in rangelands for livestock production (Shao et al., 2017), and variable plantation densities in forest (North et al., 2019) and crop management are among the popular practices in relevant fields. In western US conifer forests, microclimate homogenization can result from fire suppression, due to dense tree infilling, and from high-severity fires, due to canopy consumption. A principle ecological objective with fuels treatments (mechanical thinning and prescribed fire) is to restore fine-scale forest heterogeneity by reducing fuels, by lowering tree density, and by creating openings. In particular, fuels treatments often aim to restore a spatial pattern of individual trees, clumps of trees, and openings (ICO) that has been consistently found in forests that historically have had frequent (≤ 30 year), low-intensity fire regimes (Churchill et al., 2013; Fry et al. 2014). When an ICO structure is restored, fine-scale microclimate and habitat heterogeneity increases, increasing plant and animal species richness and evenness (Ryu et al., 2009; North et al., 2022). In turn, this heterogeneity is perpetuated when the forest burns at low severity, because fire effects vary with fine-scale differences in fuel and microclimate conditions (Moritz et al., 2014; Chamberlain et al. 2023). Variable microclimate conditions following fuel reduction practices are sometimes used as an indicator of effective forest treatment (Bigelow and North, 2012). For example, recent research (Ziegler et al. 2017; Ritter et al. 2020, 2023) suggests the ICO pattern may reduce radiant and convective heat transfer, which along with lower fuel loads in the openings, may explain why ICO has been associated with reduced fire severity (Koontz et al. 2020). However, it's not clear if there's a point at which the forest becomes so open that wind speed increases or an optimal clump and opening size for reducing the heat transfer that leads to crown fire.

1.3. Microclimatic influences on ecosystems

Much of microclimate research has garnered attention for its direct and indirect impacts on both human societies and natural ecosystems. A prominent example is the phenomenon of temperature-dependent sex determination (TSD) in reptiles, such as freshwater and sea turtles (Charnier, 1966). Minor temperature variations of less than 0.5 °C can lead to the development of either male or female offspring (Bull and Vogt, 1979; Standora and Spotila, 1985). Similarly, amphibians (Janzen, 1994) and certain vertebrates (Valenzuela and Lance, 2004) exhibit temperature-dependent traits. In vegetation ecology, researchers have long investigated spatial shifts in vegetation types, species composition, richness, and structure, as well as major ecosystem processes, with microclimate serving as a primary driver. Virtually all ecological models incorporate (micro)climate data as an essential input to understanding key processes such as plant growth and mortality, photosynthesis, respiration/decomposition, species dispersal, and breeding. Collectively, these processes often determine ecosystem functions such as productivity, water conservation, and biological diversity. For instance, in fire-dependent forests in the western US, several fundamental ecosystem processes are hampered due to moisture limitations. Fire suppression has increased tree density and competition for soil moisture. Management practices such as reducing tree canopy cover enhance available water by facilitating greater snow accumulation on the forest floor and increasing water infiltration into the soil, thereby reducing water loss through snow sublimation in tree canopies (Stevens, 2017). Decreasing tree basal area also increases soil moisture availability for the remaining trees and other plants (Stephens et al., 2021). In many seasonally dry forest types, increases in water availability can 'jumpstart' ecosystem processes such as decomposition (Johnson et al., 2009), nutrient cycling (Johnson and Turner, 2019), and soil respiration (Ma et al., 2005), that have 'stalled' as soil moisture is depleted.

While a vast body of literature delves into the regulation of ecosystem processes and functions by microclimatic factors, we underscore two critical issues in understanding microclimate's role in ecological research: (1) the significance of microclimatic extremes, and (2) the combined influences of multiple microclimate variables, both of which are subject to scale-dependent regulations.

Understanding microclimatic influences on ecosystem processes requires exploring more than data mean values. Accumulating evidence highlights the profound impacts of extreme microclimates, including short-term temperature and precipitation anomalies (Kiladis and Diaz, 1989), heatwaves, droughts (Fettig et al., 2019), frosts, and rainstorms, which can precipitate enduring effects and shift ecosystems to alternative states, with or without the possibility of recovery. In investigating the regulatory mechanisms of ecosystem water use efficiency in an oak opening forest in Ohio, Xie et al. (2016) identified spring leaf area and precipitation, summer net radiation and temperature, and annual VPD as the primary explanatory variables for seasonal variation. However, the seasonal dynamics of the interaction between precipitation and drought status emerged as the key variable for intraannual variability. Notably, for photosynthesis, thresholds exist for parameters such as PAR, VPD, and temperature, beyond which stomata close at their upper limits (Chen et al., 2002; Earles et al., 2018; Grossiord et al., 2020). Moreover, temperature-driven soil respiration undergoes alterations under conditions of low soil moisture (Zou et al., 2022). On the Mongolian Plateau, standardized anomalies of vegetation indices exhibit strong correlations with drought and extreme temperature events, albeit the strength of these correlations varies according to biome type (John et al., 2013). Recent research has increasingly focused on extreme high and low temperatures, partly due to ongoing global warming trends. Studies have documented significant reductions in GPP, with reports of 30 % and 50 % decreases during the European heatwaves of 2003 (Ciais et al., 2005) and the 2010 Russian heatwave (Bastos et al., 2014), respectively. These reductions surpass those attributable to climate warming and CO_2 fertilization alone. In Mongolia, a severe cold winter during 2010–2011 led to a 26 % livestock mortality rate. Furthermore, extreme events often manifest with multiple climatic variables, such as reduced soil moisture during heatwaves (De Boeck et al., 2010; Qu et al., 2023). Detailed information regarding the magnitudes, durations, and timing of these events is crucial for comprehending their impacts on ecosystem processes.

A microclimatic variable rarely acts as the sole determinant in regulating an ecosystem process but often operates in conjunction with others, leading to nonlinear consequences of ecosystem processes (e.g., photosynthesis, evapotranspiration), and functions (e.g., production) because microclimatic variables are highly interdependent over time (Chen et al., 2004b; Rillig et al., 2019; De Pauw et al., 2022; Xia et al., 2023). In a synthesis review focusing on the controlling mechanisms of carbon exchange in terrestrial ecosystems, Templer and Reinmann (2011) noted that "single-factor manipulations can result in dramatic shifts in ecosystem carbon dynamics. However, predicting the impacts of environmental change on the magnitude and direction of ecosystem carbon exchange based solely on manipulation of individual factors is not always feasible due to additive and synergistic effects." This perspective finds increasing support from a growing body of evidence in ecology (e.g., Brosofske et al., 2001; North et al., 2005; Song et al., 2019). For instance, soil respiration was initially modeled with soil temperature as the sole driver, but subsequent research has recognized additional significant variables such as soil moisture, litter cover, leaf area, and growing season length (e.g., Concilio et al., 2009; Zou et al., 2022). Indeed, the classical temperature-respiration paradigm based on the Q10 model may falter when soil moisture reaches a critical threshold (Chen, 2021), particularly in dryland ecosystems or regions experiencing prolonged dry periods. In modeling photosynthesis, earlier empirical models were primarily based on PAR integrate factors such as CO_2 concentration, temperature, VPD, and soil moisture (Grossiord et al., 2020). Similarly, the original temperature and light-driven ET model proposed by Thornthwaite (1948) has undergone refinement to include net radiation, relative humidity, wind speed, and soil heat flux in equations such as the Penman-Monteith and Priestley-Taylor models (Chen, 2021). Clearly, comprehending covariance and its temporal and spatial dynamics is an essential prerequisite before quantifying the complex regulatory mechanisms governing ecosystem processes.

An emerging consensus in addressing multiple microclimatic factors is that each independent or interactive variable may vary in its importance as a driver, measured by its contribution to the total statistical variance. Drawing from 1119 global manipulative experiments on terrestrial carbon cycling, Song and colleagues concluded that carbon production and allocation are not equally influenced by temperature, precipitation, CO_2 enrichment, and nitrogen deposition, irrespective of their statistical significance. Crucially, they noted that the magnitude of their impact depends on the background climate and ecosystem condition (Song et al., 2019). Through simulation, Xia et al. (2023) quantified the contributions of atmospheric CO_2, temperature, precipitation, and radiation to resource availability and carbon allocation at a global scale. They observed contrasting effects of dominance on carbon allocations, with increased precipitation and CO_2 leading to significant reductions in light availability and increased carbon allocation to woody plant parts. Conversely, rising temperatures can diminish water availability, resulting in decreased carbon allocation to woody parts. All four environmental factors consistently exhibited negative effects on carbon allocation to roots, with increased precipitation causing the most substantial reduction in carbon allocation to them.

Employing artificial neural networks with 14 input variables from eddy-covariance flux towers, Moffat et al. (2010) investigated ecosystem responses to climatic variables, revealing PAR and diffuse radiation as the main variables for daytime flux, while VPD emerged as the most crucial non-radiative variable. More recently, Zou et al. (2024) utilized a gated recurrent unit (GRU) model with 28 potential drivers to simulate half-hourly net ecosystem exchange (NEE) of CO_2 using 12 years of continuous flux data from seven experimental bioenergy crops in southwest Michigan, USA. They analyzed the relative importance of biophysical variables and found that the contributions of individual variables appear more complex during the non-growing season, including incoming shortwave radiation, day of the year, temperature, Monin-Obukhov stability (i.e., effect of buoyancy on the turbulent flow of air near the object's surface), wind direction, and soil water content. Although the six most important forcing variables largely align with the literature (except wind direction), their ranked importance varied by ecosystem type and modeling scale. Across the Mongolia Plateau, Yuan et al. (2024) demonstrated that spring phenology, which directly affects ecosystem productivity, is determined by temperature in some parts of the plateau, but by precipitation in others. Similarly, complex microclimatic influences on peak growth and fall phenology were reported on the Mongolian Plateau and at high latitude regions (Bao et al., 2021). In water-limited, fire-dependent forests across California's Sierra Nevada, increases in water availability and PAR promote vigorous growth and increased resilience in restoration efforts (Meyer et al., 2007; Ma et al., 2010; Zald et al., 2022). These drivers and their relative importance, however, may differ in light-limited systems (Chen et al., 2004a; North et al., 2004). Clearly, the statistical regulatory powers of microclimatic variables on ecosystems are not uniform but vary by ecosystem, time, and the combination of all other drivers. It is worth reiterating the importance of emerging machine learning and other artificial intelligent methods (e.g., Bayesian statistics) in microclimate studies. These methods are particularly valuable for site selection at underrepresented locations (Chu et al., 2021), implementing QA/QC protocols such as data screening, outlier identification, and gap filling (Irvin et al., 2021), modeling spatiotemporal changes and aggregations (Saunder et al., 1998; Ouyang et al. 2014; Poe et al., 2020), and understanding their interactions with ecosystems (Knox et al., 2021; Zou et al., 2024).

Finally, understanding microclimatic controls and regulations of ecosystem processes requires exploration at appropriate scales and/or across multiple scales, particularly over time. In predicting forage yield in California, Murphy (1970) highlighted the significance of the initiation of fall forage growth, which depended on the first half-inch of effective rainfall in the fall, while the annual yield of this forage was influenced by the amount of precipitation received by the third week in November. Since then, numerous studies have underscored the importance of incorporating microclimatic statistics at the appropriate temporal and spatial scales. For instance, Ouyang et al. (2014) investigated the influences of PAR and air temperature on net ecosystem exchange of CO_2 over a 7-year period in oak openings located in Northwest Ohio. They observed that PAR was the primary driver at shorter time scales (e.g., hours, daily), whereas air temperature dominated NEE at seasonal-annual scales. Notably, PAR co-varied with NEE without time lag, while air temperature lagged behind PAR by 2–3 h during growing seasons. Using VPD as an example (see Fig. 6), ecosystem production and ET predictions would significantly differ if daily-to-monthly values were used instead of hourly VPD, or if VPD exceeded threshold values. Thus, utilizing microclimate information to generate summaries at the appropriate temporal scale is crucial for accurate forecasting and reducing model uncertainty. Moreover, employing microclimatic summaries at multiple scales (e.g., growing season length, growing degree days) is essential depending on the specific study objectives.

In recent years, vapor pressure deficit – a variable computed from air temperature and relative humidity – has garnered increasing recognition for its role in regulating processes related to plant physiology, soil dynamics, and ecosystem carbon/water cycling (e.g., Goetz et al., 1999; Chen et al., 2004a; Mu et al., 2007; Seager et al., 2015). In the realm of agricultural development, the Food and Agriculture Organization (FAO) employed the process-based Penman-Monteith equation to estimate reference evapotranspiration (ETo), which subsequently became the predominant algorithm in most earth system models. Central to ETo estimation is the slope of saturation vapor pressure (Δ), a fundamental parameter (Allen et al., 1994) resulting from linearization of the non-linear saturation vapor pressure curve, which allows substituting the surface temperature-based vapor pressure difference between surfaces and the atmosphere with the VPD. Recent endeavors have shifted the focus towards utilizing VPD as the primary driver in estimating actual evapotranspiration. In models concerning plant transpiration and photosynthesis, the original stomatal conductance (g_s) model proposed by Ball et al. (1987) has been revised, replacing Δ with VPD as the primary influencing factor (Leuning, 1995). Xu et al. (2024) have suggested that the global increase in VPD will intensify atmospheric demand for water vapor, thereby exacerbating aridity and drought conditions over land. More recently, Li et al. (2023) investigated the long-term changes in global GPP, ET, and water use efficiency (WUE). Their findings suggest that terrestrial ecosystem WUE, initially augmented by long-term increases in atmospheric CO_2 concentration and a warming climate, has reached saturation due to elevated VPD resulting from warming-induced effects. This elevation in VPD depresses photosynthesis while augmenting ET, ultimately leading to a saturation point in WUE.

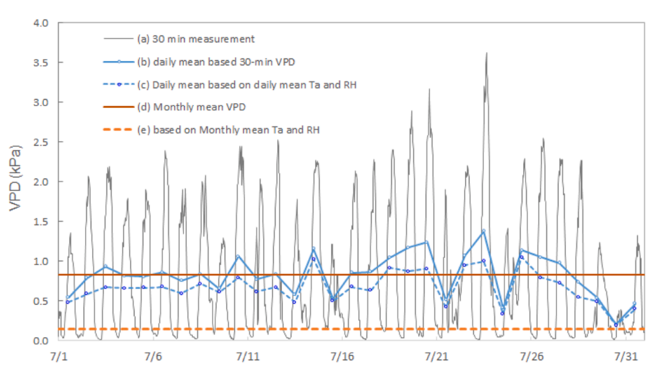

Fig. 6. Vapor Pressure Deficit (VPD, kPa) recorded by an eddy-covariance flux tower in a Switchgrass (*Panicum virgatum*) bioenergy crop field at the Kellogg Biological Station, Michigan, in July 2016. (a) VPD directly calculated from 30-minute air temperature (Ta, oC) and relative humidity (RH, %) measurements; (b) daily mean VPD of 30-minute measurements; and (c) daily VPD value computed from daily mean Ta and RH; (d) monthly mean VPD of 30-minute measurements; and (e) monthly VPD based on monthly mean Ta and RH.

Calculations of VPD, meanwhile, demand careful attention for proper applications. VPD is not a directly measured variable but instead is a calculated value from measurements of air temperature and relative humidity using non-linear saturation vapor pressure equations. Utilizing linear averages of daily, monthly, or annual temperature and relative humidity in these calculations – a practice that has been common, particularly in remote sensing and ecosystem modeling – can lead to distorted and biased VPD values (Mu et al., 2007). Complicating matters further, the primary effects of VPD occur during the day, coupled to its nonlinear relationship with temperature and humidity, making the use of averages at larger time scales inappropriate. As illustrated in Fig. 4, the 30-minute VPD data from July 2016 at a switchgrass field in southwest Michigan exhibited clear diel changes, with low values observed at nighttime and higher values during the day. There are many values exceeding 1.0–1.5 kPa when stomata begin to close, resulting in reduced photosynthesis and transpiration (Chen et al., 2002). However, the daily mean VPD for the month averaged at 0.828 kPa (range: 0.206 to 1.377 kPa), which might falsely suggest stress-free conditions for the plants. More concerning, the daily VPD calculated from daily mean air temperature and relative humidity was even lower, averaging at 0.670 kPa (range: 0.198 to 1.053 kPa), further downplaying the importance of VPD in modeling stomatal conductance. Additionally, when modeling is conducted at a monthly scale, the average VPD based on monthly mean air temperature and relative humidity drops significantly to 0.144 kPa, indicating an insignificant influence of VPD on photosynthesis, ET, and transpiration. Some authors have recognized these deficiencies and have opted to use daily maximum VPD values, although this approach may tend to overestimate the influence of VPD. In summary, it is crucial to employ relatively high-frequency (half-hourly and hourly) measurements of air temperature and relative humidity for calculating VPD, rather than relying on averaged values over longer time periods (daily, weekly, monthly, annual) (Fig. 4).

Spatially, microclimatic conditions beyond the boundaries of the studied ecosystem may play a crucial role in modeling ecosystem processes. In addition to the examples of edge effects discussed earlier in section 3, there are studies indicating distant effects as well. For instance, Brosofske et al. (1997) demonstrated a strong correlation between the temperature in small streams in western Washington and the soil temperature and moisture of uplands within the same watershed. In the Great Lakes region, water temperature of the lakes influences the microclimate (e.g., snowfall) of nearby lands through phenomena like lake effects, subsequently impacting plants, animals, and ecosystem processes (Fujisaki-Manome et al., 2017). In mountainous regions, temperatures and precipitation at high altitudes directly influence the microclimate of downstream water bodies, riparian zones, and soil moisture (Naiman et al., 1998). This effect is particularly pronounced in regions such as Central Asia and the European Alps, where snow melting serves as the primary water source for agriculture in lowlands (Lutz et al., 2014; Chersich et al., 2015). In summary, consideration of microclimatic influences on ecosystems should not be confined solely to in situ conditions but should also be considered within the context of multiple spatial scales.

1.4. Outlooks

Drawing upon over 100 years of scholarly work on microclimate, we present an overview of the critical issues surrounding the collection and utilization of microclimate records in ecosystem studies. We then delve into elucidating the structural influences on microclimate across both time and space, along with exploring their impacts on ecosystem processes and functions. We place particular emphasis on the importance of data quality assurance and quality control (QA/QC) in managing microclimatic records, highlighting their interdependent changes over time and space for various applications such as explorations of the feedback mechanisms between microclimate and ecosystems, construction of ecosystem models, and development of guidelines for ecosystem management. Throughout the review, we offer some relevant case studies from the extensive literature to exemplify these concepts, acknowledging biases toward terrestrial ecosystems and insights gained from our prior research. The scientific community is increasingly recognizing the crucial role of microclimates in advancing ecosystem science. Understanding these issues is essential for advancing microclimate research and fostering collaboration with other relevant disciplines. Here, we offer our perspectives on several key areas for future microclimate studies.

- Microclimate data should be collected and used in a way that aligns with the timing and location of ecological structures and processes. Mismatches in time (e.g., using daily mean temperature for instantaneous photosynthesis) or space (e.g., relying on data from a nearby weather station) can lead to unreliable, highly uncertain, or incorrect conclusions. This is evident in studies of microclimate across forest-open edges and in modeling fire spread, where in situ wind speed is influenced by tree clustering and microtopography.
- It is crucial to realize that feedback interactions between microclimate variables and ecosystem characteristics exist at multiple spatial and temporal scales. Both legacy effects over time and distance effects in space are common. These casual relationships and their importance nonetheless are difficult to disentangle due to their often absence in required databases and analytical methods.
- Traditional efforts to use microclimate data to model ecosystem processes and functions have focused on a few key variables (e.g., PAR, net radiation, VPD in modeling photosynthesis). It is important to recognize that these variables do not independently regulate ecological processes; rather, they are interdependent in time and space (i.e., correlated) and jointly cause changes in ecosystem processes. Attention should also be given to other variables, including those that may seem less important at first glance, before excluding them from investigations. Importantly, their significance can vary over time, across different spaces, and depending on the scale of the investigation.
- New technologies (e.g., remote sensing, smart wireless sensors, computational capabilities), the increasing number of microclimatic stations and datasets, and advanced analytical methods (e.g., Bayesian modeling, machine learning, big data analysis, network analysis, etc.) are emerging. These disruptive advancements have the potential to transform how microclimate research is conducted, addressing many of the issues discussed in this review.

CRediT authorship contribution statement

Jiquan Chen: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Kyaw Tha Paw U:** . **Malcolm North:** Writing – review & editing, Formal analysis, Data curation. **Jerry F. Franklin:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The original data for Figure 6 is available upon request and can be accessed through the AmeriFlux data portal.

Acknowledgments

We thank Dr. Yingping Wang's for his invitation to prepare a review for celebrating the 70th Anniversary of Agricultural and Forest Meteorology. Dr. Bruno Basso kindly shared drone-based measurements of land surface temperature at a scale-up plot of KBS. This material is based upon work supported by the Great Lakes Bioenergy Research Center, U. S. Department of Energy, Office of Science, Biological and Environmental Research Program under Award Number DE-SC0018409. Partial support for this research was provided by the National Science Foundation Long-term Ecological Research Program (DEB 2224712) at the Kellogg Biological Station, and by Michigan State University AgBioResearch. Other partial support came from USDA HatchProject CA-D-LAW-4526, and National Science Foundation (Grant No. 2124838).

References

Abraha, M., Chen, J., Hamilton, S.K., Sciusco, P., Lei, C., Shirkey, G., Robertson, G.P., 2021. Albedo-induced global warming impact of Conservation Reserve Program grasslands converted to annual and perennial bioenergy crops. Environ. Res. Lett. 16 (8), 084059.
Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994. An update for the definition of reference evapotranspiration. ICID bulletin 43 (2), 1–34.
Altmann, A., 2005. The treasure trove: judah Halevi's theory of climates. Aleph (5), 215–246.
Baker, T.P., Jordan, G.J., Steel, E.A., Fountain-Jones, N.M., Wardlaw, T.J., Baker, S.C., 2014. Microclimate through space and time: microclimatic variation at the edge of regeneration forests over daily, yearly and decadal time scales. For. Ecol. Manage. 334, 174–184.
Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Wofsy, S., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82 (11), 2415–2434.
Ball, J.T., Woodrow, I.E., Berry, J.A., 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Progress in Research: Proceedings of the VIIth International congress on photosynthesis providence, Rhode Island, USA. Springer Netherlands.
Bao, G., Jin, H., Tong, S., Chen, J., Huang, X., Bao, Y., Du, L., 2021. Autumn phenology and its covariation with climate, spring phenology and annual peak growth on the Mongolian plateau. Agric. For. Meteorol. 298, 108312.
Barry, R.G., Blanken, P.D., 2016. Microclimate and local climate. Cambridge University Press.
Bastos, A., Gouveia, C.M., Trigo, R.M., Running, S.W., 2014. Analysing the spatio-temporal impacts of the 2003 and 2010 extreme heatwaves on plant productivity in Europe. Biogeosciences. 11 (13), 3421–3435.
Bigelow, S.W., North, M.P., 2012. Microclimate effects of fuels-reduction and group-selection silviculture: implications for fire behavior in Sierran mixed-conifer forests. For. Ecol. Manage. 264, 51–59.
Black, T.A., Den Hartog, G., Neumann, H.H., Blanken, P.D., Yang, P.C., Russell, C., Novak, M.D., 1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. Glob. Chang. Biol. 2 (3), 219–229.
Bogner, C., Mirzaei, M., Ruy, S., Huwe, B., 2013. Microtopography, water storage and flow patterns in a fine-textured soil under agricultural use. Hydrol. Process. 27 (12), 1797–1806.
Bramer, I., Anderson, B.J., Bennie, J., Bladon, A.J., De Frenne, P., Hemming, D., Gillingham, P.K., 2018. Advances in monitoring and modelling climate at ecologically relevant scales. Adv. Ecol. Res. 58, 101–161.
Brosofske, K.D., Chen, J., Crow, T.R., 2001. Understory vegetation and site factors: implications for a managed Wisconsin landscape. For. Ecol. Manage. 146 (1–3), 75–87.
Brosofske, K.D., Chen, J., Crow, T.R., Saunders, S.C., 1999. Vegetation responses to landscape structure at multiple scales across a Northern Wisconsin, USA, pine barrens landscape. Plant Ecol. 143, 203–218.
Brosofske, K.D., Chen, J., Naiman, R.J., Franklin, J.F., 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecolog. Applicat. 7 (4), 1188–1200.
Bull, J.J., Vogt, R.C., 1979. Temperature-dependent sex determination in turtles. Science 206 (4423), 1186–1188.
Camuffo, D., 1998. MicroclIMATE FOR CULTURAL HERITage. Elsevier.
Campbell, G.S., Norman, J.M., 2000. An introduction to environmental biophysics. Springer Science & Business Media.

Canham, C.D., Denslow, J.S., Platt, W.J., Runkle, J.R., Spies, T.A., White, P.S., 1990. Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Canadian J. For. Res. 20 (5), 620–631.
Canham, C.D., Finzi, A.C., Pacala, S.W., Burbank, D.H., 1994. Causes and consequences of resource heterogeneity in forests: interspecific variation in light transmission by canopy trees. Canadian J. For. Res. 24 (2), 337–349.
Chamberlain, C.P., Cova, G.R., Cansler, C.A., North, M.P., Meyer, M.D., Jeronimo, S.M., Kane, V.R., 2023. Consistently heterogeneous structures observed at multiple spatial scales across fire-intact reference sites. For. Ecol. Manage. 550, 121478.
Chang, K.Y., Paw, U, K, T., Chen, S.H, 2018. Canopy profile sensitivity on surface layer simulations evaluated by a multiple canopy layer higher order closure land surface model. Agric. For. Meteorol. 252, 192–207.
Charnier, M., 1966. Action de la température sur la sex-ratio chez 164 Literature Cited l'embryon d'Agama agama (Agamidae: lacertilien). C. R. Séances Soc. Biol. *l'Ouest Africain* 160, 620–622.
Chazdon, R.L., Williams, K., Field, C.B., 1988. Interactions between crown structure and light environment in five rain forest Piper species. Am. J. Bot. 75 (10), 1459–1471.
Chen, J., 2021. Biophysical models and applications in ecosystem analysis. Michigan State University Press.
Chen, J., Falk, M., Euskirchen, E., Paw, U, K, T., Suchanek, T.H., Ustin, S.L., Bi, R, 2002. Biophysical controls of carbon flows in three successional Douglas-fir stands based on eddy-covariance measurements. Tree Physiol. 22 (2–3), 169–177.
Chen, J., Franklin, J.F., 1997. Growing-season microclimate variability within an old-growth Douglas-fir forest. Clim. Res. 8 (1), 21–34.
Chen, J., Franklin, J.F., Lowe, J.S., 1996. Comparison of abiotic and structurally defined patch patterns in a hypothetical forest landscape. Conservat. Biol. 10 (3), 854–862.
Chen, J., Franklin, J.F., Spies, T.A., 1992. Vegetation responses to edge environments in old-growth Douglas-fir forests. Ecolog. Applications 2 (4), 387–396.
Chen, J., Franklin, J.F., Spies, T.A., 1993a. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agric. For. Meteorol. 63 (3–4), 219–237.
Chen, J., Franklin, J.F., Spies, T.A., 1993b. An empirical model for predicting diurnal air-temperature gradients from edge into old-growth Douglas-fir forest. Ecol. Modell. 67 (2–4), 179–198.
Chen, J., Franklin, J.F., Spies, T.A., 1995. Growing-season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests. Ecolog. Applicat. 5 (1), 74–86.
Chen, J., Paw, U, K, T., Ustin, S.L., Suchanek, T.H., Bond, B.J., Brosofske, K.D., Falk, M, 2004a. Net ecosystem exchanges of carbon, water, and energy in young and old-growth Douglas-fir forests. Ecosystems. 7, 534–544.
Chen, J., Saunders, S.C., Crow, T.R., Naiman, R.J., Brosofske, K.D., Mroz, G.D., Franklin, J.F., 1999. Microclimate in forest ecosystem and landscape ecology: variations in local climate can be used to monitor and compare the effects of different management regimes. Bioscience 49 (4), 288–297.
Chen, J., Song, B., Rudnicki, M., Moeur, M., Bible, K., North, M., Braun, D.M., 2004b. Spatial relationship of biomass and species distribution in an old-growth *Pseudotsuga-Tsuga* forest. Forest Sci. 50 (3), 364–375.
Chen, J., Zhu, L., Fan, P., Tian, L., Lafortezza, R., 2016. Do green spaces affect the spatiotemporal changes of PM2. 5 in Nanjing? Ecol. Process. 5 (1), 1–13.
Chen, J.M., Black, T.A., 1992. Foliage area and architecture of plant canopies from sunfleck size distributions. Agric. For. Meteorol. 60 (3–4), 249–266.
Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437 (7058), 529–533.
Chersich, S., Rejšek, K., Vranová, V., Bordoni, M., Meisina, C., 2015. Climate change impacts on the Alpine ecosystem: an overview with focus on the soil-a review. Journal of Forest Science 61 (11), 496–514.
Chu, H., Luo, X., Ouyang, Z., Chan, W.S., Dengel, S., Biraud, S.C., Zona, D., 2021. Representativeness of Eddy-Covariance flux footprints for areas surrounding AmeriFlux sites. Agric. For. Meteorol. 301, 108350.
Churchill, D.J., Larson, A.J., Dahlgreen, M.C., Franklin, J.F., Hessburg, P.F., Lutz, J.A., 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. For. Ecol. Manage. 291, 442–457.
Cleugh, H.A., 1998. Effects of windbreaks on airflow, microclimates and crop yields. Agrofor. Syst. 41, 55–84.
Concilio, A., Chen, J., Ma, S., North, M., 2009. Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate, mixed-conifer forest. Clim. Change 92, 109–122.
Crasnow, S. (2009). Feminist perspectives on science. *the stanford encyclopedia of philosophy;* https://plato.stanford.edu/archives/fall2023/entries/feminist-science/.
De Boeck, H.J., Dreesen, F.E., Janssens, I.A., Nijs, I., 2010. Climatic characteristics of heat waves and their simulation in plant experiments. Glob. Chang. Biol. 16 (7), 1992–2000.
DeForest, J.L., Chen, J., McNulty, S.G., 2009. Leaf litter is an important mediator of soil respiration in an oak-dominated forest. Int. J. Biometeorol. 53, 127–134.
De Frenne, P., Zellweger, F., Rodríguez-Sánchez, F., Scheffers, B.R., Hylander, K., Luoto, M., Lenoir, J., 2019. Global buffering of temperatures under forest canopies. Nat. Ecol. Evol. 3 (5), 744–749.
De Pauw, K., Sanczuk, P., Meeussen, C., Depauw, L., De Lombaerde, E., Govaert, S., De Frenne, P., 2022. Forest understorey communities respond strongly to light in interaction with forest structure, but not to microclimate warming. New Phytologist 233 (1), 219–235.
Dhar, A., Forsch, K.B., Naeth, M.A., 2022. Effects of coarse woody debris on soil temperature and water content in two reconstructed soils in reclaimed boreal forest. Soil. Syst. 6 (3), 62. https://doi.org/10.3390/soilsystems6030062.
Diamond, J.M., 1997. *Guns, Germs and Steel: The Fates of Human Societies*. Vintage, p. 186.
Earles, J.M., Stevens, J.T., Sperling, O., Orozco, J., North, M.P., Zwieniecki, M.A., 2018. Extreme mid-winter drought weakens tree hydraulic–carbohydrate systems and slows growth. New Phytologist 219 (1), 89–97.
Erell, E., Pearlmutter, D., Williamson, T., 2012. Urban microclimate: designing the spaces between buildings. Routledge.
Farquhar, G.D., von Caemmerer, S.V., Berry, J.A., 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C 3 species. Planta 149, 78–90.
Fee, E., 1982. A feminist critique of scientific objectivity. Sci. People 14 (4), 5–8.
Fettig, C.J., Mortenson, L.A., Bulaon, B.M., Foulk, P.B., 2019. Tree mortality following drought in the central and southern Sierra Nevada, 432. Forest Ecology and Management, California, US, pp. 164–178.
Fletcher Jr, R.J., 2005. Multiple edge effects and their implications in fragmented landscapes. J. Animal Ecol. 74 (2), 342–352.
Franklin, T.B., 1955. Climates in miniature. a study of micro-climate and environment. Literary Licensing.
Fritschen, L.J., Gay, L.W., 1979. Environmental instrumentation. Springer Verlag, New York.
Fry, D.L, Stephens, S.L., Collins, B.M., North, M.P., Franco-Vizcaino, E., Gill, S.J., 2014. Contrasting spatial patterns in active-fire and fire-suppressed Mediterranean climate old-growth, mixed conifer forests. PLoS. One. https://doi.org/10.1371/journal.pone.0088985.
Fujisaki-Manome, A., Fitzpatrick, L.E., Gronewold, A.D., Anderson, E.J., Lofgren, B.M., Spence, C., Xiao, C., 2017. Turbulent heat fluxes during an extreme lake-effect snow event. J. Hydrometeorol. 18 (12), 3145–3163.
Geiger, R., 1965. The climate near the ground. Harvard University Press, Cambridge (MA).
Goetz, S.J., Prince, S.D., Goward, S.N., Thawley, M.M., Small, J., 1999. Satellite remote sensing of primary production: an improved production efficiency modeling approach. Ecol. Modell. 122 (3), 239–255.
Gray, A.N., Spies, T.A., Easter, M.J., 2002. Microclimatic and soil moisture responses to gap formation in coastal Douglas-fir forests. Canadian J. For. Res. 32 (2), 332–343.
Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T., McDowell, N.G., 2020. Plant responses to rising vapor pressure deficit. New Phytologist 226 (6), 1550–1566.
Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. Soc. Sci. Med. 63 (11), 2847–2863.
Harmon, M.E., Hua, C., 1991. Coarse woody debris dynamics in two old-growth ecosystems. Bioscience 41 (9), 604–610.
Harper, K.A., Macdonald, S.E., Burton, P.J., Chen, J., Brosofske, K.D., Saunders, S.C., Esseen, P.A., 2005. Edge influence on forest structure and composition in fragmented landscapes. Conservat. Biol. 19 (3), 768–782.
Hartwig, N.L., Ammon, H.U., 2002. Cover crops and living mulches. Weed Sci. 50 (6), 688–699.
Haynes, K., T. Cronin, J., 2006. Interpatch movement and edge effects: the role of behavioral responses to the landscape matrix. Oikos. 113 (1), 43–54.
Heithecker, T.D., Halpern, C.B., 2006. Variation in microclimate associated with dispersed-retention harvests in coniferous forests of western Washington. For. Ecol. Manage. 226 (1–3), 60–71.
Hernandez, J., 2022. Fresh banana leaves: healing indigenous landscapes through indigenous science. North Atlantic Books.
Heymann, M., 2010. The evolution of climate ideas and knowledge. Climate Change 1 (4), 581–597.
Hofmeister, J., Hošek, J., Brabec, M., Střalková, R., Mýlová, P., Bouda, M., Svoboda, M., 2019. Microclimate edge effect in small fragments of temperate forests in the context of climate change. For. Ecol. Manage. 448, 48–56.
Innes, J.C., North, M.P., Williamson, N., 2006. Effect of thinning and prescribed fire restoration treatments on woody debris and snag dynamics in a Sierran old-growth, mixed-conifer forest. Canadian J. For. Res. 36 (12), 3183–3193.
Imber, B., Tuana, N., 1988. Feminist perspectives on science. Hypatia 3 (1), 139–155.
Iqbal, R., Raza, M.A.S., Valipour, M., Saleem, M.F., Zaheer, M.S., Ahmad, S., Nazar, M.A., 2020. Potential agricultural and environmental benefits of mulches—a review. Bull. Natl. Res. Cent. 44 (1), 1–16.
Irvin, J., Zhou, S., McNicol, G., Lu, F., Liu, V., Fluet-Chouinard, E., Jackson, R.B., 2021. Gap-filling eddy covariance methane fluxes: comparison of machine learning model predictions and uncertainties at FLUXNET-CH_4 wetlands. Agric. For. Meteorol. 308, 108528.
Jabran, K., Jabran, K., 2019. Mulches for regulation of soil temperature. Rolef Mulch. Pest Manage. Agricult. Sustain. 47–52.
Janzen, F.J., 1994. Climate change and temperature-dependent sex determination in reptiles. Proceed. Nat. Acad. Sci. 91 (16), 7487–7490.
Jarvis, P., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philosoph. Transact. Royal Soc.London. B, Biolog. Sci. 273 (927), 593–610.
John, R., Chen, J., Ou-Yang, Z.T., Xiao, J., Becker, R., Samanta, A., Batkhishig, O., 2013. Vegetation response to extreme climate events on the Mongolian Plateau from 2000 to 2010. Environ. Res. Lett. 8 (3), 035033.
Johnson, D.W., Miller, W.W., Susfalk, R.B., Murphy, J.D., Dahlgren, R.A., Glass, D.W., 2009. Biogeochemical cycling in forest soils of the eastern Sierra Nevada Mountains, USA. For. Ecol. Manage. 258 (10), 2249–2260.
Johnson, D.W., Turner, J., 2019. Tamm Review: nutrient cycling in forests: a historical look and newer developments. For. Ecol. Manage. 444, 344–373.
Jones, M.B., 1985. Plant microclimate. Techniques in bioproductivity and photosynthesis. Pergamon, pp. 26–40.
Kemppinen, J., Lembrechts, J.J., Van Meerbeek, K., Carnicer, J., Chardon, N.I., Kardol, P., De Frenne, P., 2024. Microclimate, an important part of ecology and biogeography. Global Ecol. Biogeogr. e13834.

Kiladis, G.N., Diaz, H.F., 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. J Clim 2 (9), 1069–1090.

Kim, S., Dale, B.E., Jenkins, R., 2009. Life cycle assessment of corn grain and corn stover in the United States. Int. J. Life Cycle Assess. 14, 160–174.

Knapp, E.E., Bernal, A.A., Kane, J.M., Fettig, C.J., North, M.P., 2021. Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. In: For. Ecol. Manage., 479, 118595.

Knox, S.H., Bansal, S., McNicol, G., Schafer, K., Sturtevant, C., Ueyama, M., Jackson, R. B., 2021. Identifying dominant environmental predictors of freshwater wetland methane fluxes across diurnal to seasonal time scales. Glob. Chang. Biol. 27 (15), 3582–3604.

Koontz, M.J., North, M.P., Werner, C.M., Rick, S.E., Latimer, A.M., 2020. Local forest structure variability increases resilience to wildfire in dry western U.S. coniferous forests. Ecol. Lett. 23, 483–494.

Körner, C., Möhl, P., Hiltbrunner, E., 2023. Four ways to define the growing season. Ecol. Lett. 26, 1277–1292.

Laurance, W.F., 1991. Edge effects in tropical forest fragments: application of a model for the design of nature reserves. Biol. Conserv. 57 (2), 205–219.

Lei, C., Chen, J., Robertson, G.P., 2023. Climate cooling benefits of cellulosic bioenergy crops from elevated albedo. Global Change Biol. - Bioenergy 15 (11), 1373–1386.

Leuchner, M., Hertel, C., Menzel, A., 2011. Spatial variability of photosynthetically active radiation in European beech and Norway spruce. Agric. For. Meteorol. 151 (9), 1226–1232.

Leuning, R., 1995. A critical appraisal of a combined stomatal-photosynthesis model for C3 plants. Plant Cell Environ. 18 (4), 339–355.

Li, F., Xiao, J., Chen, J., Ballantyne, A., Jin, K., Li, B., John, R., 2023. Global water use efficiency saturation due to increased vapor pressure deficit. Science 381 (6658), 672–677.

Li, Q., Chen, J., Song, B., LaCroix, J.J., Bresee, M.K., Radmacher, J.A., 2007. Areas influenced by multiple edges and their implications in fragmented landscapes. For. Ecol. Manage. 242 (2–3), 99–107.

Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agric. For. Meteorol. 144 (1–2), 85–94.

Lutz, A.F., Immerzeel, W.W., Shrestha, A.B., Bierkens, M.F.P., 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nat. Clim. Chang. 4 (7), 587–592.

Ma, S., Chen, J., Butnor, J.R., North, M., Euskirchen, E.S., Oakley, B., 2005. Biophysical controls on soil respiration in the dominant patch types of an old-growth, mixed-conifer forest. Forest Sci. 51 (3), 221–232.

Ma, S., Concilio, A., Oakley, B., North, M., Chen, J., 2010. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. For. Ecol. Manage. 259 (5), 904–915.

MacKinney, A.L., 1929. Effects of forest litter on soil temperature and soil freezing in autumn and winter. Ecology. 10 (3), 312–321.

Matsuo, T., Martínez-Ramos, M., Bongers, F., van der Sande, M.T., Poorter, L., 2021. Forest structure drives changes in light heterogeneity during tropical secondary forest succession. J. Ecol. 109 (8), 2871–2884.

Maclean, I.M., Duffy, J.P., Haesen, S., Govaert, S., De Frenne, P., Vanneste, T., Van Meerbeek, K., 2021a. On the measurement of microclimate. Methods Ecol. Evol. 12 (8), 1397–1410.

Matlack, G.R., 1993. Microenvironment variation within and among forest edge sites in the eastern United States. Biol. Conserv. 66 (3), 185–194.

Matthews, H.A., 1937. Reality in climate: the results of recent microclimatological studies, with special reference to temperatures. Geography. 87–100.

Maclean, I.M., Duffy, J.P., Haesen, S., Govaert, S., De Frenne, P., Vanneste, T., Van Meerbeek, K., 2021b. On the measurement of microclimate. Methods Ecol. Evol. 12 (8), 1397–1410.

Meeussen, C., Govaert, S., Vanneste, T., Bollmann, K., Brunet, J., Calders, K., De Frenne, P., 2021. Microclimatic edge-to-interior gradients of European deciduous forests. Agric. For. Meteorol. 311, 108699.

Melloh, R.A., Hardy, J.P., Davis, R.E., Robinson, P.B., 2001. Spectral albedo/reflectance of littered forest snow during the melt season. Hydrol. Process. 15 (18), 3409–3422.

Meyer, M.D., North, M.P., Gray, A.N., Zald, H.S., 2007. Influence of soil thickness on stand characteristics in a Sierra Nevada mixed-conifer forest. Plant Soil. 294, 113–123.

Meyers, T.P., Paw, U, 1987. Modelling the plant canopy micrometeorology with higher-order closure principles. Agric. For. Meteorol. 41 (1–2), 143–163.

Michaelis, L, Menten, MI, 1913. Die Kinetik der Invirtinwirkung. Biochem. Z. 49, 333–369.

Moffat, A.M., Beckstein, C., Churkina, G., Mund, M., Heimann, M., 2010. Characterization of ecosystem responses to climatic controls using artificial neural networks. Glob. Chang. Biol. 16 (10), 2737–2749.

Monteith, J.L., 1965. Evaporation and environment. In: Symposia of the society for experimental biology, 19. Cambridge University Press, Cambridge, pp. 205–234.

Moritz, M.A., Batllori, E., Bradstock, R.A., Gill, A.M., Handmer, J., Hessburg, P.F., Syphard, A.D., 2014. Learning to coexist with wildfire. Nature 515 (7525), 58–66.

Mu, Q., Zhao, M., Heinsch, F.A., Liu, M., Tian, H., Running, S.W., 2007. Evaluating water stress controls on primary production in biogeochemical and remote sensing based models. Biogeosciences 112 (G1).

Murphy, A.H., 1970. Predicted forage yield based on fall precipitation in California annual grasslands. J. Range Manage. 23 (5), 363–365.

Myint, S.W., Zheng, B., Talen, E., Fan, C., Kaplan, S., Middel, A., Brazel, A., 2015. Does the spatial arrangement of urban landscape matter? Examples of urban warming and cooling in Phoenix and Las Vegas. Ecosys. Health Sustain. 1 (4), 1–15.

Naiman, R.J., Fetherston, K.L., McKay, S.J., Chen, J., 1998. Riparian forests. River Ecol. Manage. 289–323.

National Research Council, 2010. Understanding climate's influence on human evolution. National Academies Press, Washington D.C.

Norman, J.M., 1979. Modeling the complete crop canopy. Modification of the aerial environment of crops. American Society of Agricultural and Biological Engineers Monograph, pp. 249–277.

Norman, J.M., Miller, E.E., Tanner, C.B., 1971. Light intensity and sunfleck-size distributions in plant canopies 1. Agron. J. 63 (5), 743–748.

North, M., Chen, J., Oakley, B., Song, B., Rudnicki, M., Gray, A., Innes, J., 2004. Forest stand structure and pattern of old-growth western hemlock/Douglas-fir and mixed-conifer forests. Forest Sci. 50 (3), 299–311.

North, M., Oakley, B., Fiegener, R., Gray, A., Barbour, M., 2005. Influence of light and soil moisture on Sierran mixed-conifer understory communities. Plant Ecol. 177, 13–24.

North, M., Stine, P., O'Hara, K., Zielinski, W., & Stephens, S. (2009). An ecosystem management strategy for Sierran mixed-conifer forests. *General Technical Report PSW-GTR-220, 49*.

North, M.P., Stevens, J.T., Greene, D.F., Coppoletta, M., Knapp, E.E., Latimer, A.M., Wyrsch, P., 2019. Tamm Review: reforestation for resilience in dry western US forests. In: For. Ecol. Manage., 432, pp. 209–224.

North, M.P., Tompkins, R.E., Bernal, A.A., Collins, B.M., Stephens, S.L., York, R.A., 2022. Operational resilience in western US frequent-fire forests. In: For. Ecol. Manage., 507, 120004.

O`Brien, P.L., Sauer, T.J., Archontoulis, S., Karlen, D.L., Laird, D., 2020. Corn stover harvest reduces soil CO_2 fluxes but increases overall C losses. Global Change Biol. - Bioenergy 12 (11), 894–909.

Ogée, J., Brunet, Y., 2002. A forest floor model for heat and moisture including a litter layer. J Hydrol 255 (1–4), 212–233.

Odriozola, I., García-Baquero, G., Laskurain, N.A., Aldezabal, A., 2014. Livestock grazing modifies the effect of environmental factors on soil temperature and water content in a temperate grassland. Geoderma 235, 347–354.

Ouyang, Z., Chen, J., Becker, R., Chu, H., Xie, J., Shao, C., John, R., 2014. Disentangling the confounding effects of PAR and air temperature on net ecosystem exchange at multiple time scales. Ecolg. Complex. 19, 46–58.

Paw, U, 2002. Soil-plant-atmosphere models. Advanced short course on agricultural, forest and micro meteorology. Bologna, Italy, pp. 140–152.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proceed. Royal Soc. London. Series A. Math. Phys. Sci. 193 (1032), 120–145.

Poe, J., Reed, D.E., Abraha, M., Chen, J., Dahlin, K.M., Desai, A.R., 2020. Geospatial coherence of surface-atmosphere fluxes in the upper Great Lakes region. Agric. For. Meteorol. 295, 108188.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather. Rev. 100 (2), 81–92.

Pyles, R.D., Falk, M., 2004. Directional wind shear within an old-growth temperate rainforest: observations and model results. Agric. For. Meteorol. 125 (1–2), 19–31.

Pyles, R.D., Weare, B.C., Pawu, K.T., 2000. The UCD advanced canopy-atmosphere-soil algorithm: comparisons with observations from different climate and vegetation regimes. Quart. J. Royal Meteorolog. Soc. 126 (569), 2951–2980.

Potter, K.A., Arthur Woods, H., Pincebourde, S, 2013. Microclimatic challenges in global change biology. Glob. Chang. Biol. 19 (10), 2932–2939.

Qu, L.P., Chen, J., Xiao, J., De Boeck, H.J., Dong, G., Jiang, S.C., Shao, C.L., 2023. The complexity of heatwaves impact on terrestrial ecosystem carbon fluxes: factors, mechanisms and a multi-stage analytical approach. Environ. Res., 117495

Rambo, T.R., North, M.P., 2008. Spatial and temporal variability of canopy microclimate in a Sierra Nevada riparian forest. Northwest Sci. 82 (4), 259–268.

Rambo, T.R., North, M.P., 2009. Canopy microclimate response to pattern and density of thinning in a Sierra Nevada forest. For. Ecol. Manage. 257 (2), 435–442.

Reichstein, M., Rey, A., Freibauer, A., Tenhunen, J., Valentini, R., Banza, J., Yakir, D., 2023. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices. Global. Biogeochem. Cycles. 17 (4).

Rillig, M.C., Ryo, M., Lehmann, A., Aguilar-Trigueros, C.A., Buchert, S., Wulf, A., Yang, G., 2019. The role of multiple global change factors in driving soil functions and microbial biodiversity. Science 366 (6467), 886–890.

Ritter, S.M., Hoffman, C.M., Battaglia, M.A., Linn, R., Mell, W.E., 2023. Vertical and horizontal crown fuel continuity influences group-scale ignition and fuel consumption. Fire 6 (8), 321.

Ritter, S.M., Hoffman, C.M., Battaglia, M.A., Stevens-Rumann, C.S., Mell, W.E., 2020. Fine-scale fire patterns mediate forest structure in frequent-fire ecosystems. Ecosphere 11 (7), e03177.

Rosenberg, N.J., Blad, B.L., Verma, S.B., 1983. Microclimate: the biological environment. John Wiley & Sons.

Rotach, M.W., Calanca, P., 2003. Microclimate. Encyclopaed. Atmospheric Sci. 1301–1307.

Roussakov, L.F. (1924). Peculiarities of the microclimate in the midst of plants in connexion with the development of cereal rusts. *Congress in Moscow, 8th to 14th Dec.*, 201-216.

Ryu, S.R., Concilio, A., Chen, J., North, M., Ma, S., 2009. Prescribed burning and mechanical thinning effects on belowground conditions and soil respiration in a mixed-conifer forest, California. For. Ecol. Manage. 257 (4), 1324–1332.

Sayer, E.J., 2006. Using experimental manipulation to assess the roles of leaf litter in the functioning of forest ecosystems. Biolog. Rev. 81 (1), 1–31.

Saunders, S.C., Chen, J., Crow, T.R., Brosofske, K.D., 1998. Hierarchical relationships between landscape structure and temperature in a managed forest landscape. Landsc. Ecol. 13, 381–395.

Saunders, S.C., Chen, J., Drummer, T.D., Crow, T.R., 1999. Modeling temperature gradients across edges over time in a managed landscape. For. Ecol. Manage. 117 (1–3), 17–31.

Shanks, R.E., Norris, F.H., 1950. Microclimatic variation in a small valley in eastern Tennessee. Ecology. 31 (4), 532–539.

Shao, C., Chen, J., Li, L., Dong, G., Han, J., Abraha, M., John, R., 2017. Grazing effects on surface energy fluxes in a desert steppe on the Mongolian Plateau. Ecolog. Applicat. 27 (2), 485–502.

Seager, R., Hooks, A., Williams, A.P., Cook, B., Nakamura, J., Henderson, N., 2015. Climatology, variability, and trends in the US vapor pressure deficit, an important fire-related meteorological quantity. J. Appl. Meteorol. Climatol. 54 (6), 1121–1141.

Shiflett, S.A., Liang, L.L., Crum, S.M., Feyisa, G.L., Wang, J., Jenerette, G.D., 2017. Variation in the urban vegetation, surface temperature, air temperature nexus. Sci. Total Environm. 579, 495–505.

Sieber, P., Böhme, S., Ericsson, N., Hansson, P.A., 2022. Albedo on cropland: field-scale effects of current agricultural practices in Northern Europe. Agric. For. Meteorol. 321, 108978.

Skhosana, F.V., Thenga, H.F., Mateyisi, M.J., von Maltitz, G., Midgley, G.F., Stevens, N., 2023. Steal the rain: interception loses and rainfall partitioning by a broad-leaf and a fine-leaf woody encroaching species in a southern African semi-arid savanna. Ecol. Evol. 13 (3), e9868.

Song, J., Wan, S., Piao, S., Knapp, A.K., Classen, A.T., Vicca, S., Zheng, M., 2019. A meta-analysis of 1,119 manipulative experiments on terrestrial carbon-cycling responses to global change. Nat. Ecol. Evol. 3 (9), 1309–1320.

Standora, E.A., Spotila, J.R., 1985. Temperature dependent sex determination in sea turtles. Copeia 711–722.

Staudt, K., Falge, E., Pyles, R.D., Paw, U, K, T., Foken, T, 2010. Sensitivity and predictive uncertainty of the ACASA model at a spruce forest site. Biogeosciences. 7 (11), 3685–3705.

Stephens, S.L., Thompson, S., Boisramé, G., Collins, B.M., Ponisio, L.C., Rakhmatulina, E., Wilkin, K., 2021. Fire, water, and biodiversity in the Sierra Nevada: a possible triple win. Environ. Res. Commun. 3 (8), 081004.

Stevens, J.T., 2017. Scale-dependent effects of post-fire canopy cover on snowpack depth in montane coniferous forests. Ecolog. Applicat. 27, 1888–1900.

Templer, P.H., Reinmann, A.B., 2011. Multi-factor global change experiments: what have we learned about terrestrial carbon storage and exchange? New Phytol. 192 (4), 797–800.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38 (1), 55–94.

Townsend, D.E., Fuhlendorf, S.D., 2010. Evaluating relationships between spatial heterogeneity and the biotic and abiotic environments. Am. Midl. Nat. 163 (2), 351–365.

Unwin, D.M., 1980. Microclimate measurement for ecologists. Academic Press Inc.

Valenzuela, N., Lance, V. (Eds.), 2004. Temperature-dependent sex determination in vertebrates. Smithsonian Books, Washington, DC, pp. 1–194.

Van de Water, K., North, M., 2011. Stand structure, fuel loads, and fire behavior in riparian and upland forests, Sierra Nevada Mountains, USA; a comparison of current and reconstructed conditions. For. Ecol. Manage. 262 (2), 215–228.

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

Van't Hoff, J.H., Hoff, J.H., 1884. Etudes De Dynamique Chimique. F. Muller & Company.

Waggoner, P.E., Reifsnyder, W.E., 1968. Simulation of the temperature, humidity and evaporation profiles in a leaf canopy. J. Appl. Meteorol. Climatol. 7 (3), 400–409.

Waring, R.H., Running, S.W., 2010. Forest Ecosystems: Analysis at Multiple Scales. Elsevier.

Warneke, C.R., Caughlin, T.T., Damschen, E.I., Haddad, N.M., Levey, D.J., Brudvig, L.A., 2022. Habitat fragmentation alters the distance of abiotic seed dispersal through edge effects and direction of dispersal. Ecology. 103 (2), 2022, e03586.

Weathers, K.C., Cadenasso, M.L., Pickett, S.T., 2001. Forest edges as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere. Conservat. Biol. 15 (6), 1506–1514.

Webster, C., Rutter, N., Zahner, F., Jonas, T., 2016. Measurement of incoming radiation below forest canopies: a comparison of different radiometer configurations. J. Hydrometeorol. 17 (3), 853–864.

WMO (1993). *Instruments and observing methods*. World Meteorological Organization Report No. 55. Geneva, Switzerland. 58 pp.

WMO (2021). *Guide to Instruments and Methods of Observation, Volume 1*. World Meteorological Organization, WMO No. 8. Geneva, Switzerland. 559 pp.

Wolfe, J.N., 1951. The possible role of microclimate. Ohio J. Sci. 51 (3), 134–138.

Wolfe, J.N., Wareham, R.T., Scofield, H.T., 1949. Microclimates and macroclimate of Neotoma, a small valley in central Ohio. Ohio Biolog. Surv. 8, 1–267.

Wolfe, J.N., Wareham, R.T., Scofield, H.T., Transeau, E.N., 1943. The microclimates of a small valley in central Ohio. Eos, Transact. Am. Geophys. Union 24 (1), 154–166.

Xia, J., Chen, Y., Yuan, W., Wang, Y.P., 2023. The effects of multiple environmental factors on global carbon allocation. Ecol. Process. 12 (1), 60.

Xie, J., Chen, J., Sun, G., Zha, T., Yang, B., Chu, H., Ouyang, Z., 2016. Ten-year variability in ecosystem water use efficiency in an oak-dominated temperate forest under a warming climate. Agric. For. Meteorol. 218, 209–217.

Xu, L., Pyles, R.D., Paw, U, K, T., Chen, S.H., Monier, E, 2014. Coupling the high-complexity land surface model ACASA to the mesoscale model WRF. Geosci. Model. Dev. 7 (6), 2917–2932.

Xu, L., Pyles, R.D., Snyder, R., Monier, E., Falk, M., Chen, S.H., 2017. Impact of canopy representations on regional modeling of evapotranspiration using the WRF-ACASA coupled model. Agric. For. Meteorol. 247, 79–92.

Xu, M., Chen, J., Brookshire, B.L., 1997. Temperature and its variability in oak forests in the southeastern Missouri Ozarks. Clim. Res. 8 (3), 209–223.

Xu, M., Chen, J., Qi, Y., 2002. Growing-season temperature and soil moisture along a 10 km transect across a forested landscape. Clim. Res. 22 (1), 57–72.

Xu, W., Xia, X., Piao, S., Wu, D., Li, W., Yang, S., Yuan, W., 2024. Weakened increase in global near-surface water vapor pressure during the last 20 years. Geophys. Res. Lett. 51 (2), e2023GL107909.

Yan, Y., Yan, R., Chen, J., Xin, X., Eldridge, D.J., Shao, C., Xu, L., 2018. Grazing modulates soil temperature and moisture in a Eurasian steppe. Agric. For. Meteorol. 262, 157–165.

Yu, Y., Zhu, J., Gao, T., Liu, L., Yu, F., Zhang, J., Wei, X., 2022. Evaluating the influential variables on rainfall interception at different rainfall amount levels in temperate forests. J Hydrol 615, 128572.

Yuan, Z., Bao, G., Dorjsuren, A., Oyont, A., Chen, J., Li, F., Du, L., 2024. Climatic constraints of spring phenology and its variability on the Mongolian Plateau from 1982 to 2021. Biogeosciences 129 (2), e2023JG007689.

Zald, H.S., Callahan, C.C., Hurteau, M.D., Goodwin, M.J., North, M.P., 2022. Tree growth responses to extreme drought after mechanical thinning and prescribed fire in a Sierra Nevada mixed-conifer forest, USA. For. Ecol. Manage. 510, 120107.

Zenone, T., Chen, J., Deal, M.W., Wilske, B., Jasrotia, P., Xu, J., Philip Robertson, G., 2011. CO_2 fluxes of transitional bioenergy crops: effect of land conversion during the first year of cultivation. Global Change Biol. - Bioenergy 3 (5), 401–412.

Zheng, D., Chen, J., Song, B., Xu, M., Sneed, P., Jensen, R., 2000. Effects of silvicultural treatments on summer forest microclimate in southeastern Missouri Ozarks. Clim. Res. 15 (1), 45–59.

Zheng, D., Chen, J., 2000. Edge effects in fragmented landscapes: a generic model for delineating area of edge influences (D-AEI). Ecol. Modell. 132 (3), 175–190.

Zhu, Q., Chen, J., Wu, L., Huang, Y., Shao, C., Dong, G., Li, X., 2024. Changes in albedo and its radiative forcing of grasslands in East Asia drylands. Ecol. Process. 13 (1), 1–15.

Ziegler, J.P., Hoffman, C., Battaglia, M., Mell, W., 2017. Spatially explicit measurements of forest structure and fire behavior following restoration treatments in dry forests. For. Ecol. Manage. 386, 1–12.

Zou, H., Chen, J., Shao, C., Dong, G., Duan, M., Zhu, Q., Li, X., 2022. Model selection for ecosystem respiration needs to be site specific: lessons from grasslands on the Mongolian Plateau. Land. 11 (1), 87.

Zou, H., Chen, J., Li, X., Abraha, M., Zhao, Z., Tang, J., 2024. Modeling net ecosystem exchange of CO_2 with gated recurrent unit neural networks. Agric. For. Meteorol. *Vol*.