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Land Use Affects the Local Climate of a Tropical Mountain Landscape in Northern Ecuador

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Changes in land use affect biodiversity and the biophysical structure of ecosystems, causing negative impacts on ecosystem services, such as climate regulation. However, few studies have evaluated the effect of land use changes on the local climate, particularly in tropical mountain systems such as the Andes. Therefore, this study compares 4 land use types (native forest, planted forest, maize monoculture, and pasture) in a mountain landscape in northern Ecuador as a proxy to assess the impact of land use change on local climate regulation. We estimated gap fraction with photographic techniques and recorded temperature and relative humidity using dataloggers set at 2 heights (0 m and 1 m) above ground level across the land use types. As we expected, native forests provided a more stable microclimate, demonstrating significantly lower temperatures and higher relative humidity values than the other land use types. This effect on microclimate was significantly explained with highest temperatures at intermediate gap fraction levels. In addition, we observed that native forests provided a buffer effect for the variations in mesoclimate; only native forests showed an evident reduction in local temperature over the range of mesoclimates. Local temperature variations registered in human-altered systems (planted forests and pastures) were significantly explained by the mesoclimate variation, with the exception of monocultures that exhibited a mismatch between the 2 scales of climate. These results highlight the importance of native forest for microclimate regulation, an ecosystem service that can act synergistically with other biodiversity and conservation goals to sustainably manage landscapes in Andean mountain systems.

Keywords: *ecosystem services; land use change; mesoclimate; microclimate; vegetation cover.*

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Introduction

Land use change is a major threat to the integrity of ecosystems because it affects their biophysical structure, taxonomic and functional diversity, and ecological processes (Cardinale et al 2012) and, therefore, alters their ability to provide ecosystem services (Costanza et al 2014). In this context, ecosystem transformation significantly influences the regulation of macroclimate, mesoclimate, and microclimate, acting at different spatial scales (Sahagún and Reyes 2018).

Climate regulation of ecosystems goes much further than carbon sequestration through biogeochemical processes (Foley et al 2003). Regional and local climates are also regulated by ecosystems through biophysical processes that affect the equilibrium of energy and water on the planet's surface (West et al 2011). Forest stands act as biophysical thermoregulators of the microclimate, since they modify evapotranspiration and albedo (Valladares 2006). If a natural ecosystem is deforested, this system will absorb less radiation; however, the climate will be drier because net radiation will be released in large amounts as sensible heat (Foley et al 2003; West et al 2011).

Therefore, changes in vegetation and soil coverage strongly influence the temperature and humidity of the surrounding air (Meir et al 2006; Chapin et al 2008), and, generally, the effects on the local and regional climate exceed the recorded variation in air temperature at a global scale, due to the increase in greenhouse gases in the atmosphere (Costa and Foley 2000).

Studying the modification of general microclimatic conditions, such as temperature, relative humidity, evapotranspiration, wind speed, and environmental conditions of the soil, that result from changes in vegetation cover provides information for the management, conservation, and restoration of ecosystem services (Briceño et al 2010). Amaya-Gonzáles et al (2019) suggested that the microclimate of each layer (air, canopy, and soil) changes due to land use transformation. Correspondingly, Guntiñas (2009) found that, in agricultural soils, plowing and periods in which the soil is without vegetation increase aeration, modify the climate of the upper soil layer (humidity and temperature), and frequently accelerate the decomposition of edaphic organic matter. This affects the provision of soil ecosystem services (Amaya-Gonzáles et al 2019). Likewise, these changes will have implications for the quality and sustainability of the pedosphere (Valladares 2006).

There is renewed interest in the study of microclimates. This connects global climate change with local weather conditions. In addition, it predicts the responses and physiological distributions of species in the context of environmental change (Sears et al 2011; Montejo-Kovacevich et al 2020).

The Andean landscape of Ecuador encompasses a mosaic of ecosystems with different management regimes arranged in different land use types (Foster 2001). Native mountain ecosystems have been reduced to small remnants, historically affected by the conversion of land cover to agricultural land (Cardinale et al 2012; Guarderas et al 2022). The impact of land use change on the local microclimate of the high Andean landscapes has been little evaluated (Faye et al 2014), despite the important implications of climate variation on food production and food sovereignty in high Andean ecosystems (Intergovernmental Panel on Climate Change 2017). For this reason, in this study we investigated 4 land use types (native forest, planted forest, pasture, and monoculture) representative of the study area in an Andean landscape of northern Ecuador as a proxy to understand the effect of land use change on the local microclimate. Native forest was used as a reference to make comparisons between land use types.

We expect the native forest to present more stable microclimatic conditions with lower temperatures and higher relative humidities than the other land use types. These effects could be explained by differences in gap fraction, which is distinct between land use types. We also expect the microclimatic variation recorded in this study to follow the pattern of variation recorded at a mesoclimatic scale, evidencing seasonal changes, with a distinct buffering effect of native forests.

Methods

Study area

This research was carried out in the Andean landscape of the community of Guaraquí in La Esperanza parish (0°4′19.2″N, 78°15′36.0″W) of Pedro Moncayo county. This is located in the Pichincha province of Ecuador, between 3075 and 3516 masl (Figure 1).

The study area has a climate typical of the high Andean region of northern Ecuador, with a bimodal peak of high precipitation that occurs from April to May and October to November. The dry period is from July to September (Cáceres-Arteaga et al 2018). It has a cold temperate climate, with average annual temperatures that vary from 8°C to 13°C and average annual precipitation ranging from 750 mm to 1250 mm (Gobierno Parroquial Rural La Esperanza 2015).

This mountain landscape encompasses native ecosystems such as the *páramo* grassland and evergreen high montane forest of the western Andes (Ministerio del Ambiente de Ecuador 2014). It also includes other land use types modified by human activities (Ministerio del Ambiente de Ecuador and Ministerio de Agricultura y Ganadería 2014), such as planted forests, pastures, and monocultures (Figure 1). In the study area, native forest vegetation is represented by species such as *Oreopanax ecuadorensis* Seem., *Piper nubigenum* Kunth., and *Barnadesia arborea* Kunth., while planted forests are dominated by *Eucalyptus globulus* Labill. and *Pinus radiata* D. Don. The pasture is characterized by *Pennisetum clandestinum* Hochst., and crop fields are dominated by maize monocultures (*Zea mays* L.) (Solórzano 2020).

Field phase

Because this research is part of a project that integrated several components to understand the effect of land use change on biodiversity and various ecosystem services, we used 2 × 50 m transects as a frame of reference for the project. We installed a pair of dataloggers in the center of 2 transects per land use typology to evaluate microclimate patterns across land uses (Briceño et al 2010). We used Hobo U23-001-Pro-V2 dataloggers (Onset Computer Corporation, Bourne, MA, USA) to register temperature and relative humidity in 2 layers: air and soil (Faye et al 2014). These variables were recorded at an interval of 5 minutes (Faye et al 2014, 2017).

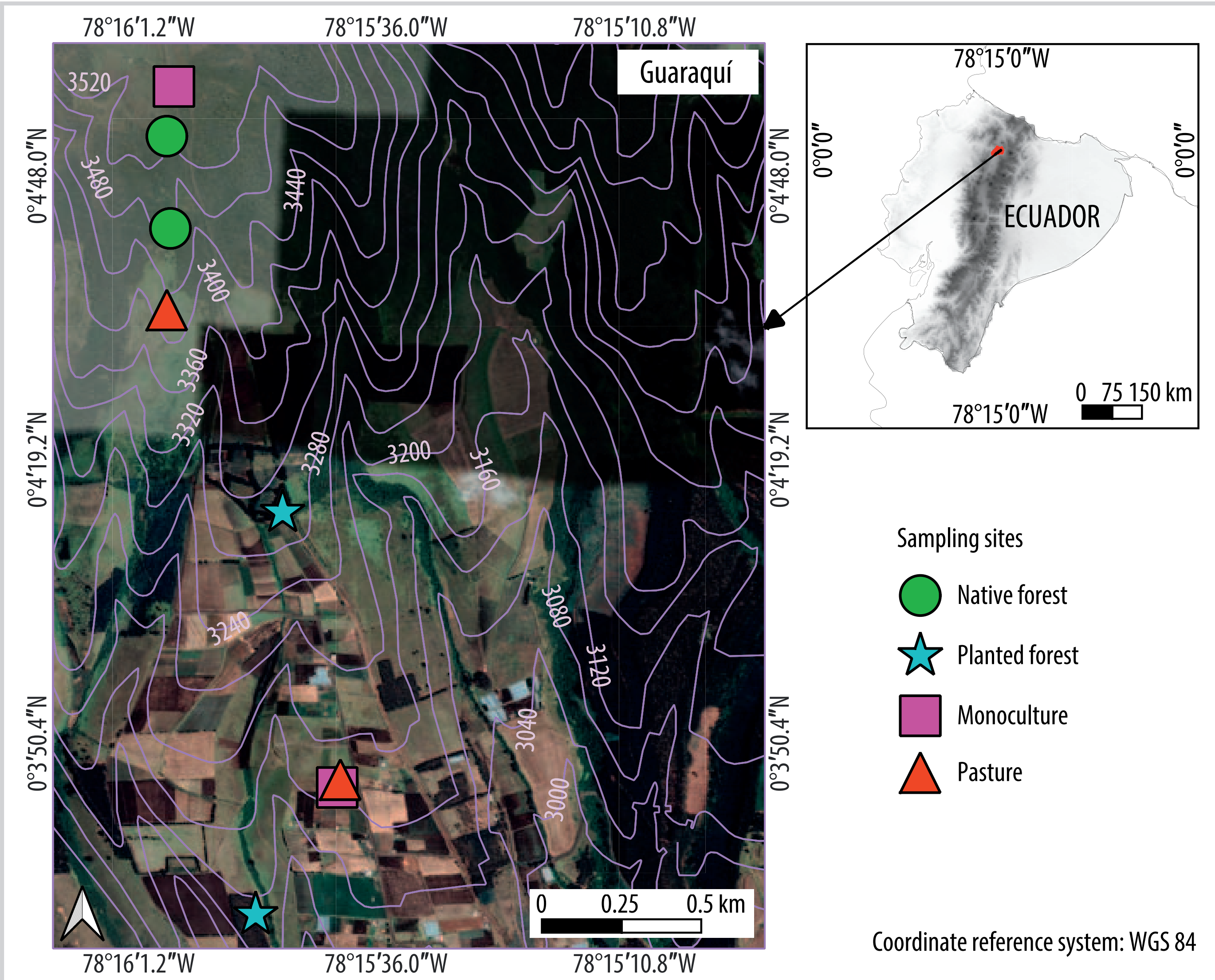
The air layer dataloggers were placed on wooden stakes at a height of 1 m and were protected with 20 cm^2 of white plastic to reduce solar radiation heating; the plastic roof was placed 5 cm higher than the logger (Faye et al 2014; Amaya-Gonzáles et al 2019). The soil layer loggers were placed on the same wooden stake at 0 m. Loggers were left in situ, and data were recorded from April to November (8 months) to cover the rainy and dry season of 2019.

To relate canopy vegetation cover to the microclimatic variation across land use typologies, we used the canopy gap fraction. This is defined as the fraction of open sky that is not obstructed by vegetation, which represents the amount of light radiation reaching the lower stratum of a forest (Gonsamo et al 2010). To obtain this proxy, a Sony WX500 compact camera with Zeiss F/6.4 lens with 30× optical zoom and a GPS Essentials compass were used, following the methodology proposed by Beckschäfer (2015).

Gap fraction depends on the proportion of direct and diffuse radiation reaching the ecosystem, which can be affected by latitude, season, and time of day, as well as atmospheric characteristics such as transmissivity and cloudiness of the site (Valladares 2006). All photos were taken from 08:00 to 10:00 (Garrido et al 2017) on cloudy days in June 2019, which corresponds to the end of the rainy season. In addition, 5 photographs were taken with the camera oriented north, capturing distinct directions: north, northeast, southeast, southwest, and northwest. These photos were taken where the pair of dataloggers were installed (Appendix S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00016.S1) and in 4 more points along the transect. In addition, because the study area is located at the equator, no latitudinal variability is expected among sites.

Photographs were taken at a height of 1 m from the ground because this is a representative height to study the microclimate in the low stratum of native forests (Garrido et al 2017), corresponding to our reference system. Accordingly, we standardized this height to be able to make comparisons across land use types, using the digital camera placed horizontally on a tripod at 1 m from the ground (Valladares 2006) (Appendix S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00016.S1).

FIGURE 1 Location of the study area with the sampling sites. (Source: Google Earth)



Data analysis

Since our study registered microclimatic variability from April to November 2019, for comparison, we pooled the data from the sensors within each land use type and summarized the data in monthly averages, obtaining 8 months ($n = 8$) for each of our microclimatic variables: mean temperature, mean relative humidity, and minimum night temperature. Prior to conducting analyses of variance (ANOVAs) to compare each microclimatic variables across land use types and between the 2 datalogger placement heights, the homogeneity and homoscedasticity of the data were verified using Shapiro–Wilk and Levene tests, with a 95% confidence interval. When significant differences were found, a Tukey test was used to obtain the exact pairwise comparisons between land use types, with a confidence interval of 95%.

For the gap fraction analysis, the Hemispherical 2.0 macro tool of the ImageJ program was used (Beckschäfer 2015), which calculated the ratio between the number of white pixels (sky) and the total number of pixels (white plus black, the latter representing vegetation) in the binary images (Gonsamo et al 2010). Mean, maximum, and minimum values of gap fraction were also obtained for each land use type.

The daily variation over the months was plotted for temperature and relative humidity by pooling the data from dataloggers within land use types and from both heights (0 m and 1 m). We disaggregated these data into minimum, maximum, and average values for each hour, representing a curve for each of the study months. In addition, we summarized these data in a smooth curve that showed the general trend of each variable.

ANOVAs and Pearson correlations between average temperatures and average relative humidities recorded in the 4 land use types were carried out using the computer software JASP version 0.12.2 (JASP Team 2020).

To understand the potential drivers of microclimate variation across land use types, we fitted a generalized additive model (GAM) to explain the variation in monthly mean temperature as a function of gap fraction, datalogger placement height, and relative humidity. The logit transformation was used for both explicative variables as they are proportions (Warton and Hui 2011).

TABLE 1 Microclimatic variables (gap fraction, temperature, and relative humidity) grouped by replicates that were performed by land use type and grouped for the 2 heights (0 m and 1 m).

Sampling site	Gap fraction (%)			Temperature (°C)			Relative humidity (%)		
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Native forest	86.82	5.99	20.54	27.21	1.89	8.94	100	27.07	91.78
Planted forest	48.91	9.02	30.57	28.52	4.92	11.10	100	17.92	79.75
Monoculture	91.71	62.03	80.03	37.62	–1.50	11.91	100	1.00	81.68
Pasture	100.00	100.00	100.00	42.03	–3.04	10.75	100	1.00	78.31

Note: Microclimatic variables are reported with their respective average (mean). Max, maximum; min, minimum.

Finally, to determine whether the mesoclimate affected variation of the local climate registered across land use types, for each land use type we fitted another GAM of monthly means in local temperature as a function of mesoclimate temperatures and precipitation. Mesoclimate data (temperature and precipitation) from the study area were downloaded from the Terra Climate gridded database (Abatzoglou et al 2018) (https://www.climatologylab.org/terraclimate.html), using the climateR package (https://doi.org/10.5281/zenodo.2672843).

The computational methods for the GAMs were carried out using the mgcv package version 1.8-34 (Wood 2011). Likewise, the daily and monthly trends, as well as all figures comparing microclimatic variables across land use types, were generated in R version 3.6.2 (R Core Team 2020), using the ggplot2 package version 3.3.3 (Wickham 2016).

Results

Gap fraction

The gap fraction varied between 5.99 and 100% across land use types, while the average values were between 20.54 and 100% (Table 1). The lowest values were reported in native forest (5.99%), followed by planted forest (9.02%), while the highest values were recorded in pasture (100%) (Table 1).

Comparison of microclimatic variables by height (0 m and 1 m) between the different types of land use

Monthly mean temperature and monthly mean relative humidity differed significantly between the different land use types (ANOVAs, Appendices S2 and S3, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00016.S1), yet no significant effects were found for height (0 m and 1 m) or the interaction between height and land use type.

As shown in Figure 2A, the average temperature recorded in the native forest was significantly lower than all other land use types (Tukey $P \leq 0.001$), in the data obtained at both 0 m (8.93°C) and 1 m above the ground (8.89°C). In pasture, the average temperature reached 10°C, which was marginally lower than the temperature recorded in monocultures and planted forests, which varied between 11°C and 13°C. No significant difference was found between the average temperatures for monoculture and planted forest (Tukey $P > 0.05$) (Figure 2A).

However, in the microclimatic variables averaged between the replicates for each of the land use types (Table 1), the highest temperatures were recorded in pasture (42.03°C) and monoculture (37.62°C). The lowest temperatures, −3.04°C and −1.5°C, were found in pasture and monoculture, respectively.

Figure 2B shows that the average relative humidity recorded in the native forest had statistically higher values than all other land use types (Tukey $P \leq 0.001$), at both 0 m (95.6%) and 1 m (89.5%), while the relative humidities registered in planted forests, monocultures, and pastures varied between 70 and 95%, without significant differences between them (Tukey $P \geq 0.05$).

The ANOVA comparing the monthly minimum nocturnal temperature (Appendix S4, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00016.S1) between the different land use types and the interaction

FIGURE 2 Monthly mean temperature (A), monthly mean relative humidity (B), and monthly minimum night temperature (C) in the 4 land use types at 2 heights with respect to the ground level (0 m and 1 m). The error bars represent the 95% confidence interval ($n = 8$ for each land use type at each layer).

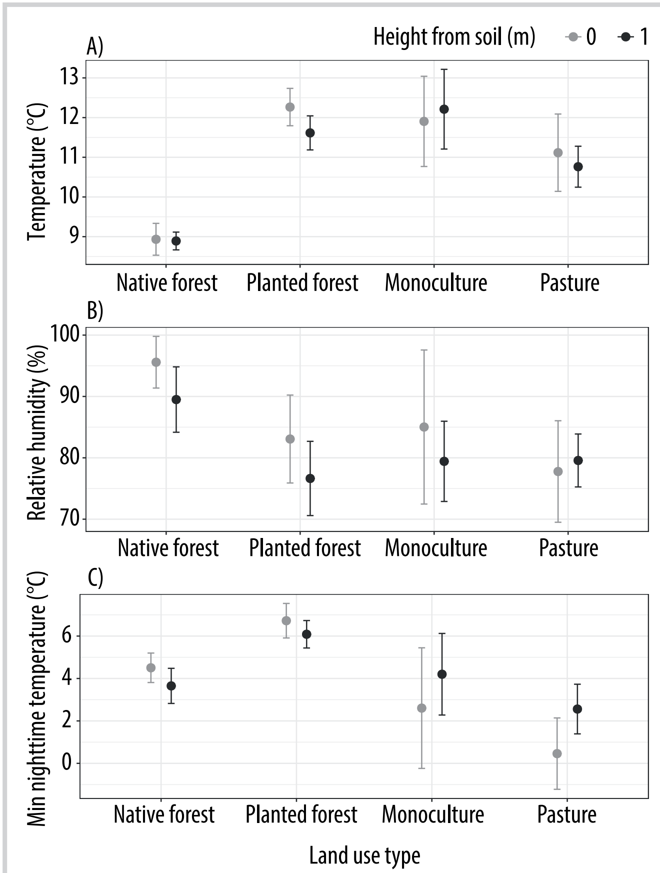
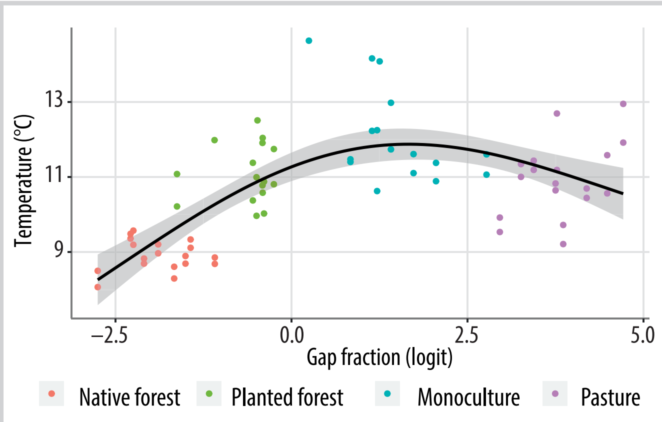


FIGURE 3 Generalized additive model of monthly mean temperature as a function of gap fraction (logit-transformed) and pooled for the 2 heights (0 m and 1 m) ($n =$ 8 for each land use type).

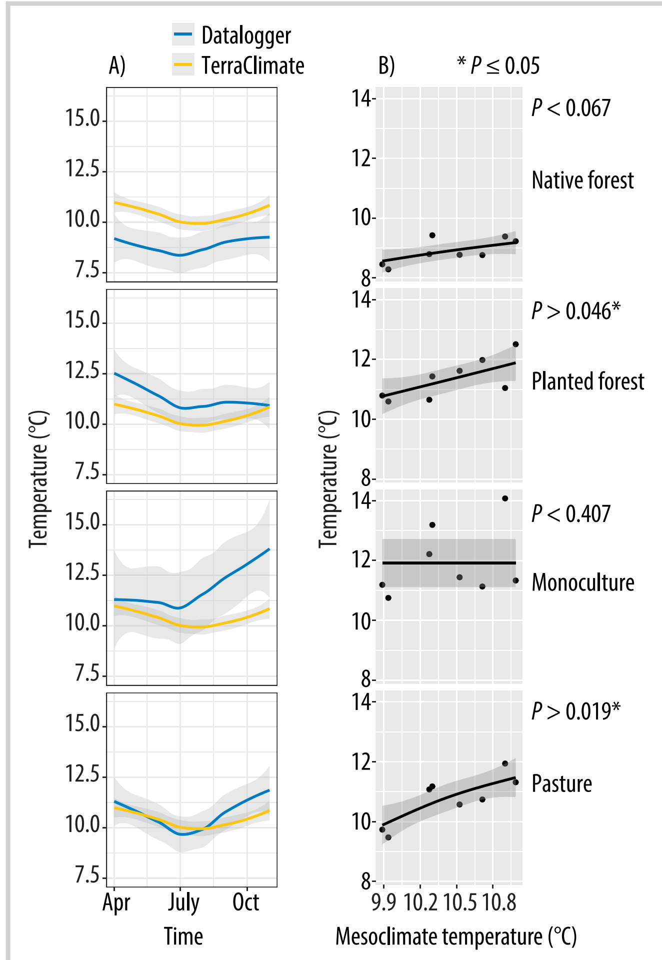


between the land use types and the 2 heights (0 m and 1 m) revealed significant differences ($F = 27.014$; $P \leq 0.001$ and $F =$ 2.890; $P = 0.044$).

As shown in Figure 2C, the monthly minimum night temperatures recorded in monoculture and pasture were lower than the rest of the land use types at their respective heights (0 m and 1 m). Similarly, there was a greater variation in temperature at 0 m in the monoculture and pasture.

Significant effects of gap fraction explaining the variation (50%) of monthly mean temperature were demonstrated with the GAM ($F = 13.33$, $P < 0.001$), whereas relative humidity did not seem to have an effect on monthly mean temperature (Figure 3; Table 2). Figure 3 clearly illustrates the distinct clustering of land use types along the *y*-axis, where the lowest gap fractions were observed within native forests, followed by planted forests, monocultures, and pastures. Monthly mean temperature showed a hump-shaped relationship with gap fraction (Figure 3).

FIGURE 4 Mesoclimate effect on monthly mean local temperature. (A) Monthly mean temperatures recorded by dataloggers (blue line) and obtained from the TerraClimate grid (yellow line). (B) Generalized additive model of monthly mean local temperature as a function of mesoclimate temperatures for the 4 land use types ($n = 8$ for each land use type).



Monthly variation of microclimatic variables and its relationship with mesoclimate

The temporal variation of the mesoclimate and microclimate temperatures across land use types is represented in Figure 4. Across land use types, we noted a decreasing trend of temperatures from April to August and an increasing pattern from September to November 2019 (Appendix S5, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00016.S1). This pattern was also observed at the regional scale (using the TerraClimate data) (Figure 4A). The lowest humidities were recorded in August and September in all 4 land use types (Appendix S5, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00016.S1).

TABLE 2 Generalized additive model of monthly mean temperature as a function of gap fraction, monthly mean relative humidity, and height of the datalogger from the ground for the 4 land use types taken together. The model deviance explained is 50.40%; the adjusted R^2 is 0.48.

Explanatory variable	Statistic			
Approximate significance of smooth terms		*P* value	*F* ratio	EDF
s(Gap fraction)		<0.001*	30.66	1.94
s(Monthly mean relative humidity)		0.392	0.00	<1
Parametric coefficients	Estimate	SE	*t* value	*P* value
Intercept	10.54	0.190	56.63	<0.001*
Height	0.30	0.260	1.17	0.246

Note: s(x), smooth function of x variable; EDF, effective degrees of freedom; SE, standard error.
*$P \leq 0.001$.

TABLE 3 Generalized additive model of monthly mean local temperature as a function of mesoclimate temperatures and mesoclimate precipitation for each of the 4 land use types.

Component/statistic	Native forest			Planted forest			Pasture			Monoculture		
Explanatory variable	*P* value	*F* ratio	EDF	*P* value	*F* ratio	EDF	*P* value	*F* ratio	EDF	*P* value	*F* ratio	EDF
s(Mesoclimate temperature)	0.067	2.3	0.99	0.046*	2.98	10.5	0.019*	5.47	1.3	0.407	0.00	<1.0
s(Mesoclimate precipitation)	0.818	0.0	<1.00	0.613	0.00	<1.0	0.358	0.00	<1.0	0.391	0.00	<1.0
Model statistic												
Deviance explained (%)	47.80			54.10			68.10			0.00		
Adjusted R^2	0.39			0.46			0.61			0.00		

Note: s(*x*), smooth function of the *x* variable; EDF, effective degrees of freedom.
$^*P \leq 0.05$.

The local temperature during the entire study period was lower for the native forest compared to the mesoclimate data, which contrasts with the patterns observed across the other land use types (Figure 4A). The planted forest and monoculture exhibited higher local temperature values than those representing the mesoclimate temporal variation in temperatures (Figure 4A), while pastures followed a similar trend to the mesoclimate (Figure 4A).

A greater mismatch between the microclimate and mesoclimate is evident for monocultures during all sampling months (Figure 4A). The GAM of monthly local temperature shows that mesoclimate temperature explains a significant amount of variation in the local climate in pastures ($F = 5.47$, $P = 0.019$) and planted forests ($F = 2.98$, $P = 0.046$). This effect was marginally not significant in native forests ($F = 2.3$, $P = 0.067$), whereas the microclimate within the monoculture was not explained by mesoclimate (Figure 4B; Table 3). The only significant explanatory variable of mesoclimate was temperature (Figure 4B; Table 3). Precipitation did not explain the variation in monthly mean local temperature within any land use type (Table 3).

Daily variation of microclimatic variables

Figure 5A shows that the lowest daily temperatures were evident in August (pasture: 4.71°C, native forest: 5.55°C, monoculture: 5.61°C, and planted forest: 7.75°C) from 3:00 to 6:00 h, without being less than 0°C, while the highest daily temperatures were recorded in September (monoculture: 22.44°C, pasture: 20.36°C, planted forest: 16.92°C, and native forest: 15.86°C) from 11:00 until 13:00 h. Only in the planted forest was the highest temperature recorded during the rainy season, in April (17.32°C) at 11:00 h. Figure 5A also shows that the maximum temperature was recorded from 13:00 h in native forest and from 11:00 h in the other land use types.

Figure 5B shows that the highest relative humidity was reported during the rainy season in May in the native forest (99.28%), monoculture (98.56%), and planted forest (98.28%) from 4:00 to 6:00 h, which was different from the pasture that registered 96.14% relative humidity in November at 4:00 h. The lowest relative humidity was obtained during the dry season in August and September in the 4 land use types (native forest: 62.5%, monoculture: 52.38%, planted forest: 48.63%, and pasture: 45.47%) from 10:00 to 14:00 h; however, in monoculture, a low value was also recorded in July (51.09%) at 7:00 h.

Correlations between microclimatic variables in each of the land use types

Appendix S6 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00016.S1) shows no statistically significant correlations between the microclimatic variables (temperature versus relative humidity) recorded in each of the land use types. However, a low negative correlation was evident only in the native forest ($r = -0.206$; $P = 0.445$).

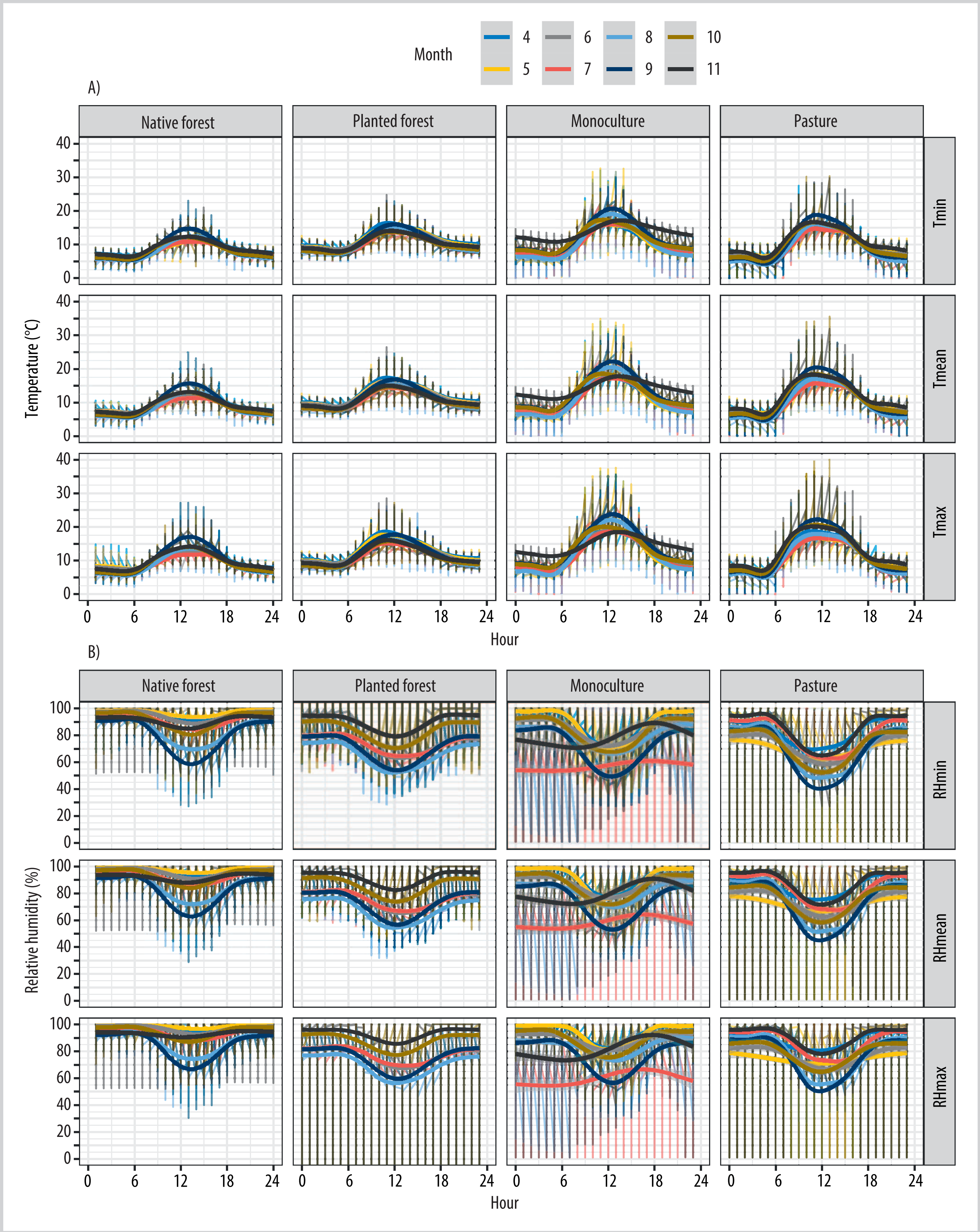
Discussion

In this study, we found that land use can have a significant impact on the local climate in mountain landscapes in the Andes, as has been demonstrated globally (Meir et al 2006; Chapin et al 2008; Duveiller et al 2018) and in other tropical regions (Osborne et al 2004). As we expected, native forests generate a particular microenvironment, providing more stable weather conditions, which are significantly different from the other land use types (eg planted forests, monocultures, and pastures). Similar results were found for lowland and montane tropical forests along the western and eastern slopes of the Ecuadorian Andes (Montejo-Kovacevich et al 2020).

Specifically, the native forests demonstrated a significant cooling effect where the temperature was on average 2°C lower than that recorded in pasture and 3°C lower than in the planted forest and monoculture. Native forests differed from the rest of the land use types in the daily timing of maximum and minimum temperatures, as well as in the microclimatic variations, which were less intense. Likewise, relative humidity in the reference system was 12% higher than in the other land use types.

These microclimatic differences could be attributed to the influence of vegetation cover (Briceño et al 2010) observed in native forests, affecting albedo and evaporative cooling (Valladares 2006; Duveiller et al 2018). As we demonstrated, gap fraction significantly explains the variation in temperature observed across land use types, suggesting that changes in vegetation cover could impact radiative and nonradiative biophysical properties that may, in turn, affect the local climate (Duveiller et al 2018). However, a hump-shaped relationship was detected, where temperature rises as the openness of the canopy vegetation increases in a gradient from native forest to monoculture but decreases when pastures are included. This result can be explained by the low canopy vegetation cover of the

FIGURE 5 Maximum, medium and minimum daily temperature variation (A) and maximum, medium, and minimum daily variation in relative humidity (B) recorded for each hour in the 4 types of land use during the sampling months ($n = 192$ for each land use type). A smooth curve that showed the general trend of each variable per month is also presented. The data were pooled by the 2 heights.



agricultural land, which can cause a nocturnal cooling effect that decreases the high diurnal temperatures. In addition, because of the temporal variation of the growing and harvesting cycle of the main crop (maize), a high temporal variation in the canopy gap fraction would be expected. However, this monthly variation was not included in our study, as we registered this variable in June, when the plants reached more than 1 m high, interacting with the solar radiation.

Additionally, we argue that the lower temperature and higher relative humidity found in native forests could be explained by vertical stratification, as suggested by Duval and Campo (2017). The upper stratum captures most of the solar radiation during the day, so the average percentage of gap fraction reaching the lower stratum is less than 10%.

Likewise, Montejo-Kovacevich et al (2020) found that within tropical forests there are microclimatic differences along the vertical stratification. Here the lower stratum presents a 2°C reduced temperature and relative humidity 11% higher than the upper stratum, generating less diurnal heating and little nocturnal cooling.

In contrast, the planted forest, despite recording a relatively low gap fraction (approximately 30%), did not show a cooling effect compared to the reference system. This land use type is dominated by eucalyptus and pine trees that can have very extended canopies (Huber et al 2010) but lack vertical structure (Solórzano 2020). In addition, the dominant trees are introduced species that grow rapidly and require large amounts of water, producing a dry microclimate, that is, high temperatures and low humidity in both dry and rainy seasons (Huber et al 2010). This explains the local climate observed in this land use type (Figure 5). Likewise, the microclimatic conditions recorded in the 2 other anthropically altered environments (monoculture and pasture) could be explained by a lack of vertical forest structure and vegetation cover to attenuate the surface climate.

The cooling effect of the native forest was also evident when the local microclimate was compared with the regional climate; however, in this land use type there was an evident reduction in local temperature over the range of mesoclimate. As demonstrated by Briceño et al (2010) and Duval and Campo (2017), the vegetation cover characteristic of forests stabilizes microclimatic variations and works as a buffer for mesoclimatic changes. Furthermore, according to Huber et al (2010) the lack of vegetation cover and vertical stratification could result in a higher significant relationship between mesoclimate and microclimate in human-altered systems, as seen in the trends observed in pastures and planted forests (Figure 4B). A similar pattern was reported by Valladares (2006) in grassland, where less variation between mesoclimate and microclimate was detected due to low attenuation caused by the 0.20 m high vegetation cover over the ground.

Similarly, our results demonstrate marginally lower temperatures in pastures compared to those observed in planted forest and monoculture. In this regard, Senra (2009) suggests that under adequate management conditions the use of 50 to 70% pasture by livestock allows the herbaceous cover to reduce high evaporation and high soil temperatures, in addition to decreasing other negative impacts on soil properties such as compaction, erosive effects of raindrops on the surface, run-off, and wind erosion. In contrast, Costanza et al (2014) argue that the presence of cattle, even if it is minimal, causes wear on soils and vegetation in the long term, which causes effects contrary to those already mentioned, such as lower water capture and low evaporation in the soils. Our results for relative humidity in the pasture do not differ from the values of planted and monoculture forests, depicting the latter scenario. In addition, this could explain the ability of the studied pasture to exhibit extremely high and low temperatures compared to the other land use types (Table 1).

On the other hand, the monoculture presented a mismatch with the temporal mesoclimate pattern, which could be attributed to the cycle of the main crop. Extreme values of temperature and relative humidity (maximum and minimum) were recorded in this land use type during the harvesting season (June to September) and the beginning of the growing period of maize (November to October) in northern Ecuador (Boada and Espinosa 2016). We particularly detected a greater alteration of the microclimatic variables in September, when the soil lacked vegetation cover after the harvest, coinciding with the dry season (Gobierno Autónomo Descentralizado de Pichincha 2015). This trend was also apparent in the agricultural landscape studied by Faye et al (2017).

In addition, the microclimatic variation of monoculture could also be explained by factors such as conduction and convection that affect the recording of climatic variables (Maclean et al 2021). When the surface is uncovered, without cultivation, the direct effect of the solar radiation causes high soil temperatures and the datalogger would also record the surface temperature through conduction. Maclean et al (2021) suggest that air flow at 1 m from the ground can modify the heat exchange of the datalogger by convection, causing high microclimatic variation.

The daily microclimatic trends showed higher variation in monoculture and pasture than in the other land use types. These results corroborate the temporal fluctuation patterns observed throughout the year in the same land use types. We also observed similarity across land use types in the occurrence of daily microclimatic peaks during the year. The 4 land use types exhibited the highest diurnal temperatures and lowest diurnal relative humidities in September (Figure 5), which corresponds to the months with the most extreme values of the dry season in the climatic regime of the study area (Cáceres-Arteaga et al (2018).

Furthermore, to understand the variation in the monoculture microclimate, tillage practices that exist in mountain agriculture may also have an impact on the local and global climate (Guntiñas 2009). Tillage causes the loss of soil organic matter, mostly carbon, which is released as CO_2 to the atmosphere (Reicosky and Saxton 2007). According to the FAO (2020), intensive tillage is responsible for 10% of all greenhouse gas emissions. Thus, Ruiz et al (2015) argue that it is necessary to eliminate tillage and promote polycultures to mitigate climate change. In addition, Guntiñas (2009) suggests that the lack of restoration, the constant use of tillage, and the unsustainable management of monocultures and pastures in Andean landscapes could generate irrecoverable losses in ecosystem services such as climate regulation and soil quality.

The tropical Andes is a region severely affected by human activities and extremely vulnerable to climate change (Gonda 2020). The ongoing warming and changes in precipitation patterns (Ranasinghe et al 2021) are threatening the capacity of these mountain landscapes to provide vital ecosystem services (Gonda 2020). Therefore, our results highlight the importance of maintaining and restoring native forests in this vulnerable region, as has been demonstrated in regional (Montejo-Kovacevich et al 2020) and global (De Frenne et al 2019) studies. The buffering effect within native forests could be implemented as preventive, mitigating, and adaptive measures in the face of global warming (De Frenne et al 2019).

Although the averaged microclimatic variables recorded in this study for monoculture are not so extreme, they reflect the high variation and intensity with which they reach the soil, giving rise to strong seasonal changes in the studied landscape (Figure 4B). This demonstrates the importance of integrating agricultural land in mitigation and adaptation plans for climate change, as they occupy an important extension on the earth's surface, especially in the tropics (Cardinale et al 2012; Senior et al 2017).

Limitations

As demonstrated by Montejo-Kovacevich et al (2020), differences in microclimatic conditions could be attributed to changes in elevation. In this study, to control the possible effects of elevation on microclimate variation across land use types, we established replicates at 2 different elevations within our target elevation range (Figure 1). However, due to the historical patterns of land use transition in our study area, we could not find a replicate for native forest at lower elevation. In addition, variation in the attributes of the dominant plant species in each system could also influence the results, and this factor should be included in future studies.

The observational approach used in the present study to understand the potential effect of a land use transition on the local climate is based on comparisons between neighboring zones with similar conditions but contrasting vegetation cover, and this could be affected by the sensors and loggers utilized. Maclean et al (2021) suggest that maximum temperatures may increase due to physical factors such as conduction and convection that affect the heat exchange processes of the dataloggers used. We replicated the methodology proposed by Faye et al (2014) to reduce the effect of direct radiation and reduce convective heat exchange with the dataloggers. For example, we placed solar shields at a distance of 5 cm above the sensors to allow natural air flow and reduce heat exchange by convection. However, other factors proposed by Maclean et al (2021) may artificially influence the observed differences according to the measurement technique used. Future microclimate studies should therefore use temperature sensors with a polished metal surface coating, as metals have lower absorption of solar radiation than plastics (Maclean et al 2021).

De Frenne et al (2019) point out that these problems are more likely to occur in datalogger records at 1 m high. In our study, datalogger placement height was not a significant variable in the GAM fitted to explain mean temperature; also our ANOVAs did not detect significant effects of height on local mean temperatures, relative humidity, or minimal nocturnal temperatures when data were summarized as monthly means. However, existing differences between minima (and potentially maxima) between 0 m and 1 m could be blurred out in the monthly averages.

Conclusions

Based on the results of this study, we conclude that the local microclimate in the studied Andean landscape will vary according to land use. Native forests provided a more stable microclimate, demonstrating significantly lower temperatures and higher relative humidity values than the other land use types.

This difference could be attributed to the vegetation cover and vertical stratification of the native forest, demonstrated by the low gap fraction, which stabilizes microclimatic variations within the forest and acts as a buffer to mesoclimatic changes. Only the microclimates recorded in the planted forest and pasture followed the same mesoclimatic pattern. In contrast, the monoculture mismatched the temporal mesoclimate pattern, which could be due to the crop cycle and physical factors, such as conduction and convection, that affect the recording of climatic variables.

Thus, our results demonstrate the importance of better management of intervening land use types in a tropical mountain landscape, since the increase of planted forests, monocultures, and unsustainable pastures could reduce the microclimatic regulation capacity of the landscape as a whole. The protection of native forests is relevant to mitigating the effects of climate change in mountain landscapes. It is also important in sustainable community management that promotes the growth of natural forests and the recovery of degraded land use types in the highlands of Ecuador.

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Supplemental material

APPENDIX S1 Photographs of the 4 land use types studied.
APPENDIX S2 ANOVA for the monthly mean temperature.
APPENDIX S3 ANOVA for the monthly mean relative humidity.
APPENDIX S4 ANOVA for the monthly minimum night temperature.
APPENDIX S5 Monthly mean temperature and monthly mean relative humidity.
APPENDIX S6 Correlations between monthly mean relative humidity and monthly mean temperature.

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