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Review

Review of microclimate mapping methods in forestry

Revisión de métodos de mapeo de microclimas en el ámbito forestal

Revisão de métodos de mapeamento de microclimas no ambiente florestal

Manuel Sánchez-Chero[1*]
José Antonio Sánchez-Chero[2]
Lesly Carolina Flores-Mendoza[3]
Felix Navarro Janampa[4]
Devyn Omar Donayre Hernández[4]
Mary Flor Cesare Coral[5]

[1]Facultad de Ingeniería de Industrias Alimentarias y Biotecnología, Universidad Nacional de Frontera. Sullana, Perú.
[2]Facultad de Facultad de Ciencias Económicas y Ambientales, Universidad Nacional de Frontera, Sullana, Perú.
[3]Universidad Nacional de Frontera, Sullana, Perú.
[4]Universidad Nacional de Ucayali, Ucayali, Perú.
[5]Departamento de Química de la Universidad Nacional Agraria La Molina, Lima, Perú.

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Abstract

The study of microclimates provides a several benefits that imply their importance to reduce the effects of climate change, so the mapping of microclimates emerges as an alternative for their identification and conservation. The objective of this review is to identify the techniques used in microclimate mapping. The methodology used was an exploratory review in databases such as Science Direct, Springer and IEEXplore, which determined that there is a shortage of works related to microclimate mapping, since only 19 works met the inclusion requirements of the review. It was determined that the main objective of the microclimate mapping focused on the tree canopy, the height and density of the forest structures and their effects on the climatic factors that comprise them. On the other hand, the microclimate mapping methods identified were divided into photogrammetric methods and laser scanning methods, where most of the studies were based on obtaining aerial data, either by drones (UAV, UAS, RPA, RPAS) or airplanes as in the case of airborne LiDAR technologies. It was concluded that there is little research on microclimate mapping, so the forestry scientific community is exhorted to employ the different methodologies for objectives of great impact on the environment such as the prediction of forest fires and the monitoring of forest restoration after these fires.

*Corresponding author:msanchezch@unf.edu.pe

Resumen

El estudio de los microclimas presenta una serie de beneficios que implican su importancia para reducir los efectos del cambio climático, por lo que el mapeo de estos surge como una alternativa para su identificación y conservación. Siendo el objetivo de esta revisión la identificación de técnicas empleadas en el mapeo de microclimas. La metodología empleada fue una revisión exploratoria en bases de datos como Science Direct, Springer y IEEXplore, determinando que existe una escasez respecto a trabajos relacionados al mapeo de microclimas, ya que solo 19 trabajos cumplieron con los requisitos de inclusión para la revisión. Se determinó que el objetivo principal de la cartografía microclimática se centraba en el dosel arbóreo, la altura y la densidad de las estructuras forestales y sus efectos sobre los factores climáticos que las componen. Por otro lado, los métodos de cartografía microclimática identificados se dividieron en métodos fotogramétricos y métodos de escaneo láser, donde la mayoría de los estudios se basaron en la recopilación de datos aéreos, ya sea mediante drones (UAV, UAS, RPA, RPAS) o aeronaves como en el caso de las tecnologías LiDAR aerotransportadas. Se concluyó que existen pocas investigaciones sobre el mapeo de microclimas, por lo que se exhorta a la comunidad científica del ámbito forestal a emplear las diversas metodologías para objetivos de gran impacto en el ambiente como es la predicción de incendios forestales y seguimiento de restauración de bosques luego de estos.

Palabras clave: fotogrametría, dron, láser, mapeo de microclimas, forestal.

Resumo

O estudo dos microclimas apresenta uma série de benefícios que implicam em sua importância na redução dos efeitos das mudanças climáticas, de modo que o mapeamento destes surge como uma alternativa para sua identificação e conservação. O objetivo desta revisão é identificar as técnicas utilizadas no mapeamento de microclimas. A metodologia utilizada foi uma revisão exploratória em bases de dados como Science Direct, Springer e IEEXplore, determinando que existe uma escassez de artigos relacionados com o mapeamento de microclimas, uma vez que apenas 19 artigos cumpriram os requisitos de inclusão para revisão. O foco principal do mapeamento microclimático foi identificado como sendo o mapeamento da copa das árvores, da altura e da densidade das estruturas florestais e seus efeitos sobre os fatores climáticos constituintes. Por outro lado, os métodos de mapeamento microclimático identificados foram divididos em métodos fotogramétricos e métodos de varredura a laser, sendo que a maioria dos estudos se baseou na coleta de dados aéreos, seja por drones (UAV, UAS, RPA, RPAS) ou aeronaves, como no caso das tecnologias LiDAR aéreas. Concluiu-se que há pouca pesquisa sobre mapeamento de microclima, portanto, a comunidade científica florestal é incentivada a usar as várias metodologias para objetivos de grande impacto sobre o meio ambiente, como a previsão de incêndios florestais e o monitoramento da restauração florestal após esses incêndios.

Palavras-chave: fotogrametria, drone, laser, cartografia microclimática, silvicultura.

Introduction

In recent years, microclimates have been an important factor of study to try to mitigate some of the problems generated by climate change (Carnicer *et al*., 2021), so their identification and mapping would be of vital importance to undertake actions for the conservation of species in a given territory. The localization of microclimates in forest areas, allows the identification of spaces within ecosystems that present critical climatic conditions in order to prioritize their management to prevent ecosystem degradation (De Frenne *et al*., 2021) and the identification of endemic species in a territory, thus allowing the generation of an approach based on conservation and restoration (Hu *et al*., 2024; Ulrey *et al*., 2016).

Mapping is one of the methods used to identify and locate microclimates in the forest and geographic environment, which makes it possible to know the extensions and characteristics of a specific territory. This is where techniques such as photogrammetry come into play, which allows recording and measuring objects from images, which are superimposed to generate three-dimensional models of landscapes or organisms (Ferrari *et al*., 2021; Gruen, 2021; Kudela *et al*., 2020).

In recent years, mapping techniques have evolved with technological advances, currently traditional photogrammetric methods have been replaced by the use of unmanned aerial vehicles or drones because they represent a less expensive alternative (Elkhrachy, 2021; Jiménez-Jiménez *et al*., 2021; Qubaa *et al*., 2022), the same has happened with methods employing lasers where sensors are implemented in these vehicles as a less expensive tool to the use of light aircraft (Di Stefano *et al*., 2021; Kovanič *et al*., 2023; Puliti *et al*., 2020).

Studies on microclimate mapping are diverse, ranging from the study of urban to forest microclimates, using different methods (aerial, satellite and laser) and making it difficult for researchers to find suitable mapping methods for their research. So far, no systematic review of an exploratory type that synthesizes the available microclimate mapping methods has been found. Therefore, this review was conducted with the purpose of identifying these techniques and determining the main objectives of the authors when mapping microclimates.

Methods

A scoping review was used in order to generate a synthesis of the existing evidence and identify advances and gaps in research on the use of photogrammetry for microclimate mapping. For this purpose, the guide generated by Arksey and O'Malley (2005) was used, which explains in detail the steps for conducting this type of review and which are summarized in figure 1.

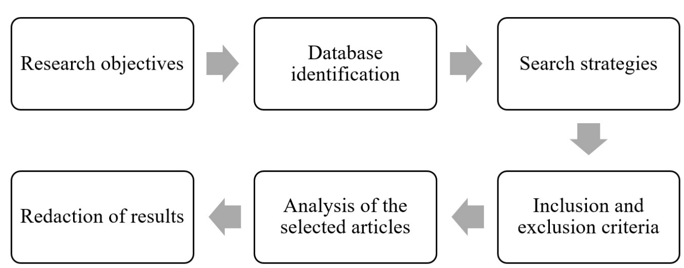

Figure 1. Steps for conducting a scoping systematic review.

Research objectives

Six objectives were determined, (1) identify the volume of studies published on the subject in the last 10 years, (2) determine the geographic scope of the publications, (3) identify the types of studies and research methods that have been used, (4) identify the objectives of the researchers in mapping microclimates, (5) identify what photogrammetry techniques have been employed for microclimate mapping, (6) identify other techniques that are being employed for microclimate mapping.

Databases and search strategies

Databases such as Science Direct, Springer and IEEXplore were used. For the search in these databases, Boolean operators such as AND and OR were used, along with search modifiers such as quotation marks and parentheses, in order to make the search more specific. Key words included terms such as "photogrammetry", "3D forest microclimate mapping" or "microclimate mapping". The search was limited to articles published between 2014 and 2023.

Inclusion and exclusion criteria

Inclusion and exclusion criteria were determined based on the research objectives, which are presented in table 1.

Table 1. Inclusion and exclusion criteria

	Inclusion criteria	Exclusion criteria
Time interval	Published between January 2014 to December 2023	Published before 2014
Type of publication	Original research articles Review articles. Conference proceedings and abstracts	Books Book chapters Websites
Language	English	All other languages
Subjects	Photogrammetry methods Mapping of forest microclimates 3D microclimate maps Other mapping methods	Non-forest microclimate mapping

Selected articles and data extraction

The data were extracted using a standardized matrix in the Microsoft Excel program, which was used to compile information such as the title of the article, year of publication, name of the journal, field of research, country, type of publication, objectives of the study, photogrammetric methods used for mapping, objectives of the researchers when mapping microclimates, and other mapping techniques used by the authors. The article selection stage is summarized in figure 2.

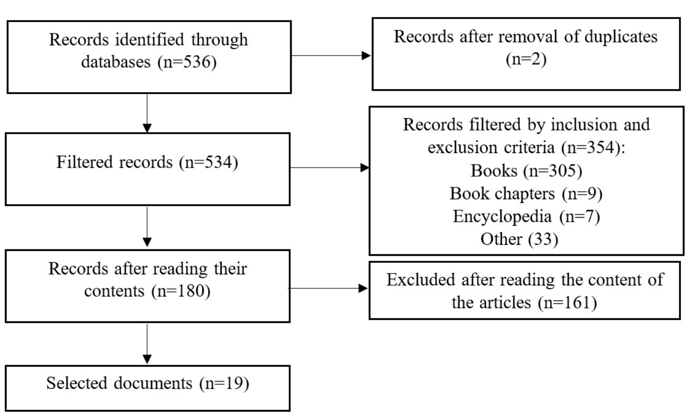

Figure 2. PRISMA diagram for systematic reviews.

Discussion

After the search in databases using the selected search terms for the review, and after its suitability evaluation using the inclusion and exclusion criteria, 19 articles were finally obtained for the review, published between 2014 and 2023 (figure 3).

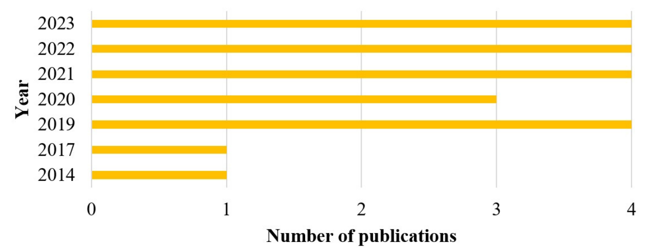

Figure 3. Year of publication of articles included in the exploratory review.

It was identified that, among the articles found, all belong to scientific journals. The documents published under journals correspond to a wide range of scientific fields such as: environmental sciences, nature conservation, environmental management, ecology, computer sciences, engineering, earth and planetary sciences, agricultural and biological sciences.

Regarding the type of publications, 80 % (n=16) correspond to research articles and 20 % (n=3) to review articles. On the other hand, regarding the geographic distribution of the authors of the 19 selected articles, it was identified that the largest number of publications have been made by collaborations between authors from different countries (n=6), on the other hand, the country with more publications is Canada (n=3), then France (n=2) and with only 1 article there are countries such as UK, USA, Netherlands, Mexico and Switzerland (figure 4).

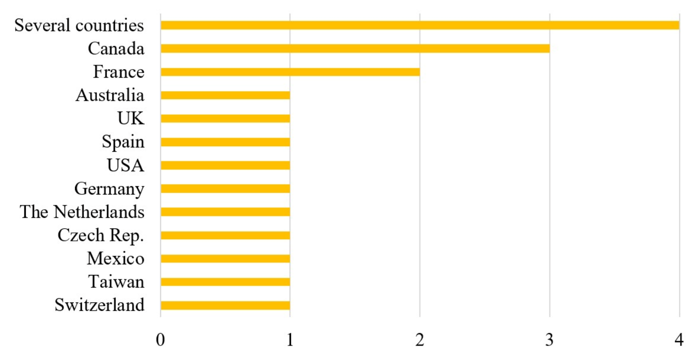

Figure 4. Year of publication of articles included in the exploratory review.

On the other hand, there is a tendency of greater interest in the study of microclimate mapping by authors who research under institutions (mainly universities) of the European continent with 11 nationalities, in second place, the American continent and Asia with 4 nationalities each and finally Oceania with one, which is similar to the estimates found in other reviews related to mapping in forest areas (Nitoslawski *et al*., 2021).

Microclimate mapping objectives

To comprehend the objectives of mapping a microclimate, it is important to understand that a microclimate comprises a set of climatic conditions in specific areas; these conditions include temperature, light availability, wind speed and humidity (Mislan and Helmuth, 2008). In forestry, the so-called tree canopy directly affects the microclimate it covers, where the quantity and quality of light obtained will depend on the tree density and height of these, also affecting the temperature and humidity of the microclimate, hence the main objective of the works found in this review is based on the mapping of the tree canopy. Table 2 shows the objectives of the research included in the review. The following are the main study objectives of the authors when mapping microclimates:

Canopy height and light availability

Authors such as Chung and Huang (2020) mapped trees in a mountainous region of Taiwan, and monitored for a period of four years (2010-2013), allowing them to investigate the effects of topography and microclimate factors in the region on tree growth and health. Brüllhardt *et al*. (2020) and Parent and Volin (2014) used mapping to generate models of vegetation height and canopy closure in order to estimate the availability of light in the studied forest space, due to its importance in the growth processes of plant structures.

Post forest fire analysis

Smith-Tripp *et al*. (2022) studied forest canopy height at the growth stage and microclimate on a monthly basis in a burned forest in British Columbia, where mapping determined that a 10 m decrease in canopy height, with respect to the approximate difference between the low- and high-severity burned portions, resulted in a 1.8 °C increase in soil temperature, an important factor that can affect the growth of certain forest species. According to Nuijten *et al*. (2023), the mapping of plant composition is a vital aspect for planning, implementing and monitoring the restoration of forest areas in the succession stage after being affected by fire. Other authors (Fernandez-Manso *et al*., 2019), generated post-fire maps to be used by forest managers as tools to identify patterns that influence the severity of the burns generated and to propose appropriate response plans after these events.

Temperature damping or amplification

Villani *et al*. (2021) and Glasmann *et al*. (2023) mapped microclimates in order to determine the influence of tree density on microclimates, analyzing the relationship between soil temperature and canopy cover, determining that in areas with higher tree cover, soil temperature decreased by up to 1.32 °C. On the other hand, Gril *et al*. (2023) and Kašpar *et al*. (2021) point out that mapping the amplification or buffering of temperatures of a microclimate has an important effect on climate change, since it allows for an understanding of thermoregulation processes, proposing species redistribution models, detecting micro refuges for conservation, acquiring information that allows for forest fire control and generating tree regeneration plans.

Quantification of forest structures

Articles by authors such as Kissling *et al*. (2022) and Qi *et al*. (2022) propose mapping as a method of quantification and analysis of forest structures, because a strong forest structure affects the functioning and resilience of forest species, ecosystems and microclimates.

The results showed that the main objective of the researchers when mapping microclimates was focused on the study of the tree canopy and its effects on the main microclimatic factors such as temperature and solar availability, since as mentioned by other authors such as Nakamura *et al*. (2017) the tree canopy is responsible for the formation of microclimates by generating the attenuation and buffering of the climatic conditions of a space, hence the articles obtained emphasize this study. On the other hand, two articles were found where the main objective was to study post forest fire conditions with the purpose of following up reforestation measures, this objective is supported by Pérez-Cabello *et al.* (2021) who mentions that monitoring the dynamics of recovery after a fire is of vital importance to evaluate resilience and obtain data to improve the management of ecosystem restoration after forest fires.

Photogrammetric techniques

In general, two types of photogrammetry can be distinguished, aerial and terrestrial, however, according to the analysis of the articles found in the last 10 years (2014-2023) there is a significant trend in the use of aerial photogrammetry. Other reviews as Colica *et al*. (2021) associate this trend due to the fact that aerial photogrammetry is not only a more technological tool but also because it provides more information in less time and avoids the exposure of surveyors to dangerous areas. Within this type of photogrammetry, the use of the already known drones is identified, among which three types stand out: UAV (Unmanned Aerial Vehicle), UAS (Unmanned Aerial System) and RPA (Remotely Piloted Aircraft), in addition to the use of satellite images.

Other techniques used for microclimate mapping

During the search for articles in the selected databases (n=19), a large number of papers using non-photogrammetric techniques for microclimate mapping were identified, being the number of articles of this type greater (N=13) than those that used and mentioned photogrammetry (n=8). These techniques are based on the use of laser technology, of which LiDAR, mobile laser scanning (MLS) and terrestrial laser scanning (TLS) stand out. Authors such as Moon *et al*. (2019) point out that LiDAR techniques present higher accuracy and very high-quality data compared to traditional methods, however, it is of higher cost than photogrammetry due to the high accuracy and technology that accompanies the technique. Other authors such as Kangas *et al*. (2018) point out that, between photogrammetric methods and the use of airborne laser, the latter is better than photogrammetry only if the acquired data are to be used for up to 15 years before acquiring new data, otherwise the accuracy of both techniques is high, being able to employ aerial photogrammetry as a cheaper alternative to LiDAR.

Conclusions

A paucity of research related to microclimate mapping has been identified in the last decade, even though the technique has been modernized with the use of drones and lasers. Although, as identified in the present review, there are a variety of techniques for microclimate mapping, the suitability of each of these will depend greatly on the objectives to be achieved, since in general, aerial techniques are preferable for studying the tree canopy, while terrestrial techniques are more useful when modeling vertical tree structures. Also, the research was only based on documents in the English language, so for future reviews the use of databases with information in other languages could broaden the picture of the use of these mapping methods in other countries. On the other hand, one of the objectives of microclimate mapping that has been little evaluated and whose study would be of vital importance for the protection of microclimates is its use as a method of forest fire prevention and monitoring in post-fire actions, either to identify factors that influence the severity of burns or to follow up on post-fire restoration actions. This specific objective of the study of microclimates and their effect on the prevention of forest fires may represent a great opportunity for researchers in European countries such as Turkey, Spain, Italy and South America (countries that constitute the Amazon region), which in recent years have been the most affected by forest fires, and that according to the findings of this review, the study of microclimate in these countries has not been considered as a method of forest fire prevention.

Table 2. Table of methods and objectives of the selected research studies.

Photogrammetric technique	Type	Objectives	Tree species or forest types	Country	Author
Arial	UAV	Canopy height and light availability	Temperate forest	Switzerland	Brüllhardt *et al*. (2020)
		Review			Zellweger *et al*. (2019)
		Soil temperature damping	Agroforestry	Tanzania	Villani *et al*. (2021)
		Effects of topography and microclimate factors on tree growth and health	Tropical forests	Taiwan	Chung and Huang (2020)
		Review	-	-	Duffy *et al*. (2021)
	UAS	Soil temperature amplification and damping	Temperate forest	Czechia	Kašpar *et al*. (2021)
	RPA	Post forest fire analysis	Sub-boreal spruce ecosystem	Canada	Smith-Tripp *et al*. (2022)
	RPAS	Post forest fire analysis	Boreal forests	Canada	Nuijten *et al*. (2023)
Satellite	Sentinel-1 Sentinel-2	Soil temperature damping	Temperate mountain forests	Germany	Glasmann *et al*. (2023)
Laser	LiDAR	Canopy height and light availability	Temperate deciduous forests	USA	Parent and Volin (2014)
		Post forest fire analysis	Mediterranean forests	Spain	Fernandez-Manso *et al*. (2019)
		Review	-	-	Zellweger *et al*. (2019)
		Forest structure quantification	temperate forest	Canada	Qi *et al*. (2022)
		Review	-	-	Camarretta *et al*. (2019)
		Soil temperature amplification and damping	lowland temperate forest	France	Gril *et al*. (2023)
		Soil temperature amplification and damping	temperate forest	Czechia	Kašpar *et al*. (2021)
		Forest structure quantification	temperate forest	Netherlands	Kissling *et al*. (2022)
	TLS	Review	-	-	Zellweger *et al*. (2019)
		Forest structure quantification	cypress forest	France	Yépez-Rincón *et al.* (2021)
		Forest structure quantification	Trees	Peru, Indonesia, and Guyana	Lin *et al*. (2023)
	MLS	Forest structure quantification	temperate forest	Canada	Qi *et al*. (2022)

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