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Bioclimatic characterization of the Subtropical Mountain Forests of Yungas at the northern extreme of Argentina: Sierras de Tartagal, Alto Macueta and Alto del Rio Seco (Salta Province)

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Abstract. The Subtropical Mountain Forests of Yungas at the northern extreme of Argentina (Sierras de Tartagal, Alto Macueta and del Alto Río Seco, Salta Province) were bioclimatically characterized for the first time. In this study, the methodology of the Bioclimatic Classification of Earth was applied. Twelve Temperature and Precipitation climatic parameters were used and three bioclimatic indices corresponding to 54 Bioclimatic Reference Localities (BRL) established in the study area were also calculated. From them we determined the bioclimatic units of each BRL at the level of Macrobioclimate, Bioclimate, Thermotypes and Ombrotypes. Subsequently, three bioclimatic maps (Bioclimate, Thermotypes and Ombrotypes) and two bioclimatic distribution maps of the forests and its vegetation belt (*Premontane Forest* and *Montane Rainforest*) were digitally developed using the QGIS software. The results obtained show that these forests are distributed within the Tropical Macrobioclimate and Tropical Pluviseasonal Bioclimate, with Upper Thermotropical and Lower Mesotropical thermotypes and Lower Subhumid and Upper Subhumid ombrotypes. The lowest vegetation belt, the *Premontane Forest*, is distributed between (≈400) 429–889 (≈900) m asl and exhibits two thermal variants: the warm Thermotropical *Premontane Forest* and the more temperate Mesotropical *Premontane Forest*. The *Montane Rainforest* is distributed at higher altitudes between (≈900) 965–1178 (≈1200) m asl under Lower Mesotropical Thermotype. Both vegetation belts present two ombric variants, whose geographic distribution is determined by the precipitation gradient operating in the region: towards the West, the more humid variants are distributed under the Upper Subhumid ombrotype, while towards the East, the less humid variants are found under Lower Subhumid ombrotype. The present work constitutes the first bioclimatic study carried out in this forest formation applying the methodology of the Bioclimatic Classification of the Earth. It also lays the foundations and contributes whith valuable information to future floristic, vegetational, ecological and biogeographical studies and those focused on the conservation and sustainable management of native forests at the northern extreme of Argentina.

Keywords: Subtropical Mountain Forests, Bioclimatic Classification of the Earth, Premontane Forest and Montane Rainforest, Tropical Pluviseasonal, Thermotropical, Mesotropical, Subhumid, extreme north of Argentina.

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Introduction

The Subtropical Mountain Forests or Yungas of the Sierras de Tartagal, Alto Macueta and del Alto Río Seco are located in the extreme north of the Argentine Republic (General San Martín Department, Salta Province). This forest formation represents a unique environment from a biological and biogeographical point of view: it is located in the most diverse sector of the Argentinean Yungas (Brown *et al.*, 2001), it is an area of endemism of tree species (Entrocassi *et al.*, 2020) and has a remnant of ancient forests represented by the *Premontane Forest*, according to Prado & Gibbs (1993) these forests belong to the “Pleistocenic Arc of the Tropical Seasonal Dry Forests” of South America.

The richness of tree species recorded so far in these forests is high (117 species) (Villalba *et al.*, in prep.), some of them have a finicole feature because they reach their southernmost distribution limit in the study area (at 22°S) and disappear southwards at higher latitudes (Villalba *et al.*, 2021), others of these species are included on the IUCN Red List (www.iucnredlist.org).

The main geophysical factors that determine the development of the Subtropical Mountain Forests or Yungas in the study area are: high amounts of solar radiation due to its latitudinal position, high temperatures, low occurrence of frost, presence of important hydrographic basins and mountain ranges oriented N-S. This last factor is responsible for the abundant orographic rains that is concentrated in the warm semester, determining a monsoon-type regime in the region.

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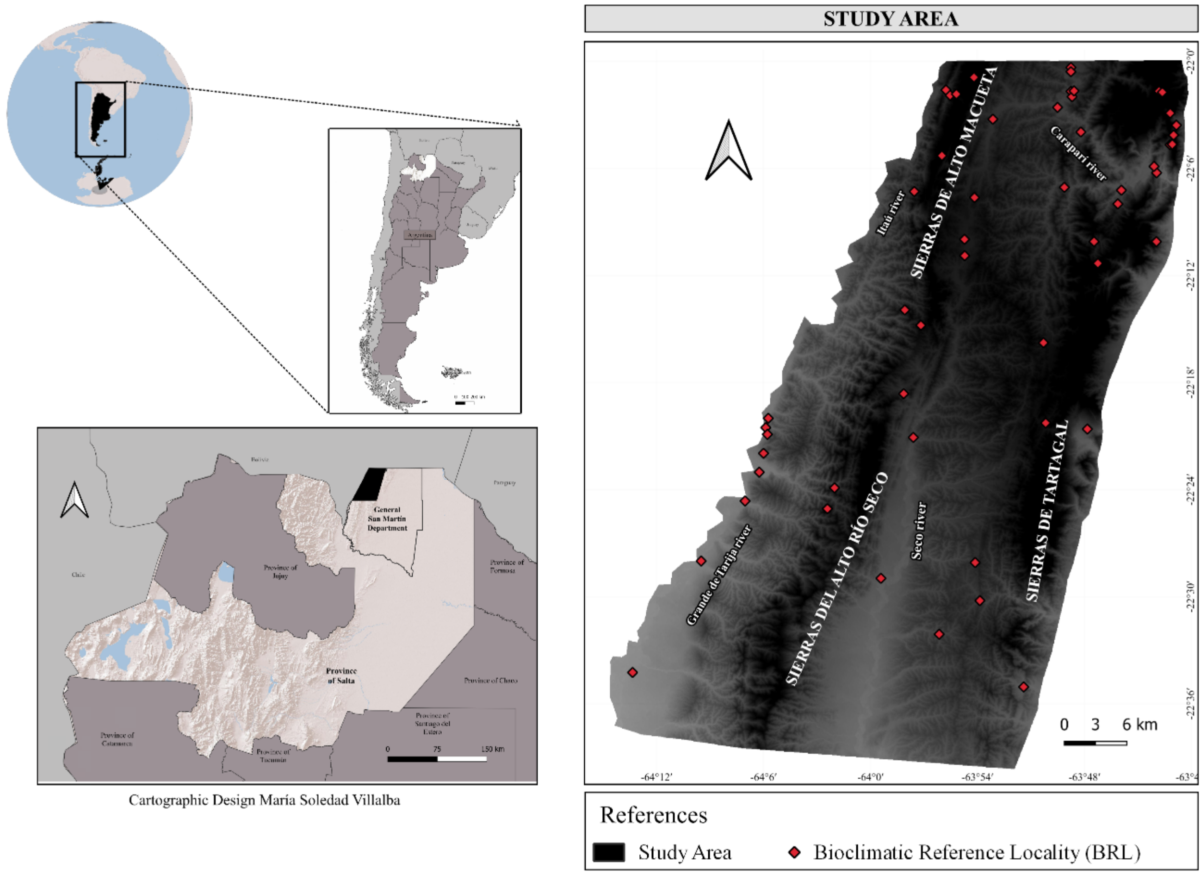


Figure 1. Location of the study area.

The climate data available for the study area come mainly from statistics (www. geoportal.idesa.gob. ar; www.wordclim.org; www.inta.gob.ar), reports and digital atlases (Bianchi & Yañez, 1992; Bianchi & Cravero, 2010; Cravero *et al*., 2017); however, there is no history of studies that have determined the bioclimatic units (Bioclimate, Thermotypes and Ombrotypes) within which these forests are distributed and their characteristic vegetation belts (*Premontane Forest* and *Montane Rainforest*). So far and as reference studies, only the Bioclimatic Typology carried out for the Province of Jujuy and in particular for the Yungas of the Serranías de Zapla is available (Entrocassi *et al*., 2014; Entrocassi *et al*., 2020).

This paper presents the bioclimatic characterisation of the Subtropical Mountain Forests or Yungas of the Sierras de Tartagal, Alto Macueta and del Alto Río Seco. For this purpose, the theoretical and methodological body of the Bioclimatic Classification of the Earth (Rivas-Martínez, 1995, 1997, 2004) was used. This classification is a predictive model that makes it possible to establish different hierarchical bioclimatic units and to analyse the relationship between their climatic values and the distribution of vegetation. The application of this classification made it possible to produce a set of digital bioclimatic maps. The present work is the first bioclimatic study carried out for the Yungas of this region and lays the foundations for future research on a larger scale in the province of Salta.

Materials and Methods

Study area

The study area is included in the sub-Andean orographic system formed by the Sierras de Tartagal, Alto Macueta and del Alto Río Seco, located in the General San Martín Department (Salta Province) in the northern extreme of the Argentine Republic (22°00’-22°37’S /63º44’-64º14’W) (Figure 1). It includes an important network of subwatersheds (Itaú, Grande de Tarija, Carapari and Seco rivers) which belong to the Bermejo river basin. It is comprised within the “Integrated Territorial Management Area Serranías de Tartagal”, which includes a mosaic of large natural forest areas, localities and communities with small human settlements and lands destined for exploitation (mainly gas, oil and timber).

From a phytogeographical point of view, the study area belongs to the Province of the Yungas (Amazonian Domain) (Cabrera, 1994) and is characterised by the presence of Subtropical Mountain Forests or Yungas which belong to the classical “Tucumano-Bolivian” vegetation (Hauman, 1931); these forests extend along an altitudinal gradient of approximately 800 m and present two vegetation belts: *Premontane Forest* (≈400 to ≈900 m asl) and *Montane Rainforest* (≈900 to ≈1200 m asl) (Villalba *et al*., 2021). According to Navarro & Maldonado (2002) and Rivas-Martínez *et al*. (2011) these forests are assimilated to the Pluviseasonal Sub-Andean Vegetation of the Bolivian-Tucuman Biogeographic Province (Tropical South-Andean Region).

Bioclimatic Characterization

The bioclimatic characterization was carried out based on the information generated by 54 Bioclimatic Reference Localities (hereinafter BRL) located in the study area, 47 localities are situated in the *Premontane Forest* and 7 in the *Montane Rainforest*. The bioclimatic units of each BRL were determined using 12 climatic parameters of temperature and precipitation and 3 bioclimatic indices considered of diagnostic value (Table 1), according to the methodology proposed in the Bioclimatic Classification of Earth by Rivas-Martínez (1995, 1997, 2004).

First, we determined annual and monthly temperature and precipitation values (T, Ti, P and Pi) for each BRL by processing raster layers using the Geographic Information System QGIS version 3.20.1 (Quantum GIS Development Team, 2021). Raster data were available on the WorldClim portal (worldclim.org) and on the Spatial Data Infrastructure of the Salta Province (geoportal.idesa.gob.ar) corresponding to the Climate Atlas of the Argentine Republic (Bianchi & Cravero, 2010; Cravero *et al*., 2017).

With the values of T, Ti, P and Pi obtained for each BRL, the remaining 8 climatic parameters (Tp, M, m, Tpd2, Pp, Ppd2, Pss and Psw) were calculated. Subsequently, the 3 bioclimatic indices (It, Io and Iod2) were calculated using the arithmetic formulae established in the Classification of Rivas-Martínez.

The following bioclimatic units were then determined for each BRL: Macrobioclimate, Bioclimate and Bioclimatic Belts (Thermotypes and Ombrotypes) with their respective horizons (upper and lower).

Although the Macrobioclimate of the area was established in the bioclimatic map of South America (Rivas-Martínez *et al*., 2011), it was also determined by calculating the corresponding parameters and indices, following the methodology applied in this work. To determine the Macrobioclimate, the values of the Mean annual temperature (T), Mean maximum temperature of the coldest month (M), Thermicity index (It), Precipitation in the warmest six months of the year (Pss) and Precipitation in the coldest six months of the year (Psw) were used. As all BRLs were located above 200 m asl, an altitude correction was made for each of them by increasing T in 0.6 °C, M in 0.5 °C and It in 13 units for every 100 m above this altitude.

To determine the Bioclimate, the value of the Annual ombrothermic index (Io) and the Ombrothermic index of the driest two month of the year (Iod2) were used. To determine the Thermotype and Ombrotype and their horizons, the value of the Thermicity index (It) and the Annual ombrothermic index (Io) were used.

Table 1. Climatic parameters and bioclimatic indices used in the Bioclimatic Characterisation of the Subtropical Mountain Forests or Yungas of the extreme north of Argentina (Sierras de Tartagal, Alto Macueta and del Alto Río Seco).

Climatic parameters
Mean annual temperature (T)
Mean monthly temperature (Ti)
Mean maximum temperature of the coldest month (M)
Mean minimum temperature of the coldest month (m)
Annual positive temperature (Tp)
Positive temperature of the driest six months of the year (Tpd2)
Mean annual precipitation (P)
Mean monthly precipitation (Pi)
Positive yearly precipitation (Pp)
Positive precipitation of the driest six months of the year (Ppd2)
Precipitation in the warmest month of the year (Pss)
Precipitation in the coldest six months of the year (Psw)
Bioclimatic indices
Thermicity index (It)
Annual ombrothermic index (Io)
Ombrothermic index of the driest two months of the year (Iod2)

Digital bioclimatic cartography

The bioclimatic data resulting from the 54 BRLs were combined with QuickMapServices base maps and vector layers created in QGIS (points, lines and polygons) and with spatial information in vector format (political division and water courses) (www.ign.gob.ar). The combination of all these resources allowed the elaboration of three digital maps for the study area: Bioclimate Map, Thermotype Map and Ombrotype Map. Finally, two digital maps of the bioclimatic distribution of the Subtropical Mountain Forests or Yungas of the study area were made up, where their vegetation belts were bioclimatically characterised (*Premontane Forest* and *Montane Rainforest*) and their distributions were established within the Thermotypes and Ombrotypes previously determined for the study area. To produce these maps, vector layers were generated by processing with QGIS, using the Thermotype and Ombrotype Maps obtained and the vector layer of contour lines extracted from Google Earth. Information on the altitudinal distribution of vegetation belts in the study area was extracted from the study by Villalba *et al.* (2021).

Results and Discussion

The results obtained allow us to establish that the Subtropical Mountain Forests or Yungas of the Sierras de Tartagal, Alto Macueta and del Alto Río Seco located in the extreme north of Argentina (General San Martín Department, Salta Province) are completely distributed in the Tropical Macrobioclimate and Pluviseasonal Bioclimate, occupying the Upper Thermotropical and Lower Mesotropical thermotypes and the Upper Subhumid and Lower Subhumid ombrotypes (Table 2; Maps 1–5).

This subtropical forest formation develops within the following thermal ranges: Mean annual temperature (T) between 18.2–21.4 °C, Mean maximum temperature of the coldest month (M) between 18.3–22.7 °C and Mean minimum temperature of the coldest month (m) between 5.4–9.9 °C (Table 2). Temperatures vary mainly according to the altitudinal gradient imposed by the existing mountain ranges, which determines the development of two vegetation belts in the study area: the *Premontane Forest* and the *Montane Rainforest*. In turn, the altitudinal variation of temperatures gives rise to two thermotypes (Thermotropical and Mesotropical), whose spatial distribution is related to the geographical location, continuity, direction and altitude of the mountain ranges and intermontane valleys of the area. However, temperatures do not show significant variations in N-S and E-W directions, possibly because the latitudinal and longitudinal gradient of the study area is small (less than 1°S and 1°W) and insufficient to produce changes in the distribution of vegetation. For this reason, both *Premontane Forest* and *Montane Rainforest* are distributed throughout the territory from N-S and E-W, although, as will be seen below, the areas they both occupy differ in their extension and continuity.

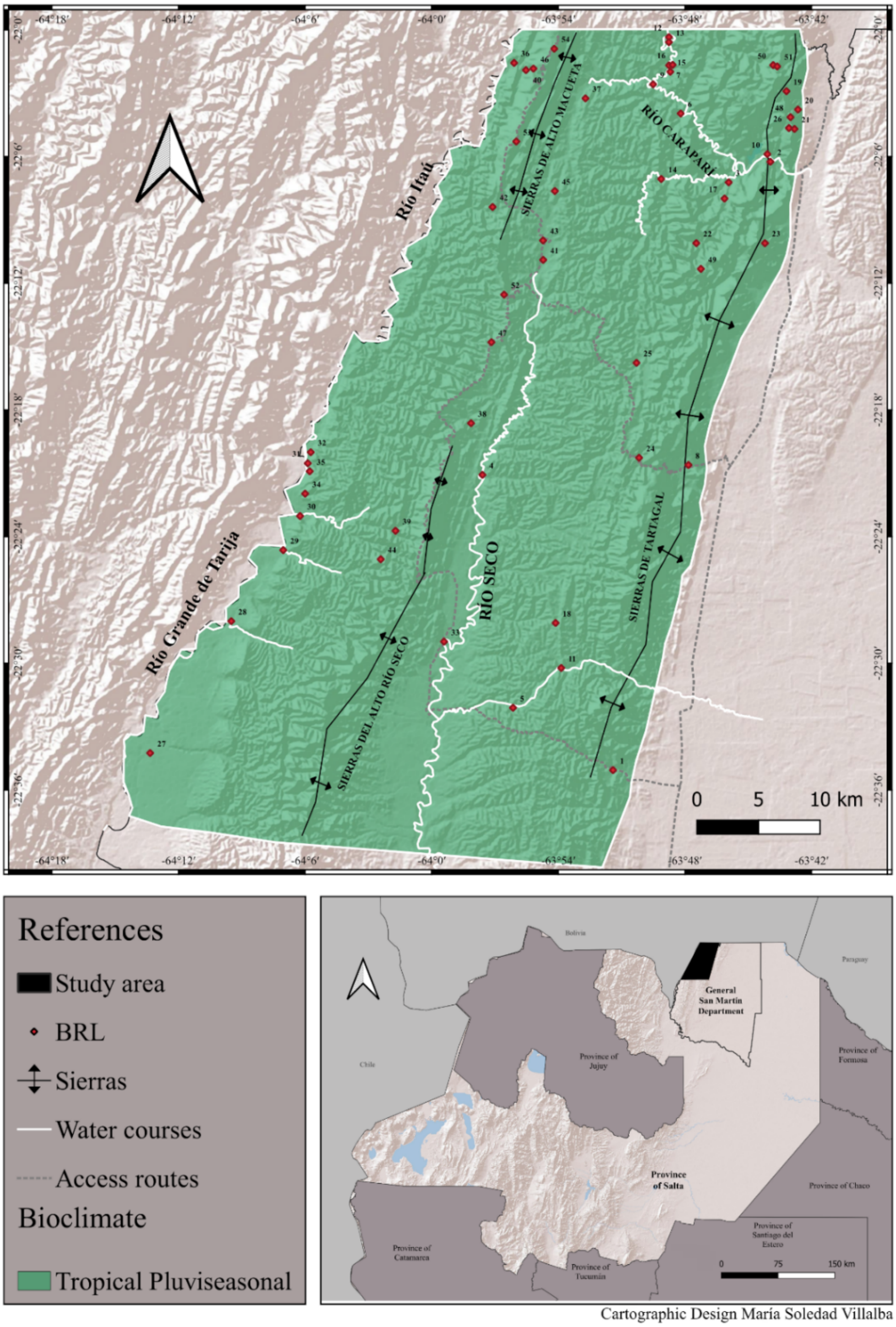
With respect to Mean annual precipitation (P), these forests are distributed in a range between 961 mm (in the east) and 1,471 mm (in the west) (Table 2). The increase in rainfall towards the west determines the establishment of two ombrotypes (Lower Subhumid and Upper Subhumid). This increase occurs because the humid air masses, coming from the east, initially ascend the Sierras de Tartagal and originate clouds of great vertical development (*cumulonimbus*) that cross their peaks and advance towards the west, where the orographic processes intensify and originate abundant precipitation that reaches maximum values in that region (Bianchi & Yáñez 1992; Bianchi *et al.*, 2005; Bianchi & Cravero, 2010).

Table 2. Bioclimatic characterisation of the Subtropical Mountain Forests or Yungas of the extreme north of Argentina (Sierras de Tartagal, Alto Macueta and del Alto Río Seco). Abbreviations are: Vegetation Belts, VB; Premontane Forest, PF; Montane rainforest, MR; Cardinal Location, CL; Bioclimatic Reference Localities, BRL; Macrobioclimate, MB; Bioclimate, B; Thermotypes, Tt; Ombrotypes, Ot;Tropical, Tr; Pluviseasonal, Ps; Upper Thermotropical, UTtr; Lower Mesotropical, LMtr; Lower Subhumid, LShu; Upper Subhumid, UShu; Altitude (m asl), A; Mean annual temperature (ºC), T; Mean annual precipitation (mm), P; Mean maximum temperature of the coldest month (ºC), M; Mean minimum temperature of the coldest month (ºC), m; Annual positive temperature, Tp; Thermicity index, It; Annual ombrothermic index, Io; Ombrothermic index of the driest two months of the year, Iod2.

			BRL	BIOCLIMATIC UNITS												
VB	**CL**	**N.**	**Toponymy**	**MB**	**B**	**Tt**	**Ot**	**A**	**T**	**P**	**M**	**m**	**Tp**	**It**	**Io**	**Iod2**
PF	E	1	Vespucio	Tr	Ps	UTtr	LShu	559	21.2	961	22.1	9.2	2544	524	3.8	0.48
PF	E	2	Caraparí inferior	Tr	Ps	UTtr	LShu	565	21.4	1013	22.0	9.1	2568	525	3.9	0.48
PF	E	3	Itanguá sur	Tr	Ps	UTtr	LShu	603	21	1027	21.8	8.9	2520	517	4.1	0.46
PF	E	4	Río Seco 1	Tr	Ps	UTtr	LShu	618	20.7	1159	21.7	8.8	2484	512	4.7	0.47
PF	E	5	Finca Santa Bárbara	Tr	Ps	UTtr	LShu	631	20.8	1026	21.6	8.7	2496	512	4.1	0.49
PF	E	6	Cañitas	Tr	Ps	UTtr	LShu	638	20.9	1062	21.6	8.7	2508	512	4.2	0.46
PF	E	7	Caraparí superior	Tr	Ps	UTtr	LShu	638	20.9	1067	21.6	8.7	2508	512	4.3	0.43
PF	E	8	El Robledal	Tr	Ps	UTtr	LShu	645	20.8	1000	21.5	8.6	2496	510	4.0	0.46
PF	E	9	Batallano	Tr	Ps	UTtr	LShu	650	20.9	1079	21.5	8.6	2508	510	4.3	0.43
PF	E	10	Embalse Itiyuro	Tr	Ps	UTtr	LShu	667	20.9	1015	21.4	8.5	2508	508	4.0	0.49
PF	E	11	Arroyo Aguay	Tr	Ps	UTtr	LShu	673	20.6	1018	21.4	8.5	2472	504	4.1	0.47
PF	E	12	Colodro norte	Tr	Ps	UTtr	LShu	677	20.8	1071	21.4	8.5	2496	506	4.3	0.41
PF	E	13	Colodro sur	Tr	Ps	UTtr	LShu	677	20.6	1070	21.4	8.5	2472	504	4.3	0.44
PF	E	14	Itanguá medio	Tr	Ps	UTtr	LShu	680	20.7	1061	21.3	8.4	2484	505	4.3	0.47
PF	E	15	Cuña Muerta sur	Tr	Ps	UTtr	LShu	683	20.7	1067	21.3	8.4	2484	504	4.3	0.44
PF	E	16	Cuña Muerta norte	Tr	Ps	UTtr	LShu	691	20.7	1068	21.3	8.4	2484	503	4.3	0.44
PF	E	17	Itanguá inferior	Tr	Ps	UTtr	LShu	717	20.6	1024	21.1	8.2	2472	499	4.1	0.47

PF	E	18	Laguna del Cielo	Tr	Ps	UTtr	LShu	735	20.3	1032	21.0	8.1	2436	494	4.2	0.48
PF	E	19	Quebrada El Chorro norte	Tr	Ps	UTtr	LShu	744	20.3	1021	20.9	8.0	2436	493	4.2	0.34
PF	E	20	Quebrada El Chorro sur	Tr	Ps	UTtr	LShu	750	20.4	1017	20.9	8.0	2448	493	4.2	0.42
PF	E	21	Aguaragüe oeste 2	Tr	Ps	UTtr	LShu	763	20.3	1016	20.8	7.9	2436	491	4.2	0.39
PF	E	22	Tuyunti norte	Tr	Ps	LMtr	LShu	764	20.3	1041	20.8	7.9	2432	490	4.3	0.45
PF	E	23	Capiazuti	Tr	Ps	LMtr	LShu	788	20.3	1005	20.7	7.8	2436	488	4.1	0.48
PF	E	24	Arroyo Yacuy	Tr	Ps	LMtr	LShu	813	19.9	1030	20.5	7.6	2388	481	4.3	0.46
PF	E	25	Laguna de las Catas	Tr	Ps	LMtr	LShu	814	20	1060	20.5	7.6	2400	482	4.4	0.46
PF	E	26	Aguaragüe oeste 1	Tr	Ps	LMtr	LShu	866	19.7	1016	20.2	7.3	2364	472	4.3	0.41
PF	W	27	San Telmo	Tr	Ps	UTtr	UShu	429	21.2	1440	22.0	9.9	2544	531	5.7	0.43
PF	W	28	Arroyo de la Quebrada Deslinde	Tr	Ps	UTtr	UShu	444	21.1	1458	22.7	9.8	2532	537	5.8	0.46
PF	W	29	Arroyo de la Quebrada Corredero	Tr	Ps	UTtr	UShu	463	21.1	1455	22.6	9.7	2532	535	5.7	0.46
PF	W	30	Arroyo de la Quebrada Astilleros	Tr	Ps	UTtr	UShu	468	21.1	1454	22.6	9.7	2532	534	5.7	0.46
PF	W	31	Río Tarija	Tr	Ps	UTtr	UShu	476	21	1463	22.6	9.7	2520	532	5.8	0.46
PF	W	32	Madrejones	Tr	Ps	UTtr	UShu	481	21	1471	22.5	9.6	2520	532	5.8	0.46
PF	W	33	Río Seco	Tr	Ps	UTtr	LShu	560	21.1	1089	22.1	9.2	2532	523	4.3	0.48
PF	W	34	Astilleros	Tr	Ps	UTtr	UShu	574	20.5	1449	22.0	9.1	2460	515	5.9	0.47
PF	W	35	Río Itaú	Tr	Ps	UTtr	UShu	580	20.5	1458	21.9	9.0	2460	515	5.9	0.47
PF	W	36	Arroyo Campo Largo	Tr	Ps	UTtr	UShu	682	20.5	1229	21.3	8.4	2460	502	5.0	0.39
PF	W	37	Alto Macueta	Tr	Ps	UTtr	LShu	706	20.5	1142	21.2	8.3	2460	500	4.6	0.42
PF	W	38	Válvula 5	Tr	Ps	UTtr	UShu	706	20.3	1208	21.2	8.3	2436	498	5.0	0.48
PF	W	39	San Pedrito	Tr	Ps	LMtr	UShu	745	19.9	1238	20.9	8.0	2388	489	5.2	0.49
PF	W	40	Tres Curvas	Tr	Ps	LMtr	UShu	769	20	1225	20.8	7.9	2400	487	5.1	0.40
PF	W	41	El Chorrito	Tr	Ps	LMtr	UShu	790	20	1161	20.7	7.8	2400	484	4.8	0.46
PF	W	42	El Arazal	Tr	Ps	LMtr	UShu	797	19.9	1239	20.6	7.7	2383	482	5.2	0.43
PF	W	43	Acambuco	Tr	Ps	LMtr	UShu	805	19.9	1164	20.6	7.7	2388	482	4.9	0.46
PF	W	44	Finca Falcón	Tr	Ps	LMtr	UShu	814	19.8	1221	20.5	7.6	2376	480	5.1	0.49
PF	W	45	Acambuco norte	Tr	Ps	LMtr	UShu	829	19.8	1162	20.4	7.5	2376	478	4.9	0.43
PF	W	46	Campo Largo	Tr	Ps	LMtr	UShu	880	19.5	1209	20.1	7.2	2340	469	5.2	0.41
PF	W	47	El Mutingial	Tr	Ps	LMtr	UShu	889	19.3	1216	20.1	7.2	2316	466	5.3	0.48
MR	E	48	Filo Aguaragüe	Tr	Ps	LMtr	LShu	965	19.4	1015	19.6	6.7	2328	457	4.4	0.38
MR	E	49	Tuyunti	Tr	Ps	LMtr	LShu	967	19.2	1033	19.6	6.7	2304	455	4.5	0.45
MR	E	50	Aguaragüe este 1	Tr	Ps	LMtr	LShu	1078	18.9	1031	18.9	6.0	2268	439	4.5	0.30
MR	E	51	Aguaragüe este 2	Tr	Ps	LMtr	LShu	1178	18.3	1028	18.3	5.4	2196	421	4.7	0.32
MR	W	52	La Maroma	Tr	Ps	LMtr	UShu	973	19	1200	19.6	6.7	2279	452	5.3	0.49
MR	W	53	Alto Macueta sur	Tr	Ps	LMtr	UShu	993	18.9	1220	19.5	6.6	2268	449	5.4	0.43
MR	W	54	Campamento PAE norte	Tr	Ps	LMtr	UShu	1160	18.2	1186	18.5	5.6	2184	422	5.4	0.38

The *Premontane Forest* (hereafter PF) is the lowest vegetation belt of the forests in the study area, distributed between (≈400) 429–889 (≈900) m asl and occupies and occupies the most part of the territory. It extends through the warmer areas with Upper Thermotropical thermotype up to 763 m asl, from this altitude it ascends to the Lower Mesotropical thermotype until it disappears at 889 (≈900) m asl, at which altitude it is replaced by the *Montane Rainforest*. According to its altitudinal distribution within two thermotypes, it is possible to recognise two thermal variants of the PF. The first variant is the warm *Thermotropical PF* (T=20.1–21.4°C; It=491–537), which is distributed at lower altitudes in the valleys of the Itaú, Grande de Tarija, Seco and Caraparí rivers and on the foothills and lower slopes of the Sierras de Tartagal, Alto Macueta and del Alto Río Seco (between 429 and 763 m asl). The second variant is the more temperate *Mesotropical PF*

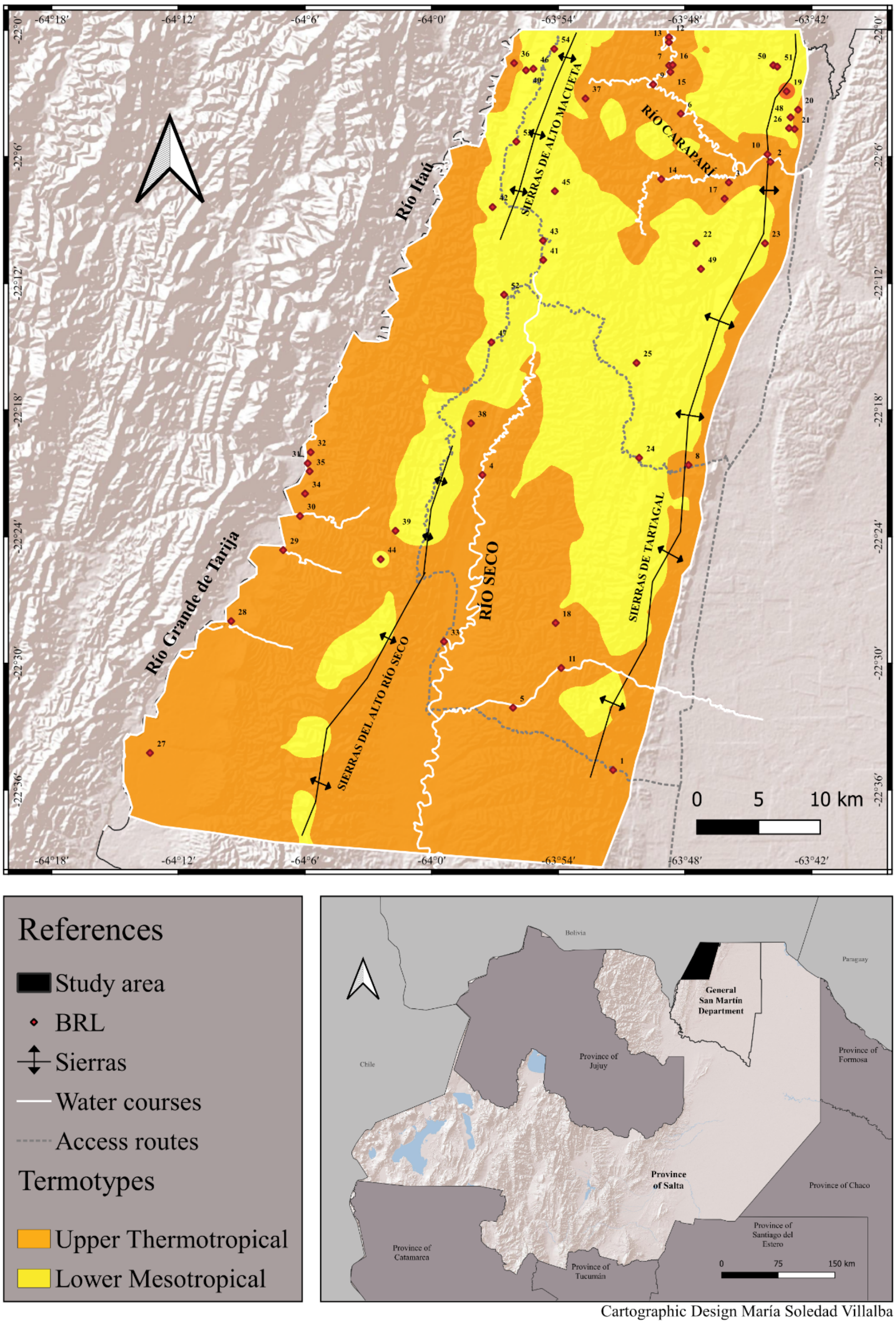


Map 1. Bioclimate of the study area.

(T=19.3–20.3 °C; It=466–490) which is distributed at higher altitudes on the slopes and medium altitude peaks of the Sierras de Tartagal, Alto Macueta and del Alto Río Seco and in the Acambuco Valley (between 764 and 889 m asl; except for the BRL "San Pedrito" at 745 m asl), it occupies a smaller area than the *Thermotropical PF* and has a continuous distribution in the east, northwest and centre and discontinuous in the northeast and south of the study area (Table 2; Maps 2 and 4).

The ombrotypes that characterise the PF are Lower Subhumid and Upper Subhumid. According to their distribution in these two ombrotypes, two ombric variants of the PF can also be recognised. The first variant is the *Upper Subhumid PF* (P=1161–1471 mm; Io=4.8–5.9; except for the BRLs "Alto Macueta" and "Río Seco"), exhibits more humidity and it is found to the west in the Sierras de Alto Macueta and del Alto Río Seco and along the valleys of the Itaú and Grande de Tarija rivers (between 429 and 889 m asl). The second variant is the *Lower Subhumid PF* (P=961–1159 mm; Io=3.8–4.7), which is less humid and is distributed eastwards in the Sierras de Tartagal and its foothills and in the valleys of the Seco and Caraparí rivers (between 559 and 866 m asl) (Table 2; Maps 3 and 5).

The *Montane Rainforest* (hereafter MR) is distributed in a disjunct manner on the higher slopes and peaks between



Map 2. Thermotypes of the study area.

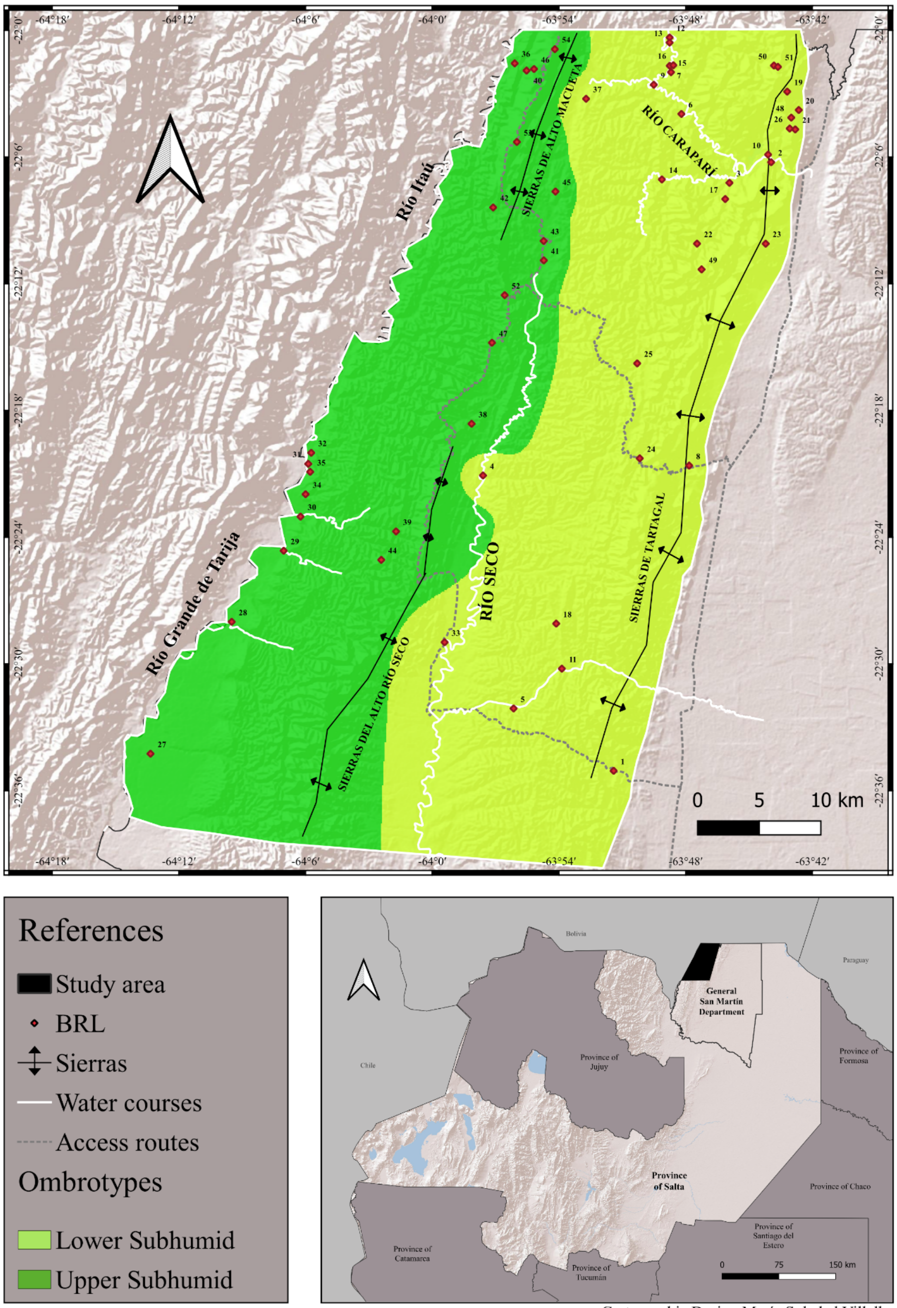
(≈900) 965–1178 (≈1200) m asl, occupies a smaller area than the PF due to the discontinuity of the mountain ranges at these altitudes. It is better represented towards the east of the study area, where the Sierras de Tartagal have greater continuity in their foothills and reach elevations close to 1230 m asl. To the west, the MR occupies less surface area because the Sierras de Alto Macueta and del Alto Río Seco are lower (between 700 and 1140 m asl) and exhibit a notable discontinuity, decreasing sharply in altitude towards the south.

The MR develops completely in the more temperate areas with Lower Mesotropical thermotype (T=18.2–19.9 °C; It=421–461) and does not present thermal variants (Table 2; Maps 2 and 4). The ombrotypes that characterise it are also Lower Subhumid and Upper Subhumid. According to their ombrotypes, two ombric variants of the MR can be recognised, whose geographical distribution is determined by the precipitation gradient of the study area. To the west, in more humid and elevated areas of the Sierras de Alto Macueta and del Alto Río Seco (between 973 and 1160 m asl) the *Upper Subhumid MR* variant is found (P=1186–1246 mm; Io=5.2–5.4; while to the east, in less humid areas of the Sierras de Tartagal (between 965 and 1178 m asl) the *Lower Subhumid MR* variant is distributed (P=1015–1033 mm; Io=4.4–4.7), this variant occupies a larger area than the previous one (Table 2; Maps 3 and 5).

Conclusions

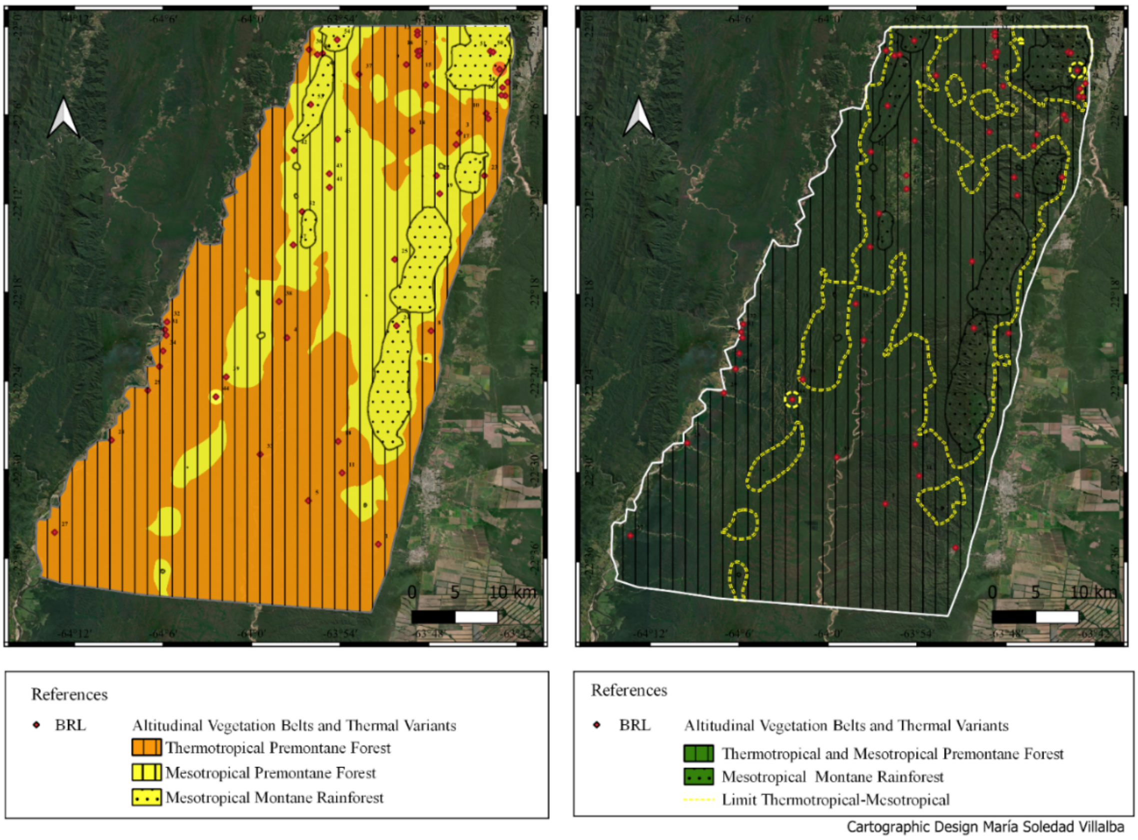
The bioclimatic characteristics of the Subtropical Mountain Forests or Yungas of the study area are determined by altitude, temperature and precipitation gradients. The joint variation in altitude and temperature determines two thermotypes, as a result of which the *Premontane Forest* presents two thermal variants (thermotropical and mesotropical), while the *Montane Rainforest* is only mesotropical. Consequently, the geographical variation of precipitation also determines two ombric variants in both vegetation belts, with the wettest ones being circumscribed towards the west, regardless of their altitude. Therefore, according to their thermotypes and ombrotypes, the thermotropical and mesotropical *Premontane Forest* and the mesotropical *Montane Rainforest*, located to the west, are wetter than those located to the east of the study area.

The bioclimatic characteristics of the subtropical forests of the extreme north of Argentina largely determine their high biodiversity and biological singularity. Currently, these forests face risks such as fragmentation and reduction of their distribution area due to the advance of the agricultural frontier, the increase in the frequency and magnitude of fires and the forest exploitation. This situation merits extreme efforts to ensure their effective conservation and avoid irreversible losses in their biodiversity and the ecological deterioration of the region.

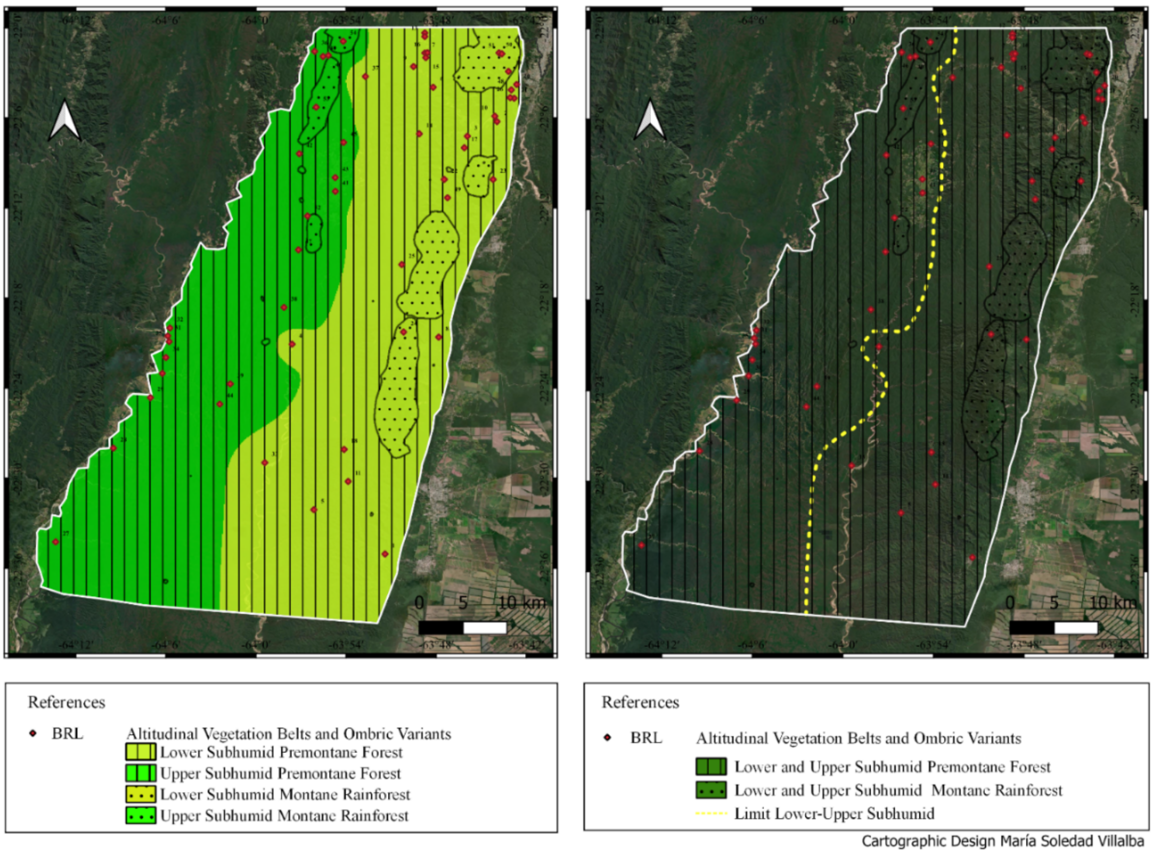


Cartographic Design María Soledad Villalba

Map 3. Ombrotypes of the study area.



Map 4. Bioclimatic distribution of the Subtropical Mountain Forests or Yungas of the extreme north of Argentina (Sierras de Tartagal, Alto Macueta and del Alto Río Seco): Altitudinal vegetation belts (*Premontane Forest* and *Montane Rainforest*) and thermal variants.



Map 5. Bioclimatic distribution of the Subtropical Mountain Forests or Yungas of the extreme north of Argentina (Sierras de Tartagal, Alto Macueta and del Alto Río Seco): Altitudinal vegetation belts (*Premontane Forest* and *Montane Rainforest*) and ombric variants.

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Authorship

GE, MSV: Conceptualization, Methodology, Formal analysis; MSV, GE: Writing; GE, EMC: Final supervision.

Conflict of interest

None.

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