STUDIES ON THE THERMAL CONDITIONS OF SOILS AT THE UPPER TREE LINE IN THE PÁRAMO OF PAPALLACTA (EASTERN CORDILLERA OF ECUADOR)

With 14 figures, 7 tables, 2 photos and 1 supplement (II)

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Zusammenfassung: Studien der thermischen Bedingungen der Böden an der oberen Waldgrenze des Páramo de Papallacta (Ostkordillere Ecuador)

Bodentemperatur und Bodenwärmefluss innerhalb und außerhalb von Waldbeständen sind wichtige Indikatoren zur Bestimmung der thermischen Wachstumsbedingungen an der oberen Waldgrenze. Die Ergebnisse zeigen, dass im Waldgrenzökoton des Páramo de Papallacta die Bodentemperaturen (in 50 cm Tiefe) ausgewählter Waldbestände signifikant niedrigere Werte aufweisen, als bislang aus anderen tropischen Hochgebirgen berichtet wurde. Waldrelikte stocken hier bis zu einer Bodentemperatur von 1,9 °C sowie einem jährlichen Mittel von 4,25 °C. Die Differenz zwischen dem kalten Waldboden und dem warmen Boden des benachbarten Graspáramo ist im Papallacta-Gebiet mit ~1–2 °C weitaus geringer, als andere Studien aus tropischen Gebirgen zeigen. Dies ist eine Folge der homogenen pedologischen Verhältnisse, der konstanten Bodenfeuchte im Wurzelraum und des hohen Humusgehaltes, der generell eine niedrige Wärmeleitfähigkeit des Bodens an allen Standorten verursacht. Der Wärmefluss in der Wurzelzone (10 cm Tiefe) ist nicht nur das Ergebnis der Abschattung des Waldbodens durch die Baumkronen. Er ist ebenfalls signifikant von der Differenz zwischen Boden- und Lufttemperatur und der turbulenten Durchmischung bei höheren Windgeschwindigkeiten abhängig. Die Wurzelraumtemperatur (10 cm Tiefe) im Wald ist vor allem aufgrund der guten Isolierung der mächtigen Rohhumusauflage gegenüber den offenen Büschelgrasflächen deutlich reduziert. Die mittlere tägliche Wurzelraumtemperatur im Papallacta-Gebiet ist dabei niedriger als Werte, die für das Wachstum der Waldgrenzbäume in den Schweizer Alpen als physiologisch notwendig erachtet werden. Auch der Jahresgang der Bodentemperatur (50 cm Tiefe) ist im äquatorialen Untersuchungsgebiet nicht konstant. Die markante Schwankung während der Beobachtungsperiode geht auf die Wirkung eines kräftigen „La Niña"-Ereignisses zurück, das mit einer niederschlagsreichen Periode im Hochland verbunden war. Die gute Durchfeuchtung des Bodens bis in tiefere Schichten am Tag in Kombination mit einer starken nächtlichen Abkühlung bei klarem Himmel und der abkühlenden Wirkung von starken, turbulent-kalten Passatwinden sind sehr wahrscheinlich der Grund für die beobachtete Depression der Bodentemperaturen.

Summary: Microclimatological measurements of soil temperature and soil heat flux in the Páramo of Papallacta are presented in order to describe the thermal growth conditions, especially of forest patches at the upper tree line in comparison to open sites. It has been proven that –0.5 m soil temperature at selected forest sites is significantly lower than is reported for other tropical high mountains. Forest patches at the upper tree line in the Páramo of Papallacta grow below –0.5 m at soil temperatures temporarily of 1.9 °C or a yearly average of about 4.25 °C. However, differences between colder forest soils and the adjacent warmer bunchgrass sites are slighter (~1–2 °C, –0.5 m) than is presented in other investigations in tropical high mountains. This is mainly due to similar soil properties, especially the constant soil moisture in the root zone and the high humus content, which generally causes a low thermal soil conductivity at all sites. Root zone heat flux (–0.1 m), as suggested by previous studies, is not only the result of a reduced sky view factor due to canopy shading of the forest ground. It has proved to be also significantly dependent on the air-soil temperature difference and the influence of turbulence due to an increased wind speed. However, the root zone temperature (–0.1 m) is colder under forest ground which is mainly due to the better thermal insulation by means of a well-developed organic layer (moss-/peat-like) in comparison to the bunchgrass sites. Additionally, the daily mean of root zone temperature is mostly lower than assumed necessary for root growth in the course of studies conducted in the Swiss Alps. Finally, –0.5 m soil temperature is not constant in the course of the year. During the observation period presented here, this was due to a cold "La Niña" event, probably as a combined effect of increased moisture at deeper soil levels by extensive daily precipitation, increased nocturnal radiation and higher turbulence by cold trades.

1 Introduction

High mountain areas are one of the most sensitive ecosystems of the world accounting for a possible climate change. Especially in ecological transition zones, as e. g. the upper tree line, climate change may affect the structure of vegetation cover at an early stage. Because routine meteorological observations are sparsely available at the tree line, especially in the Tropics (BARRY 1992), vegetation could be a valuable indicator for monitoring climate change. However, this would require a well-known transfer function between vegetation growth and climate which is currently not available, e. g. for Páramo regions due to a lack of climate observations and plant physiological studies.

To overcome this problem, scientists have sought an appropriate, easy-to-implement climatic indicator for plant growth. Soil temperature has seemed to be a suitable tool since the work of WALTER a. MEDINA (1969) and WALTER (1973) especially in explaining the position of the upper tree line from a climate-ecological point of view. They suggested that tree growth in tropical high mountains is limited to altitudes with a mean air temperature of above 5.5–7 °C, which should correspond to a soil temperature of approximately 7 °C because root activity is strongly reduced in colder soils. The relevant soil temperature should be easily obtainable at soil depths of –0.3 m under trees and –0.6 m for non-shaded surfaces. However, several following studies revealed inconsistencies with their assumptions (e. g. WINIGER 1979, KESSLER a. HOHNWALD 1998). Hence, occurring problems have recently been discussed in two extensive review papers.

MIEHE a. MIEHE (1994) noticed that soil temperatures, which were observed by various authors at the upper tree lines of tropical high mountains, generally vary between 6 and 8.5 °C. Even values of 3.3 °C could be found at isolated outpost of trees above the tree line. Concerning the measurement of soil temperatures they stressed that an isothermal zone does not exist until soil depths of –0.7 m. Furthermore, soil temperatures in the deepest horizon vary by up to 2.3 °C in the course of the year between the dry and rainy seasons, mainly due to changes in soil moisture and/or cloudiness. Differences between tree-sheltered and non-shaded surfaces can amount to 4 °C (e. g. DRONIA 1983). MIEHE a. MIEHE concluded that it is not the soil temperature but the temperature at the canopy layer that is more likely to limit tree growth. In general, they follow the opinion of ELLENBERG (1958) that the current extension of the upper tree line is mainly man-made, e. g. due to traditional pasture systems and periodic burning.

On the other hand, KÖRNER (1998) presents evidence for the growth limitation hypothesis on the basis of global soil temperature observations. He stated that close tree canopies at the tree line create cold soils with a reduced soil heat flux due to shading effects which impair root activity. Hence, he concluded that the soil temperature in the root zone (–0.1 m) is of major importance for tree growth in relation to the altitude of the upper tree line. For *Pinus cembra* in the Central Swiss Alps he shows that root growth starts at >3 °C but does not reach a sufficient intensity at temperatures less than 6 °C. A daily mean of 5.5–7.5 °C in the root zone temperature (–0.1 m), which is commonly associated with the seasonal mean air temperature, is therefore necessary to initiate shoot growth of the trees under tree line conditions.

Thus, both comparative studies have shown the complex problem of defining thermal conditions of soils at the upper tree line. Uncertainties are generally due to the problem of to which degree the results within the cited papers are comparable. Reported observations are often made at varying soil depths, under different vegetation types as well as under different topographical and synoptic/microclimatic conditions. Sometimes there is neither information on the soil itself nor on the intensity of human influence on vegetation cover. Physiological studies as well as the related soil temperatures are mostly restricted to specific tree species. Therefore, both papers conclude that further investigations are necessary to get a more comprehensive view of microclimatological conditions at the upper tree line.

The aim of the current paper is to present microclimatological investigations in the Páramo of Papallacta which contribute to the discussion of thermal soil properties in a humid tropical high mountain environment. Measurements of soil heat flux and soil temperature in the root zone (–0.1 m) and at deeper levels (–0.3, –0.5 m) will provide information about the growth conditions of forest patches at the upper tree line in comparison to adjacent open sites.

2 *The study area*

2.1 Study area and data collection

The study area comprises a part of the Páramo of Papallacta (Lon 78°07′–78°22′ W, Lat 00°15′–00°35′ S), which is located east of Quito in the eastern Cordillera of Ecuador (Fig. 1 and Supplement II). The area of interest is centred on the pass of Papallacta and ranges from the present timberline at 3700 m asl to the altitudinal belt of cushion plants up to approximately 4400 m asl (for more details refer to LAUER a. RAFIQPOOR 2000). The study area is characterised by Bunchgrass-Páramo communities (*Festuca subulifolia* & *Festuca procera* and *Calamagrostis effusa* & *Calamagrostis intermedia* with *Puya clava-herculis*) between 3700 and 4100 m asl. As documented in the vegetation map (Supplement II) the Grass-Páramo is interspersed with extended patches of forests which are dominated by trees of *Polylepis incana*, *Gynoxys buxifolia* and *Hesperomeles heterophylla* west of the pass area as well as *Polylepis pauta*, *Neurolepis aristata*, *Gynoxys acostae* and *Escallonia myrtilloides* on the slopes east of the main watershed. Obviously, these forest

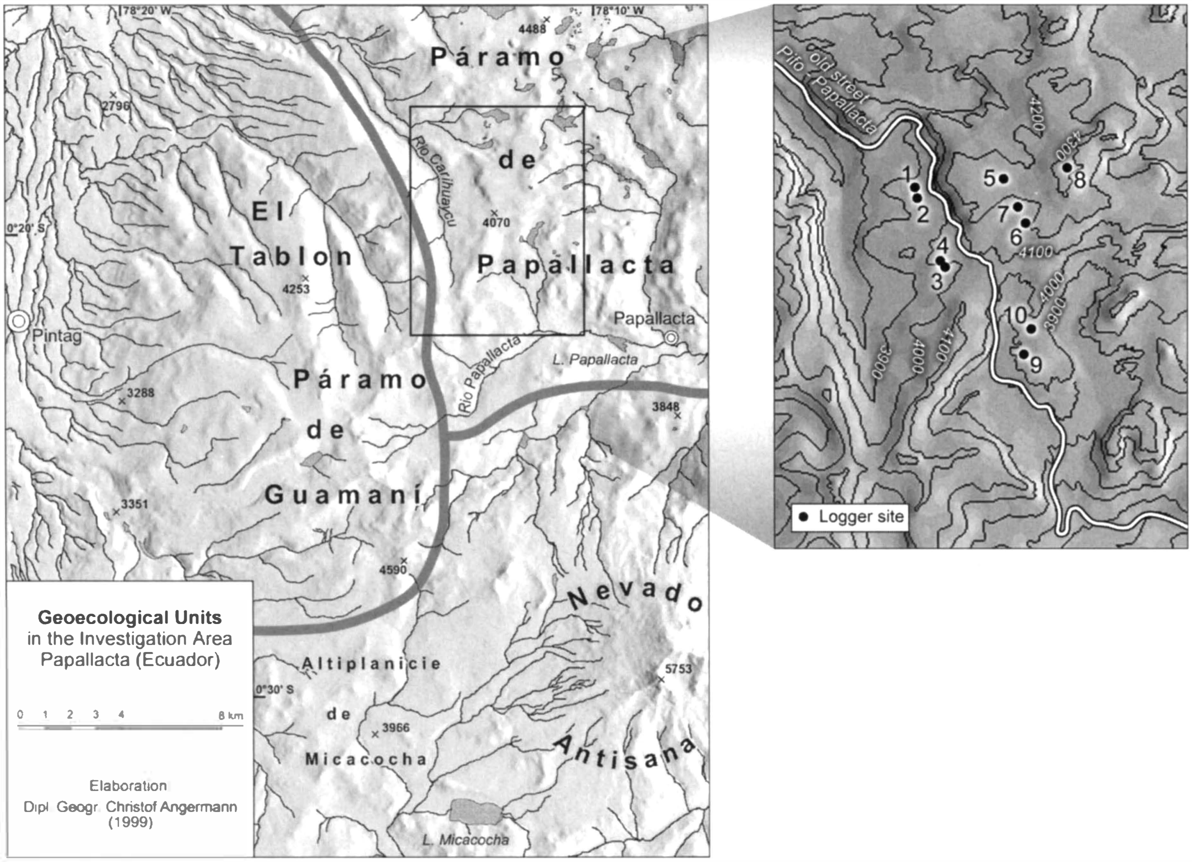

Fig. 1: Study area and observation sites
Das Untersuchungsgebiet und die Lage der Messstandorte

patches (Photo 1) which currently form the upper tree line at approximately 4100 m asl describe the potential timberline. The change of a closed forest to grassland with forest mosaics up to 4100 m is mainly due to human influence, as e. g. in the form of periodic burning in order to provide pasture land (LÆGAARD 1992). Above the Grass-Páramo follows a transition zone (4100–4200 m asl) which is generally characterised by small shrubs of the community "*Loricarion*" (s. Supplement II) and is topped by the Cushion-Páramo. The transition zone can be described as the Subpáramo because the Grass-Páramo is predominantly the result of human activity.

Even if microclimatological measurements have been performed during several field surveys in the study area since 1985, most observations which are presented in this paper are taken from two field campaigns in March 1999 and July 2000. In March 1999, ten typical locations were selected and equipped with small data loggers in order to obtain soil temperatures at soil depths of –0.5 m over a longer period. The UTL-1 V2.0 system (University of Bern, Switzerland) can measure and store hourly soil temperatures for 331 days at an hourly resolution. The minimum temperature resolution is 0.23 K. Variations in soil temperature less than 0.23 K cannot be observed with this logger. The main criterion for site selection was to cover typical plant communities of this area (Tab. 1) with special reference to the comparison of forest patches and adjacent bunchgrass sites at the upper tree line (Photo 2).

In order to examine the daily course of soil heat flux and soil temperature, especially in the root zone (–0.1 m) under various weather conditions, a portable data logger (Campbell Scientific 21X) was used. The logger was equipped with two pyranometer sensors (Li200Sz, Sky SP1110), three precision thermistor probes (Campbell 107) for soil temperature observations, three heat flux plates (Hukseflux HFP01) for soil heat flux measurements and one TDR (Time-Domain Reflectance) water content reflectometer (CS615) for the determination of the volumetric water content of the root zone.

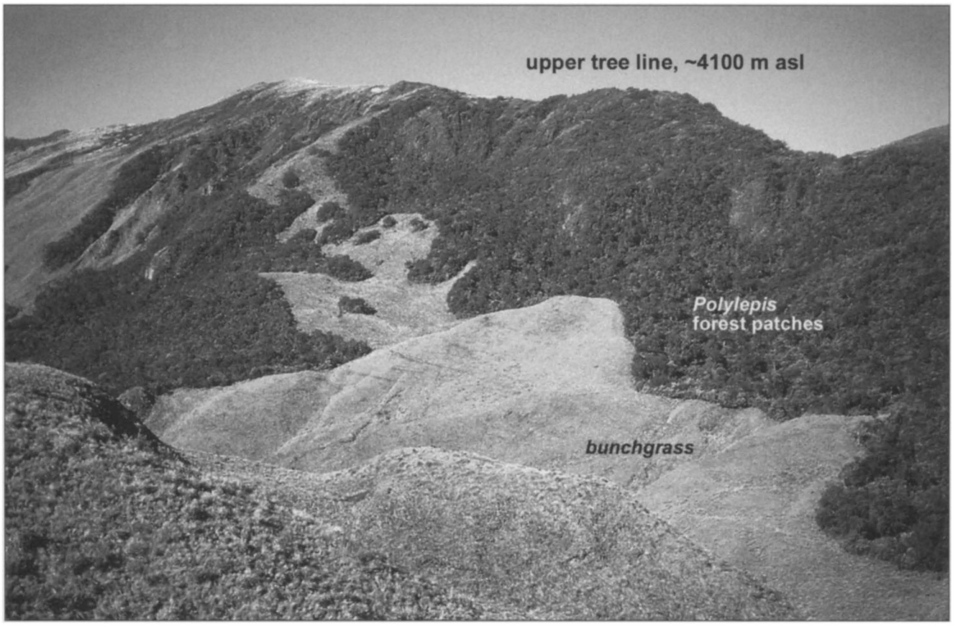

Photo 1: View on to the upper tree line in the Páramo of Papallacta with extended patches of *Polylepis* forests (*Photo:* J. BENDIX 2000)

Blick auf die *Polylepis*-Bestände an der oberen Waldgrenze des Páramo de Papallacta

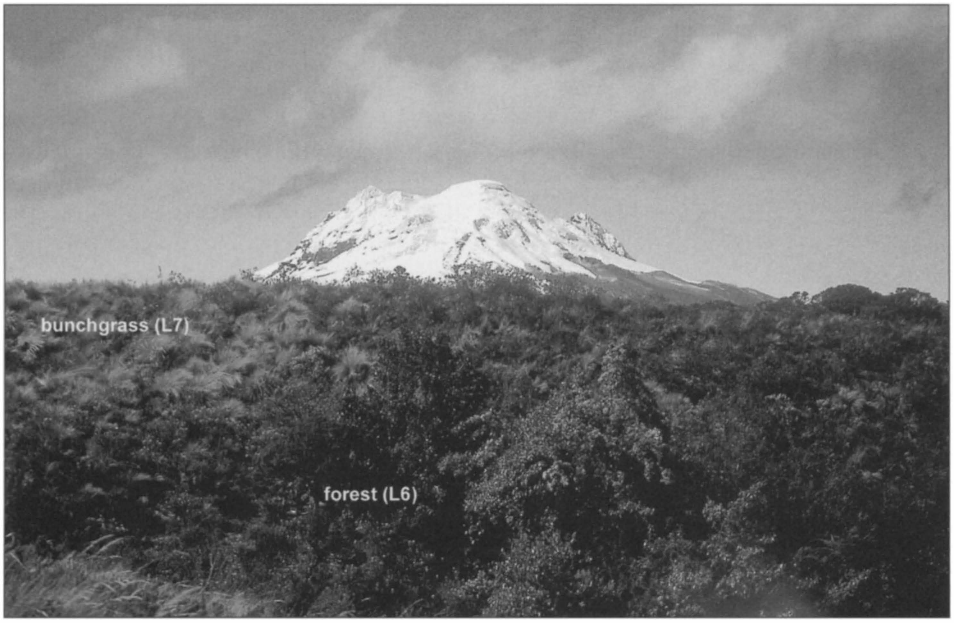

Photo 2: Typical forest at the upper tree line (Logger 6) with *Baccharis arbutifolia* and *Gynoxys buxifolia* as well as adjacent bunchgrass (Logger 7). The Antisana volcano (5753 m asl) is seen in the background (*Photo:* J. BENDIX 2000)

Ein typischer Bestand aus *Baccharis arbutifolia* und *Gynoxys buxifolia* an der oberen Waldgrenze (Logger 6) und Büschelgras-Páramo (Logger 7). Im Hintergrund der Schneegipfel des Vulkan Antisana (5753 m ü. NN)

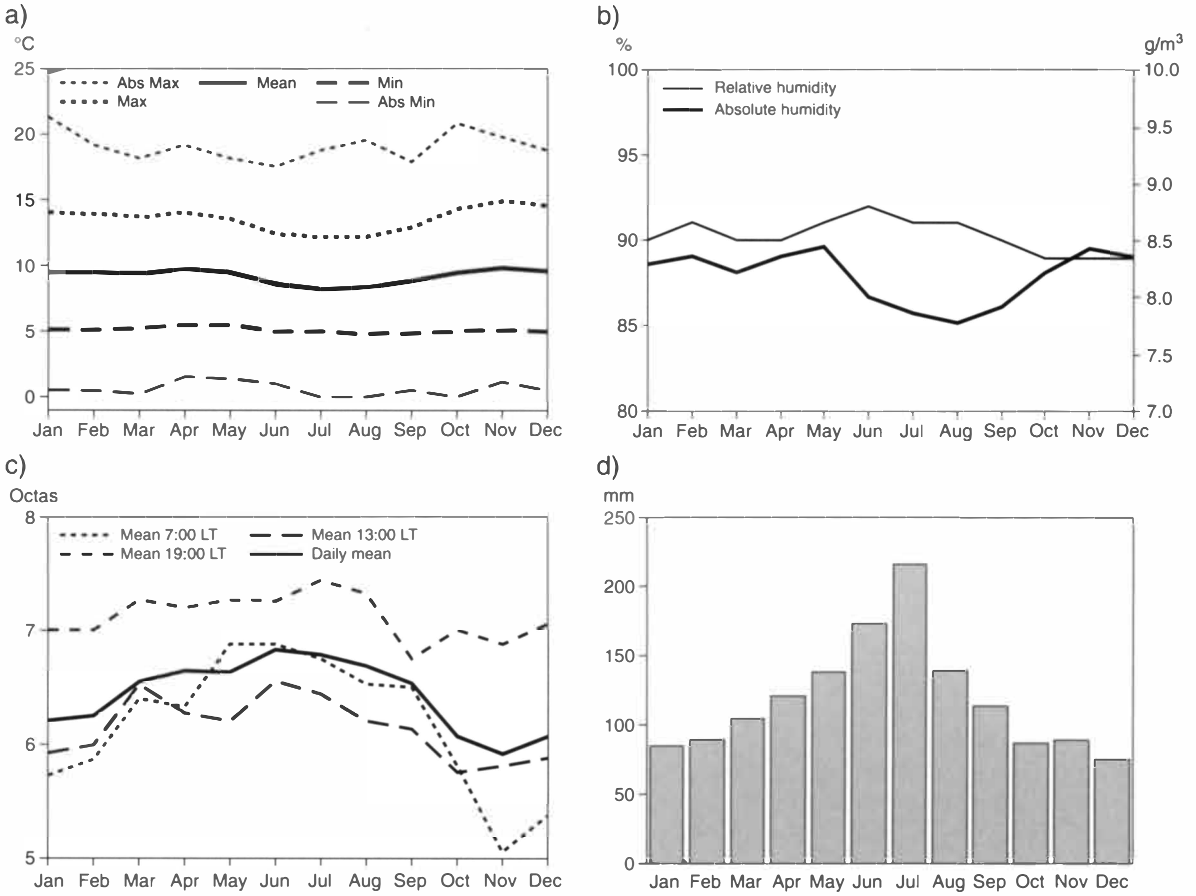

Fig. 2: Climate of Papallacta (3160 m asl); (a) air temperature, (b) relative and absolute humidity, (c) cloudiness, (d) rainfall, (period: 1963–1982) (data: INAMHI)

Das Klima von Papallacta (3160 m ü. NN); (a) Lufttemperatur, (b) relative und absolute Feuchte, (c) Bewölkung, (d) Niederschlag (Periode 1963–1982) (Daten: INAMHI)

2.2 Climatology of the study area

Like the most Ecuadorian Páramos in the eastern Cordillera (ACOSTA-SOLIS 1984), the Páramo of Papallacta can be characterised as a cold and humid environment throughout the year with a diurnal freeze-and-thaw cycle, relatively cold days, clear nights, frequent daily rain and drizzle as well as occasional high wind speeds. However, there is no direct meteorological information from the study area due to a lack of routine observations. The closest meteorological station of the national weather service INAMHI (in operation from 1963 to 1982) is Papallacta (3160 m asl) east of the main watershed (s. Fig. 1). This station shows a unique climatic regime which is typical for the altitudinal belt between approximately 900 and 3600 m asl of the eastern Andean slopes, particularly for the region of the "Ceja de la montaña" (for details refer to BENDIX a. LAUER 1992). It is characterised by only one rainy season with a maximum in June/July (Fig. 2 d) and relatively dry seasons between October and February. The

Table 1: Observation sites (for location refer to Fig. 1)

Standorte der Datalogger (zu ihrer Lage vgl. Fig. 1)

Site No	Altitude [m asl]	Vegetation cover
Logger L1	3950	Forest
Logger L2	3950	Grass-Páramo
Logger L3	4000	Forest
Logger L4	4000	Grass-Páramo
Logger L5	4226	Subpáramo
Logger L6	4060	Forest
Logger L7	4060	Grass-Páramo
Logger L8	4330	Cushion-Páramo
Logger L9	3920	Forest
Logger L10	3935	Grass-Páramo

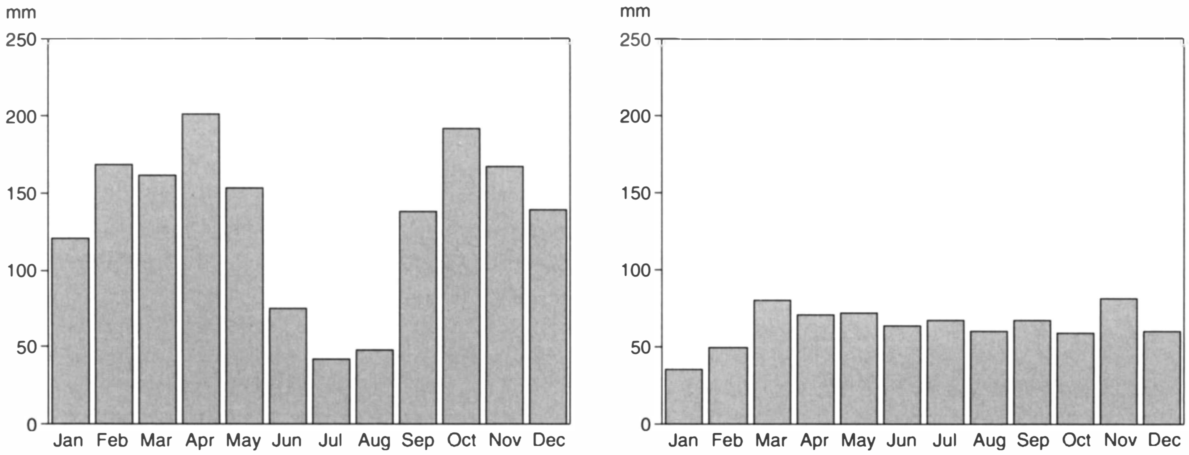

Fig. 3: Rainfall in the Páramo del Antisana (left) at Pinatura 1963–1985 (3250 m asl) and (right) Micacocha 1965–1966 and 1987–2000 (4000 m asl) (data: INAMHI)

Niederschlag an den Stationen Pinatura (3250 m ü. NN), Páramo del Antisana (links) (Periode: 1963–1985) und Micacocha (4000 m ü. NN) (Periode: 1965–1966 u. 1987–2000) (Daten: INAMHI)

yearly average precipitation is 1433.6 mm. Relative humidity and cloudiness (Fig. 2 b and c) are consequently increased during the rainy season. Cloud frequency is at its maximum in the late afternoon, especially due to well developed thermal up-slope and up-valley winds. Typical is the small annual range in air temperature which is linked to the yearly course of rainfall. The minimum temperature coincides with rainfall; the maximum, and absolute minima of air temperature of 0°C over the observation period are observed for the rainy season from July until October (Fig. 2 a). In contrast to the climate of the eastern slopes, the situation on the western slopes reveals the typical yearly course of the inter-Andean Quito basin with two rainy seasons, peak rainfall in April and October, a main dry season in July–August and a second relatively dry period in December–January (Fig. 3). Data are taken from Pinantura (yearly average = 1607 mm), located on the western slopes of the Nevado Antisana which directly borders on the Páramo of Papallacta in the south.

The different climatic situations of the eastern and western slopes have consequences for the climate of the more elevated Páramo region close to the tree line as well as for the life types and the distinction of vegetation formations. 16-year observations of rainfall at Micacocha (4000 m asl) in the Páramo del Antisana show that a real dry season does not exist, with a slight exception of rainfall reduction in January. However, the yearly average of 768.1 mm at this station is less than on both slopes. The rainfall situation is characterised by continuous drizzle formation throughout the year. Comparable weather conditions are found in other Páramos of the eastern Cordillera as e. g. the Páramo of Pisayambo (1°04′ S) (CERÓN M. 1985).

The climatic situation in the elevated Páramos of the eastern Cordillera is a result of the combination of both rainfall regimes in the pass area and is initiated by an interaction of local circulation systems and the synoptic situation (Fig. 4). The rainfall maximum in July on the eastern slopes is mainly due to well developed trades which produce barrage effects (condensation and rainfall) at the windward side of the Cordillera. However, these clouds spill over the pass area and cause rainfall (mostly drizzle) also at the western slopes of the Páramo. Snow-hail showers are possible especially if the trades are countered by an up-slope circulation from the Quito basin, and the resulting confluence in the pass area leads to deep convection. On the other hand, relatively moist air from the Quito basin is advected to the pass area from the west during the two rainy seasons by means of the valley circulation. Clouds and rain again spill over the pass area and affect the eastern slopes of the Páramo. Finally, thermal wind systems develop on typical radiation days without any synoptic disturbance at both sides of the pass, thus converging in the Páramo which leads to convection, cloud formation and rainfall, predominantly in the afternoon and the early evening. In conclusion, only the combination of these mechanisms guarantees the continuous humidity of the Páramo area throughout the year. This situation is the reason why the Sub- and Cushion Páramo are forming a uniform humid cap above the different humid slopes east and west of the main watershed.

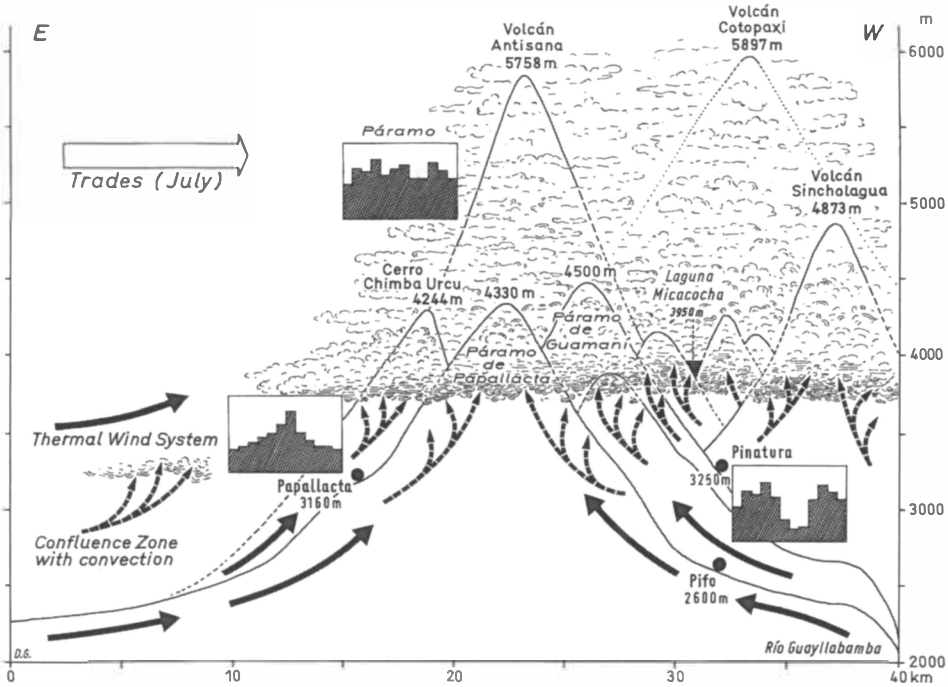

Fig. 4: Climatological situation in the Páramo of Papallacta
Klimatologische Verhältnisse im Páramo de Papallacta

2.3 Soil properties of the study area

All soils in the Páramo of Papallacta have developed on a special aeolic-volcanic sediment, the fine granular Cangahua, which covers the volcanic base with a thickness of several meters at the ridges of the Cordillera up to >100 m in the Quito basin. Selected soil parameters for some logger sites are presented in Table 2. In general, the soils of the study area are acid and black (under bunchgrass, Logger 2, 4, 7 and 10) or dark brownish in the forests and the cushion area (Logger 1, 3, 5, 6, 8 and 9). As in other Páramos of Ecuador, soils are predominantly humic. Particularly concentrations of peat-like humus in the root zone (0–0.2 m) can even exceed the average values which are presented here (Mena et al. 2000).

The highest humus content is observed at the lower sites under bunchgrass and the forest patches, but it

Table 2: Soil parameters (mean 0–0.5 m) at selected logger sites (L1 = Logger 1 etc.)
Bodenparameter ausgewählter Loggerstandorte

Logger	clay < 2 [%]	fU 2–6.3 [%]	mU 6.3–20 [%]	gU 20–63 [%]	fS 63-200 [%]	mS 200-630 [%]	gS 630–2000 [%]	Humus [%]	pH	θ [Vol-%] –0.1 m
L1	12.62	10.71	26.86	21.37	22.67	5.58	0.19	11.30	4.4	52.7
L2	15.20	10.13	24.15	22.70	23.39	4.37	0.05	17.93	4.3	55.6
L3	13.50	8.13	20.10	21.68	23.60	8.69	4.30	15.73	4.4	–
L5	2.30	7.44	28.26	20.47	1.24	30.56	9.72	4.99	4.8	–
L6	–	–	–	–	–	–	–	–	–	55.1
L7	3.67	6.51	19.16	19.16	3.87	30.78	12.48	6.50	4.7	55.4
L8	2.71	7.56	19.82	19.82	0.17	35.95	8.50	4.11	4.8	–
L9	–	–	–	–	–	–	–	–	4.5	–
L10	13.23	8.23	28.79	19.49	22.10	6.87	1.29	8,61	4.5	–

U= coarse clay, S = sand, f = fine, m = medium, g = coarse

Table 3: Thermal parameters for selected Logger sites (soil depth 0.1–0.5 m)

Thermische Parameter (10 bis 50 cm Bodentiefe) für ausgewählte Logger-Standorte

Logger site	k $W\,m^{-1}\,K^{-1}$	d_D m	$\Delta t_{0.1}$ [h]	$\Delta t_{0.3}$ [h]	$\Delta t_{0.5}$ [h]	$\Delta t_{0.5}$* [d]
L1	0.34	0.0572	6.7	20.0	33.4	254
L2	0.24	0.0503	7.6	22.8	38.0	288
L6	0.33	0.0565	6.7	20.3	33.8	257
L7	0.59	0.0744	5.1	15.4	25.7	195

decreases significantly in the more elevated zones of cushion plants due to lower production of organic matter. Additionally, the forest soil is covered by a dense mossy and peat-like organic layer of approximately 5–10 cm, which is not established in the bunchgrass and cushion plant sites. Consequently, there is a relation of humus content and water retention capacity. The majority of logger sites with high concentrations of peat-like humus are water saturated throughout the year, with a slight decrease of water retention capacity for the zone of cushion plants. The TDR measurements of volumetric water content (θ) at four logger sites, which are taken from the root zone (–0.1 m soil depth) during days with continuous solar irradiation (Tab. 2), clearly explain this situation with constant high values ranging from 52.7–55.6%. The figures represent daily means but, although they were taken during radiation days, no daily course of volumetric soil moisture content could be observed. However, it should be noted that soils become much drier below a depth of approximately 0.2 m.

Accounting for the non-organic soil components, the lower sites are mostly characterised by sandy-loamy clay soils (L1, L2, L3, L10). The sand content increases with rising elevation and soils are a compound of sandy loam (L5) or clayey sand. There are several consequences for the thermal behaviour of the Páramo soils, especially due to the high content of peat-like humus and water saturation in the root zone and the relatively dry levels between 0.3 and 0.5 m. From the comparison of heat flux measurements and soil temperatures at four logger sites, the thermal soil conductivity (k) between –0.1 and –0.5 m could be determined according to STOUTJESDIJK and BARKMANN (1992):

$$k = \frac{H \cdot \Delta z}{\Delta T} \tag{1}$$

H = heat flux through a horizontal plane [$W\,m^{-2}$], $\Delta T/\Delta z$ = Soil temperature gradient [$K\,m^{-1}$]

In comparison to tabulated values (Tab. 3 and STOUTJESDIJK a. BARKMAN 1992) of pure sand or clay soils (average k = 1.9), thermal conductivity at all sites is relatively low but, with the exception of logger 2, higher in comparison to peat with a volumetric water content of 50% (average k=0.27). Evidence for the major importance of the humus content, for the thermal behaviour of the soils is given by site 7, which shows a low humus content and the highest conductivity in comparison to site 2, which is characterised by a high humus content in combination with the lowest conductivity (Tab. 2 and Tab. 3).

An estimation of the heat flux within soils is given by the theoretical concept of a sine-shaped heat wave over the period a day (24 h) or a season (e. g. 6 months) which propagates from the soil surface to deeper levels. From tabulated values of sand and clay soils as well as peat (STOUTJESDIJK a. BARKMANN 1992), the damping depth (d_D), which indicates how temperature fluctuations at the soil surface are reduced downward in the soil, is linearly related to thermal conductivity by:

$$d_D = \frac{k \cdot 0.489704}{14.50446} \tag{2}$$

d_D = damping depth [m], k = thermal conductivity [$W\,m^{-1}\,K^{-1}$]

From this theoretical concept, the propagation time of a sine-shaped heat wave can be derived as follows (STOUTJESDIJK a. BARKMANN 1992):

$$\Delta tz = \frac{t_0 \cdot z}{2\pi \cdot d_D} \tag{3}$$

t_0 = 24 h (for daily heat wave) or length of the season in days (365 for a one year heat wave), z = soil depth [m]

Table 3 shows the resulting propagation times for a daily heat wave to 0.1 m soil depth which vary from 5.1 hours at site 7 to 7.6 hours at the most humic site 2. The delay time until the heat wave reaches a depth of 0.3 m ranges from 15.4 to 22.8 hours. For 0.5 m, the delay is between 25.7 and 38 hours. A yearly heat wave which is sine-shaped does not exist for the study area. However, from figure 2 a one could derive a weak half yearly heat wave. With a t_0 of 182.5 days, propagation times of a half-yearly heat wave to 0.5 m soil depth ($\Delta t_{0.5*}$ in Tab. 3) would range from 195 to 288 days.

3 *The –0.5 m soil temperature*

Two vertical profiles of –0.5 m soil temperatures, taken from the western and eastern slope of the study area, were measured under a standardised surface on two days in March 1999, without accounting for daily or yearly variations (Fig. 5). These altitudinal profiles were completed by three observations from the western slope of the Antisana in July 2000. Different temperature gradients were obtained. On the western slope, the gradient amounts to 0. 78 °C 100 m^{-1} whereas it decreases to 0.54 °C 100 m^{-1} on the eastern slope, which agrees quite well with earlier observations (LAUER a. RAFIQPOOR 1986). The difference between both slopes is mainly caused by the temperatures of the lower altitudes. Above 3700 m where the humid Páramo climate begins on both slopes, the two profiles become quite similar, as also in comparison with the measurements from the Páramo of Antisana. Below 3200 m, the western slopes which are oriented to the dryer Quito basin are significantly warmer than the wet eastern slopes which are characterised by elfin forests, cloudy, foggy and rainy weather. Consequences are a reduced heating by solar irradiation and a greater amount of latent heat transformation in comparison to the drier western slopes where the production of sensible heat predominates.

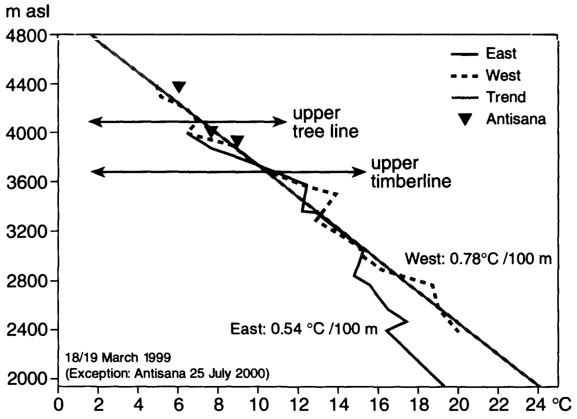

Fig. 5: Vertical profile of –0.5 m soil temperature west and east of the main watershed, horizontal reference (grass) surface (except for the cushion Páramo belt)

Vertikalprofil der Bodentemperatur in 50 cm Tiefe an den West- und Ost-Abdachungen der Hauptwasserscheide. Vegetationsbedeckung der Messstandorte: Gras als Referenzfläche (außer Polsterpáramo)

The average yearly –0.5 m soil temperatures for all logger sites and the yearly standard deviation are presented in Fig. 6. The –0.5 m soil temperature at the tree line (~ 4100 m asl) ranges between 4.3 to 4.6 °C (L6, L3), the difference to the adjacent bunchgrass plots amounts to 0.8 °C (L7–L6) and 1.2 °C (L4–L3) and is significantly lower than reported in MIEHE a. MIEHE (1994) and WINIGER (1979). This is mainly due to the similar soil components (non-organic material, humus, soil moisture). The same behaviour is observed for the lower sites of forest and bunchgrass (Logger 1 and 2). Mean yearly temperature is 5.9 °C in the forest, with a difference to the grass plot of 0.9 °C (L2–L1). With 4.7 °C, the *Polylepis pauta* forest on the eastern slopes is slightly colder due to wetter and more humic conditions. Consequently, greater differences to the adjacent bunchgrass occur (L10–L9 = 1.9 °C). A relative high yearly average of 5.2 °C is observed for the transition zone at logger 5, whereas the highest point is significantly colder (3.3 °C) because this site is directly exposed to the cold trades with high wind speeds during most of the year (see also LAUER et al. 2001). Relatively high temperatures at Logger 5 are probably due to the eastern orientation of the site. Slopes with this aspect are slightly more heated by solar radiation in the morning whereas sites with a western aspect are disadvantaged by a reduced irradiation due to thermally induced cloud formation in the afternoon.

The overall variation in the average –0.5 m soil temperature is generally higher under the non shaded surfaces with a maximum standard deviation of 1 °C in the transition zone at logger 5. This is obviously due to higher extremes of incoming shortwave and outgoing longwave radiation at the unsheltered sites in comparison to the canopy-sheltered and organic litter-insulated forest soils. The variations in soil temperature occurring at the upper tree line are predominantly due to seasonal rather than to daily changes, as is revealed, for example, in Fig. 7 for logger sites 6 and 7. Daily variations in the –0.5 m soil temperature which are greater than the logger resolution can be neglected for all logger sites.

The average course of the –0.5 m soil temperature over the year is similar at all logger sites (Fig. 8). A significant temperature depression is observed, which is centred on August 1999. The mean monthly maximum is reached for the most sites between December 1999 and January 2000. The average difference between the monthly minimum and maximum temperature varies from 1.1 °C in the forest at site 1 to 2.8 °C in the transition zone at site 5 (Tab. 4). It should be noted that the temperature difference between the forest and the adjacent bunchgrass sites becomes significantly smaller during the cold period, with the exception of sites 9/10.

Additionally, the differences between absolute minimum and maximum soil temperatures during the ob-

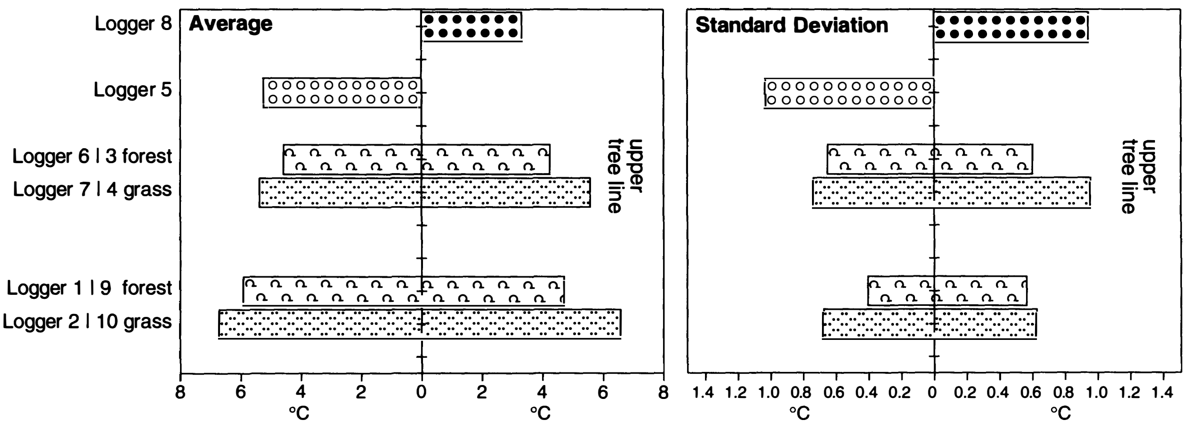

Fig. 6: Average –0.5 m soil temperatures (left) and standard deviation (right) from 12 March 1999–4 February 2000 (0:00–23:00 LT)

Mittlere Bodentemperatur in 50 cm Tiefe (links) und die Standardabweichung (rechts) für die Zeit zwischen 12. März 1999 bis 4. Februar 2000 (0:00–23:00 Ortszeit)

servation period are greater than the average monthly differences (Tab. 4). Absolute minimum temperatures occur for all logger sites during mid- to late-August 1999. At the upper tree line, minimum temperatures for the forests vary from 2.83 °C (Logger 3) to 1.92 °C (Logger 6) and hence, are significant lower than the minimum temperature for the highest tropical tree site (3.3 °C, momentary observation) which is reported by MIEHE a. MIEHE (1994).

An interesting feature is that the maximum amplitude in soil temperature over the year is sometimes higher within the forests than for bunchgrass sites (L6/L7, L9/L10). This was not expected due to stronger radiation processes at non-shaded surfaces. It is obvious that environmental factors must play an important role on soil temperature development. For example, the forest at site 9 is located in a west-orientated dale and is consequently colder than the adjacent bunchgrass site (L 10) which is situated on a well-illuminated, periodically burned ridge.

It is obvious that the average soil temperature is lower than 7 °C at all sites of the upper tree line. To account for biological processes which are related to the growth limitation of trees as is done by WALTER a. MEDINA (1969) and KÖRNER (1998), it is more appropriate, especially in the light of the annual variability in –0.5 soil temperature, to use the concept of thermal time which integrates the soil temperature with the time (days, hours) above a threshold (MORECROFT et al. 1998). The results for the forest sites are given in Tab. 5. No one of the forest sites show –0.5 m soil temperatures ≥7 °C. Only the site with the lightest canopy (L1) reveals an above-average count of hours ≥6 °C. For the other forests, significantly colder soils are observed. At sites L6 and L9, 50% of the hours are colder than 4.7 °C and at L6 even colder than 4.3 °C.

Table 4: Variation of –0.5m soil temperature for March 1999 to February 2000 [°C]

Variation der Bodentemperatur (50 cm Tiefe) zwischen März 1999 und Februar 2000 [°C]

Logger	Average	Minimum, d, h [LT]	Maximum, d, h [LT]	Maximum T	Average T
L1	5.92	5.12, 28-08, 09:00	6.74, 14-04, 11:00	1.62	1.1
L2	6.76	5.12, 23-08, 00:00	7.93, 14-04, 21:00	2.81	1.9
L3	4.25	2.83, 23-08, 01:00	5.12, 14-04, 11:00	2.29	1.7
L4	5.54	2.38, 16-08, 19:00	7.46, 21-12, 22:00	5.08	2.7
L5	5.24	2.38, 18-08, 23:00	6.98, 10-01, 16:00	4.60	2.8
L6	4.61	1.92, 16-08, 16:00	5.81, 11-04, 01:00	3.89	1.8
L7	5.38	3.29, 19-08, 06:00	6.51, 12-01, 09:00	3.22	2.0
L8	3.32	1.47, 24-08, 04:00	5.21, 08-01, 13:00	3.65	2.5
L9	4.67	2.83, 16-08, 15:00	5.58, 23-12, 14:00	2.75	1.6
L10	6.57	4.89, 20-08, 11:00	7.46, 11-01, 20:00	2.57	1.7

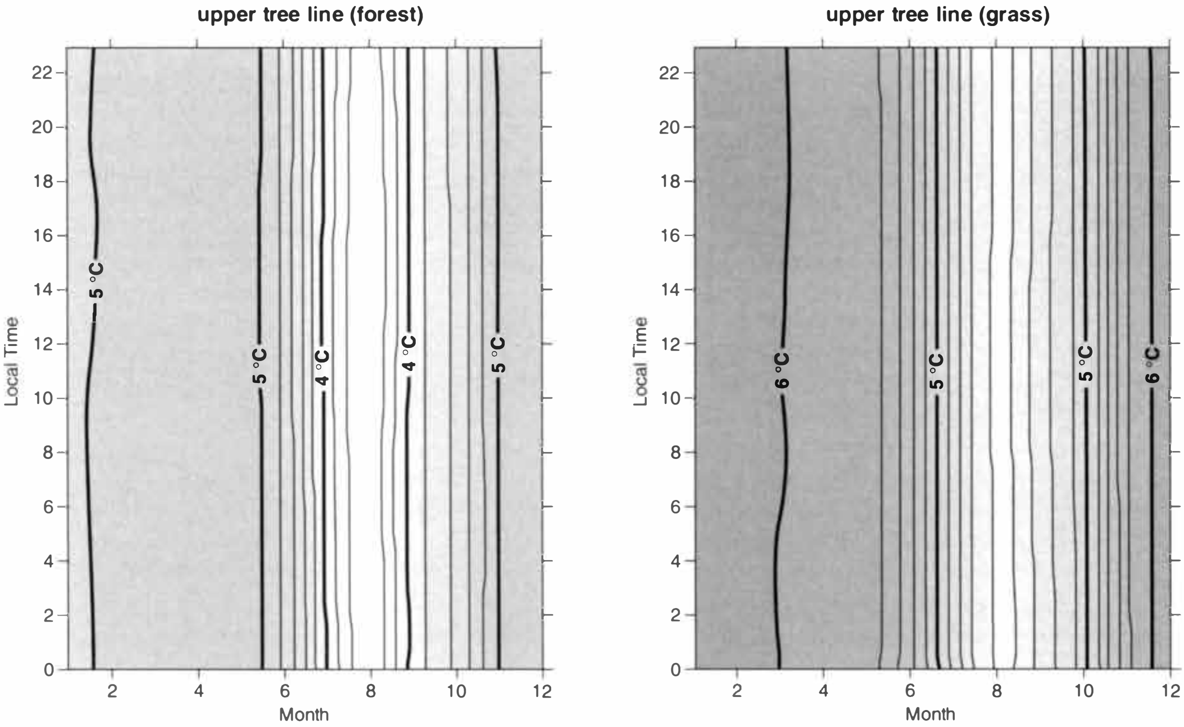

Fig. 7: Thermo-isopleths of the -0.5 m soil temperature at the upper tree line, (left) Logger 6 and (right) Logger 7
Thermoisoplethendiagramme der Bodentemperatur (50 cm Tiefe) im Wald (Logger 6) und Büschelgras-Páramo (Logger 7) an der oberen Waldgrenze des Páramo de Papallacta

4 Case studies on soil heat flux and soil temperature

In order to test the hypothesis of soil heat flux reduction in the root zone due to canopy shading as formulated by Körner (1998), but also to study the influence of different synoptic weather situations on soil temperature, two pairs of forest / adjacent grass Páramo (L1/2 and L6/7) sites at the upper tree line were examined intensively. High resolution measurements (temporal resolution 1 minute) of soil temperature, soil heat flux (–0.1, –0.3 and –0.5 m), soil volumetric water content (–0.1 m) and solar irradiation were carried out for 10 days (9:00–18:00 LT) under different weather conditions. Additionally, air temperature, relative humidity, wind speed/direction (2 m) and cloudiness were observed.

4.1 Root zone (–0.1 m) heat flux

The soil heat flux (Fig. 9) under a reference surface (short cut grass, no inclination, 100% sky view) was measured for comparison purposes during a 24 h period of relatively calm and sunny weather with reduced cloudiness. Generally, soil heat flux in the root zone reflects the trend of solar irradiation with a time lag of approximately 1 hour. A comparable phase shift was also observed for bare soils in other studies (e.g. Collier et al. 1996). During daylight, the soil heat flux is positive, which means that flux is orientated from the soil surface downward to the root zone whereas it becomes negative at night, which marks a transfer of energy from the root zone to the soil surface and the atmosphere. The maximum downward flux of 34.78 W m^{-2} is reached at 14:18 LT, following a peak in global radiation of 1020 W m^{-2}. Two peaks of solar irradiation in the afternoon are also reflected in the heat flux as a momentary weakening of the general decrease.

Table 5: Forests at the upper tree line: Percent of hours ≥ a given threshold of –0.5 m soil temperature.
Prozentualer Anteil der Stunden ≥ bestimmter Schwellenwerte der Bodentemperatur (50 cm Tiefe)

Threshold	7 °C	6 °C	5 °C	4 °C
L1	0	52.9	100	100
L3	0	0	5.0	64.9
L6	0	0	33.1	80.7
L9	0	0	34.2	83.3

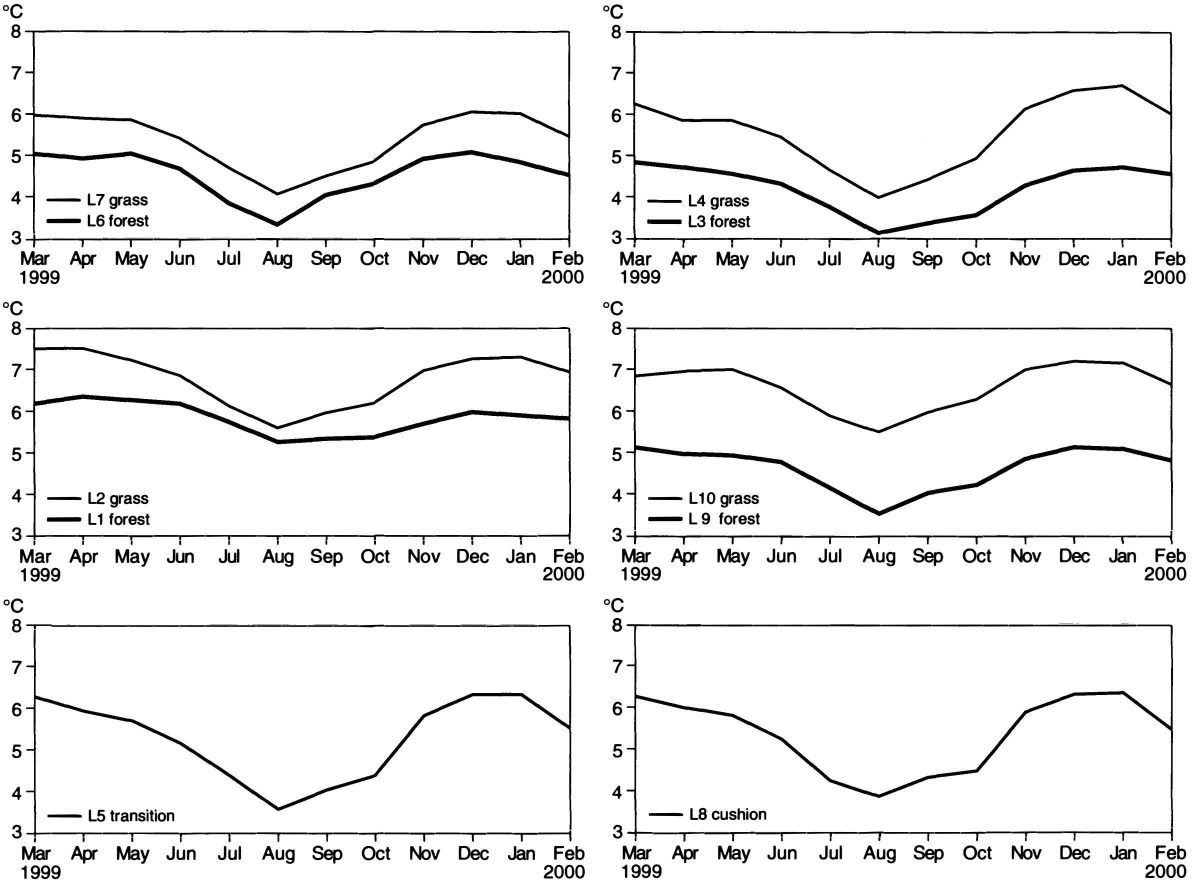

Fig. 8: Monthly averages of –0.5 m soil temperature
Monatsmittel der Bodentemperatur in 50 cm Tiefe

Finally, the soil heat flux of the root zone becomes negative almost abruptly after sunset with an absolute minimum at 6:00 LT, which implies that soil is cooled by nocturnal radiation. It should be noted that the flux balance in the root zone for the 24 hour period is negative, which means that more energy (–51.03 kJ m^{-2} 24 h^{-1}) is transferred towards the soil surface than vice versa. Thus, a good correlation between global radiation and soil heat flux can be assumed for a standard situation. This coincides with other studies which found a linear relationship between the sum of global radiation and soil heat flux (–0.02 m) during daylight for short grass (KOITZSCH et al. 1990).

The daily course of soil heat flux in the root zone of the Páramo bunchgrass sites also follows the curve of global radiation (Fig. 10). However, the great variation of weather conditions during the selected days causes a corresponding variability in the –0.1 m soil heat flux (Tab. 6). The weather at sites L2 and L7 during March 1999 was generally characterised by all-day cloudiness

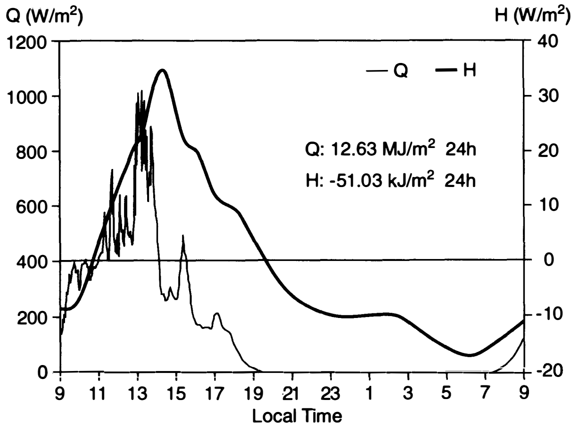

Fig. 9: Soil heat flux (–0.1 m) and solar irradiation for a short lawn at Cumbaya (2400 m asl), Quito-Basin
Bodenwärmefluss (in 10 cm Tiefe) und solare Strahlung für einen Rasen-Standort in Cumbaya (2400 m ü. NN) im Quito-Becken

Table 6: Selected observations during the case studies (refer to Figs. 12 and 13)
Ausgewählte Untersuchungen während der Fallstudie (vgl. Fig. 12 und 13)

Logger	$\int Q_{gr}0$ MJ m^{-2} d^{-1}	$\int Q_{fr}0$ MJ m^{-2} d^{-1}	$\int H_{-0.1}0$ kJ m^{-2} d^{-1}	ΔH kJ m^{-2} d^{-1}	T–0.1a °C	T–0.1x °C	T2a °C	T2x °C	Vx m s^{-1}	Cloud Octas
Grass										
L2, 99	9.32	–	115.9	10.90	8.1	8.6	6.4	9.3	5.8	7–8
L2, 00	15.20	–	62.6	15.62	5.4	6.5	9.0	12.4	5.3	0–7
L7, 99	4.12	–	9.8	3.87	6.7	6.9	6.0	9.6	3.6	7–8
L7, 00	13.14	–	23.5	8.89	7.5	7.8	7.6	10.5	7.4	0–8
Forest										
L1, 99	14.23	2.52	89.9	12.1	7.0	7.8	10.1	22.7	8.8	3–8
L1, 00	18.76	5.64	-55.6	3.9	4.4	4.5	4.7	6.4	12.8	1–8
L6, 99	8.14	0.69	-4.6	5.49	5.5	5.7	7.4	13.9	3.4	7–8
L6, 00	22.31	3.94	133.3	10.68	3.3	3.8	8.0	13.5	7.8	1–6

d = 9:00 - 18:00 LT, a = daily average, x = daily maximum, gr = grass, fr = forest ground

(7–8 Octas), drizzle and rain as well as relatively cold air temperatures (mean ~6 °C) and reduced wind speed. On 14th March, periods of increased direct radiation are restricted to cloud gaps. The two peaks in radiation can be also detected for the soil heat flux with a delay of approximately 1 hour at around 15:00 and 16:40 LT.

An absolute cloudy situation was obtained seven days later (21 March 1999) on site L7 where predominantly diffuse radiation was available. Hence, soil heat flux in the root zone oscillates around 0 W m^{-2}.

In contrary, the two days in July 2000 were characterised by a high intensity of solar radiation, increased air

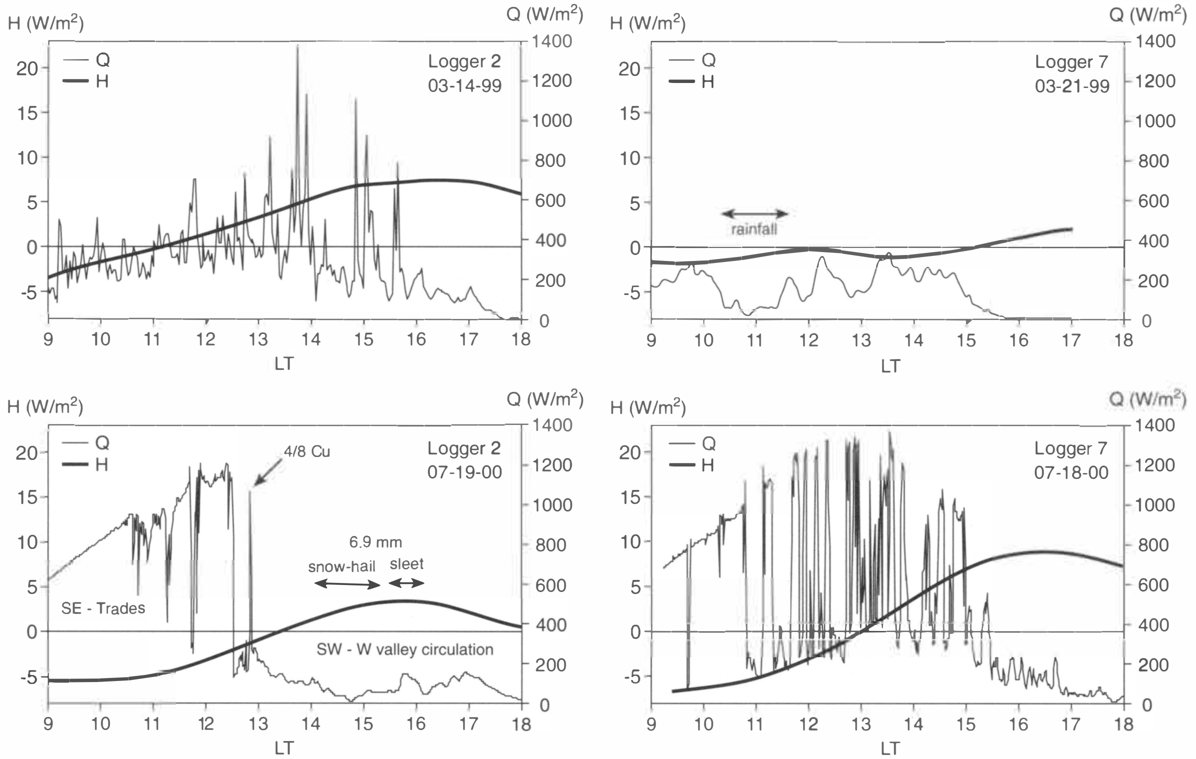

Fig. 10: Soil heat flux (-0.1 m) and temporal sum of global radiation for the bunchgrass sites (L 2 and L7)
Bodenwärmefluss (10 cm Tiefe) und Globalstrahlungssumme von zwei Standorten des Büschelgras- Páramo

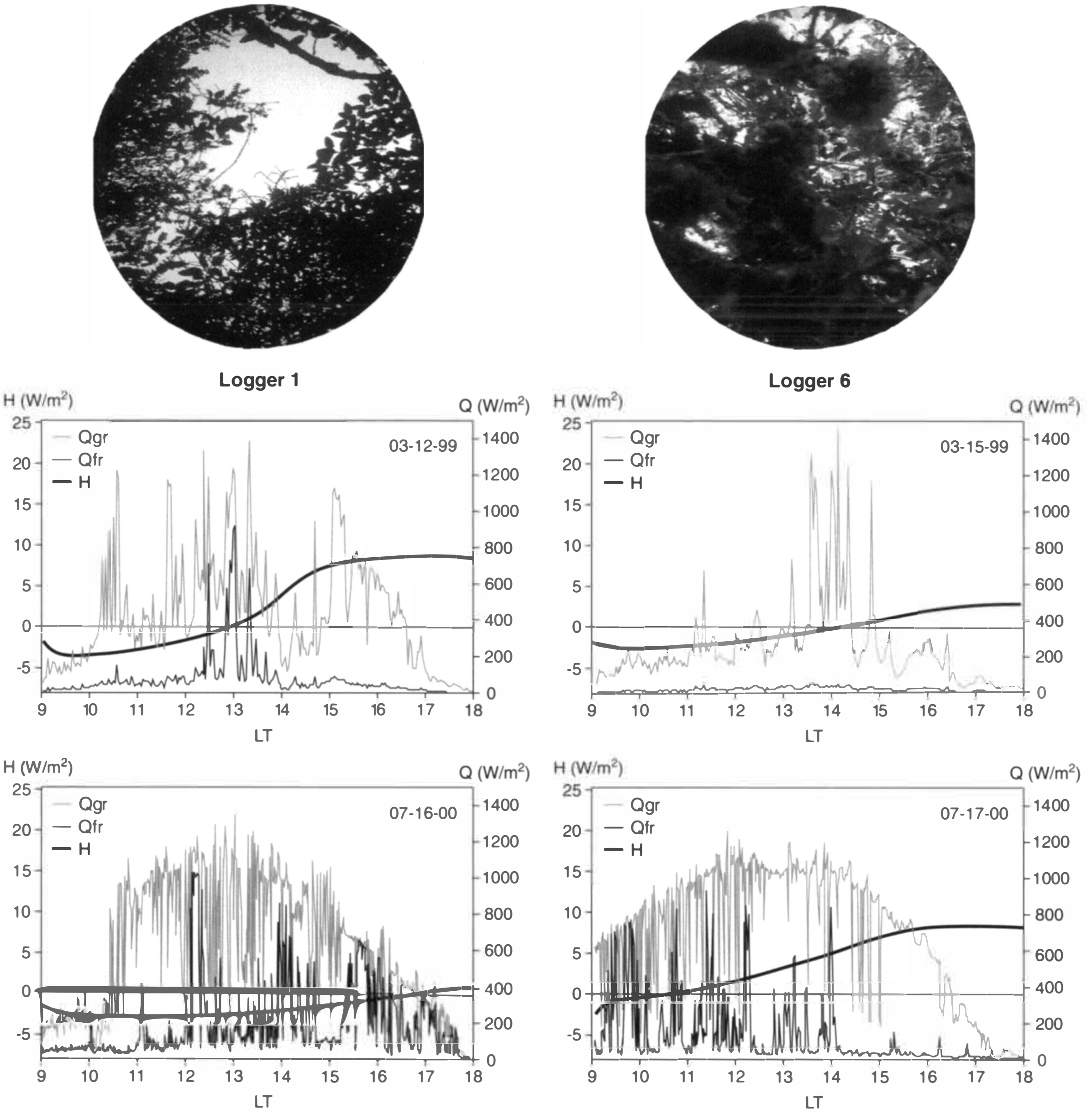

Fig. 11: Sky view and soil heat flux (-0.1 m) for the forest sites (L1 & L6) as well as temporal integrated values of global radiation in and outside the forest

Horizontblick und Bodenwärmefluss (10 cm Tiefe) für zwei Waldstandorte sowie zeitlich integrierte Werte der Globalstrahlung im und außerhalb des Waldbestandes

temperature, less cloudiness and slightly increased wind speed (Tab. 6). Due to clear nights, the soil heat flux in the morning hours is significantly lower than in March 1999. Hence, the maximum of soil heat flux on both days is reached with a delay of approximately three hours compared to the maximum of global radiation which is rather strong until noon. However, this weather situation causes a well developed thermal wind system so that up-valley winds from the Quito basin (SW-W) replaced the south-easterly stream flow of the morning hours from 11:00 to 17:00 on 18th July. On 19th July, up-valley winds between 13:00 and 16:00 LT caused deep convection, increased cloudiness and a snow-hail shower as well as sleet in the afternoon. As a result, the heat flux in the root zone was higher on 18th July than during the next day.

Although the daily course of soil heat flux in the root zone is similar to the development of global radiation, the comparison of daily integrated values of global radiation ($\int Q_{gr}0$) and the daily amplitude of soil heat flux (ΔH) do not show such a clear relation. A correlation yields only $r^2 = 0.15$. On the other hand, the mean air temperature (T2a) shows a significantly stronger correlation ($r^2 = 0.69$) with the ΔH. Hence, the air temperature seems to be more important for the soil heat flux in the root zone: The lower the mean air temperature, the lower the daily amplitude of soil heat flux. However, the average air temperature itself is highly correlated ($r^2 = 0.84$) to the daily integral of global radiation, which means that not the radiation at one specific point but the increase in air temperature in a wider area (or synoptically induced cooling) seems to dominate the soil heat flux at a single point.

The same comparison is performed for the forest sites L1 and L6 (Fig. 11; Tab. 6). As expected, the relation between the daily course of root zone heat flux and solar radiation on the forest ground is less significant than was obtained for the bunchgrass sites. Site L1 is characterised by a lighter canopy layer (sky view = 28.5%) which is more dense for L6 (sky view = 14.2%). Consequently, the integrated solar radiation reaching the forest ground ($\int Q_{fr}0/\int Q_{gr}0$) is lower at site L6 compared to site L1 during both cloudy (March 99, L1 = 17.7%, L6 = 8.5%) and sunny conditions (July 00, L1 = 30.1%, L6 = 17.7%) (Tab. 6). Like the relation of sky view for site L1:L6, the relation of radiation reaching the ground is approximately 2:1. One hypothesis, which is discussed by KÖRNER (1998), that restrictions in sky view due to increasing canopy density should reduce soil heat flux and lead to a colder root zone cannot be confirmed completely, especially accounting for single day observations (Tab. 6). Although L6 has a denser canopy and radiation at forest ground was decreased on 17th July in comparison to site L1 (16th of July), L6 revealed a higher integrated sum and a higher daily amplitude of soil heat flux. Nevertheless, the root zone soil temperature was lower under site L6. The strongest correlation between mean daily air temperature and soil heat flux amplitude ($r^2 = 0.8$) again points to the close relation of these parameters, whereas the correlation to the average root zone temperature is significantly weaker ($r^2 = 0.35$). This can be explained by the weather situation. On 16th July, the soil heat flux is negative most of the day, which means heat is transferred from the root zone to the forest ground (Fig. 11). The mean air temperature outside the forest is similar to the root zone temperature on the forest ground and it is likely that the mean air temperature is colder under the canopy most of the day. Therefore the gradient between soil and air seems to initiate heat transfer from the soil to the forest atmosphere. Additionally, soil-atmosphere heat transfer is amplified by strong turbulence caused by cold SE-trades with high wind speeds up to 12.8 m s^{-1}. Soil cooling, which is initiated by turbulence, was also proven as an important parameter for the development of soil temperatures in the root zone during other studies (GREEN et al. 1984).

On the following day, the air temperature was significantly higher than the root zone temperature in the forest and the wind speed was reduced, which leads to a positive soil heat flux, although solar radiation on the forest ground was significantly lower due to the reduced sky view at logger site 6 (Tab. 6).

To summarise, the relation between root zone temperature and heat flux is strongly dependent on the prevailing weather situation. During turbulent weather with air temperatures in the forest colder than root zone temperature, heat flux can become negative, even in the case of strong solar radiation. On calm radiation days however, the radiative warming of air temperature in a wider area seems to play the major role for a positive –0.1 m soil heat flux. Nevertheless, the mean as well as the maximum root zone temperature is lower beneath the dense canopy at site L6 for all days independent of the –0.1 m soil heat flux (Tab. 6). Similar results could be obtained for other woodlands (refer to MORECROFT et al. 1998).

4.2 Soil heat flux and soil temperature

The influence of root zone thermal properties on deeper soil levels is presented in Fig. 12 for two bunchgrass sites. On both days, a well developed daily amplitude of –0.1 m soil heat flux as well as of –0.1 m soil temperature is observed. Although there is no complete diurnal course of measurements available, the propagation of the temperature waves agrees quite well with the theoretical time lag which is presented in Table 3. At site L2, delay between minimum and maximum –0.1 m temperature amounts to ~7.5 h (7.6 h in Tab. 3) and for site L7 to ~6 h (5.1 h in Tab. 3). Soil temperature at –0.5 m is constant throughout the day, but a slight decrease is observed for –0.3 m. The –0.1 m soil temperature increases more than at deeper layers in the afternoon between 14:00 and 16:00 LT. It should also be noted that the –0.3/–0.5 m heat flux is positive or oscillates around 0 W m^{-2}, which means that there is a predominantly weak energy flux from the soil surface to deeper soil levels.

In contrary to the bunchgrass sites, the root zone temperature (–0.1 m) of the forests only slightly increases later in the day and the maximum is not reached be-

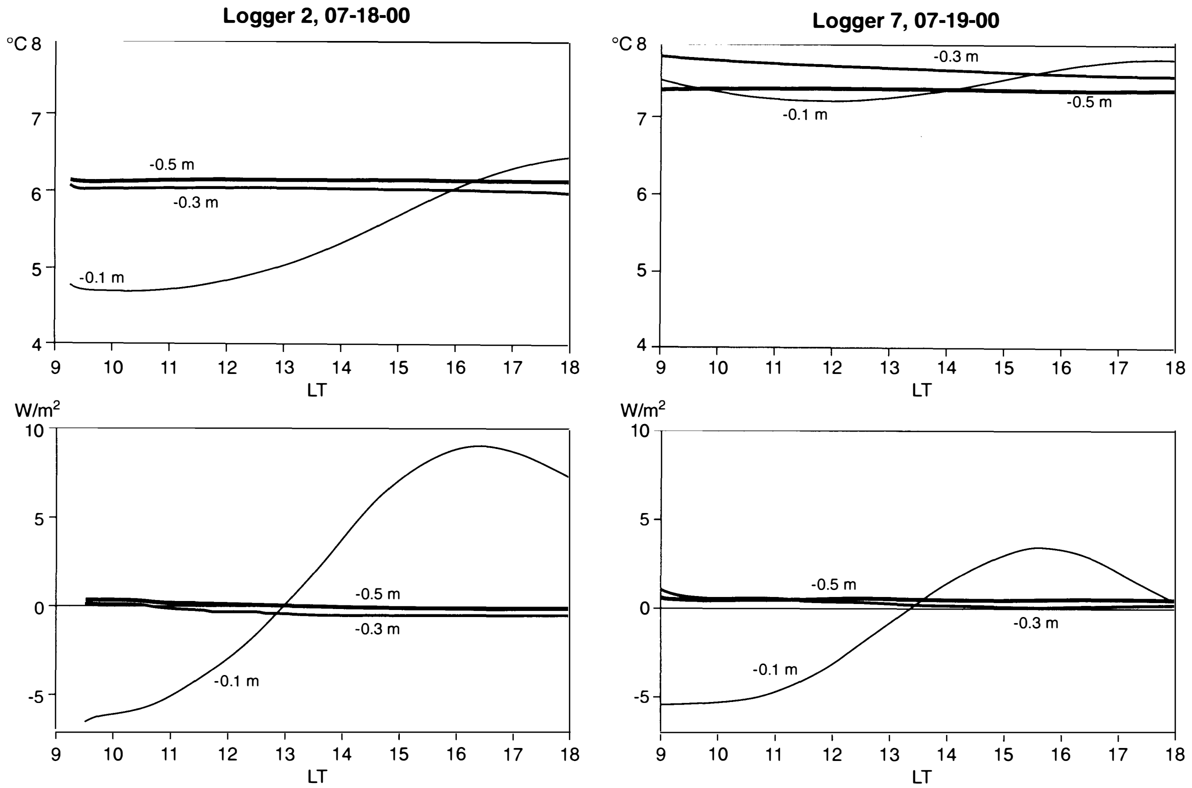

Fig. 12: Soil heat flux and soil temperatures for the grass Páramo sites
Bodenwärmefluss und Bodentemperaturen für Standorte im Gras-Páramo

fore 18:00 LT (Fig. 13). At all depths, the daily amplitude in soil temperature is lower in comparison with the bunchgrass sites. Although the –0.1 m heat flux can become clearly positive (site L6), the heat flux at deeper levels remains negative, which means a flux direction towards the root zone. Consequently, the –0.5 m soil temperature at both sites is warmer than at the root zone, which is opposite to the situation at the bunchgrass sites.

This effect cannot be due to thermal properties of the soil itself as reported in Table 3 because for instance, both forest sites reveal a faster propagation time for a sine shaped heat wave than the bunchgrass site L2. Consequently, the insulation of the soil surface due to the peat-like organic layer in combination with the reduced irradiation on the forest ground during the day and a reduced air temperature in the forest which is significantly colder than the soil temperature, especially during cold trade events, cause a reduced penetration depth of solar heating and the resulting colder soils in the forest. Thermal insulation by means of organic layers has been proven to produce significantly colder soils (up to 4 °C in comparison to sites without an organic layer) also during other studies (HOGG a. LIEFFERS 1991).

Although only single day observations of the –0.1 m soil temperature are available, the mean daily root zone temperature (9:00–18:00 LT) meets the required threshold temperature for root growth (>6–7 °C, as presented in KÖRNER 1998 for the Swiss Alps) on only one day (03-12-99). The root zone temperature was significantly lower on the other days, also keeping in mind that mean temperatures would become still lower by accounting for measurements from 0:00–23:59 LT, which are currently not available (Tab. 7).

5 Discussion

The study has shown that the –0.5 m soil temperature in forests at the upper tree line, which is often used to estimate the ecological heat capacity for tree growth, is significantly lower in the Páramo of Papallacta than is reported for other tropical sites. Additionally, it has been proven that the –0.5 m soil temperature is not constant in the course of the year but reached a distinct

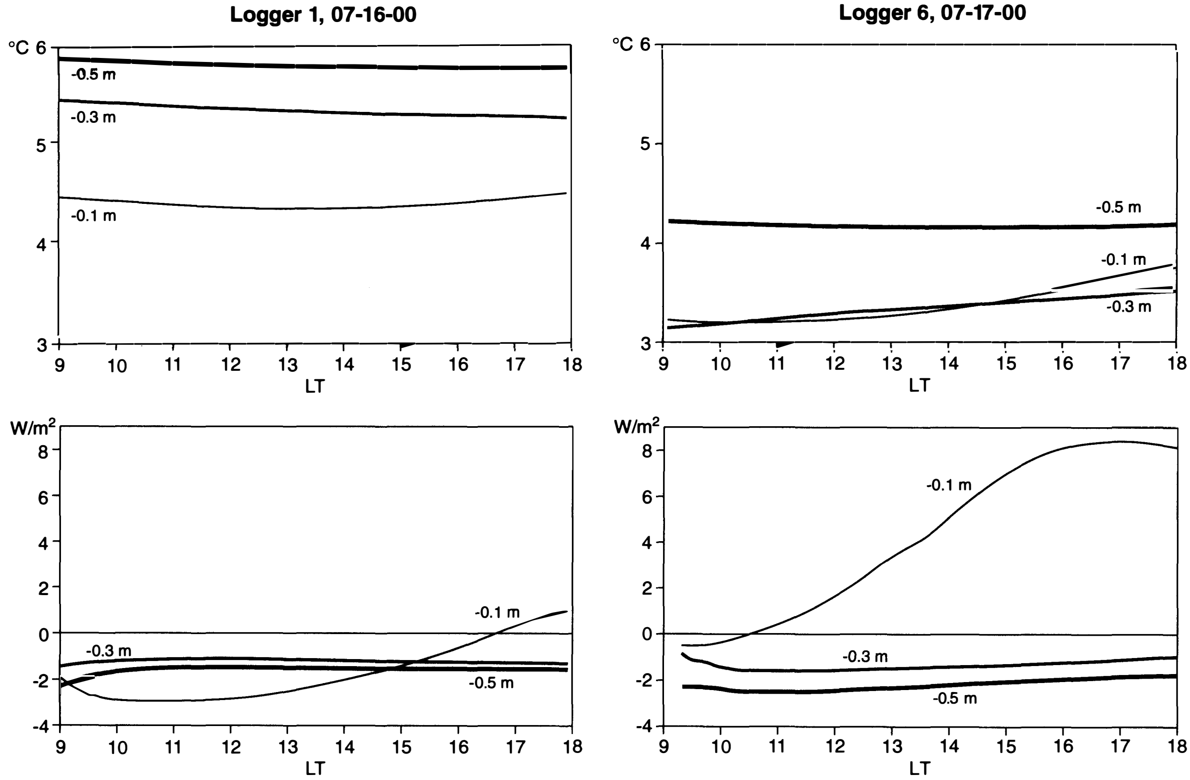

Fig. 13: Soil heat flux and soil temperatures for the forest sites
Bodenwärmefluss und Bodentemperaturen für Standorte im Ceja-Wald

minimum at all sites in August 1999. Conspicuously, the temperature difference between open sites and the adjacent forests decreases during this minimum. Therefore, it is most likely that the decrease of the soil temperature difference between forests and the adjacent grass sites in August 1999 is due to a general change in the climate regime. Possible causes could be (1) a significant decrease in air temperature due to a reduced irradiation in the area or a high frequency of cold trades, (2) an increase of turbulence due to constant high wind speeds or (3) a change in the soil moisture regime which can cause soil temperature variations of 2–3 °C (WINIGER 1979).

Evidence for a combined effect (1–3) is given by the synoptic situation in 1999. This year is characterised by an exceptional "La Niña" episode afiter one of the strongest Super-El Niño 1997/98 (BENDIX 1999) in this century. The cold Pacific event already began in October 1998, peaked in January to March 1999 and persisted until September 1999 (CPC 2000). A La Niña situation is generally most likely to produce above-average precipitation in the area of the Páramo of Papallacta (VUILLE et al. 2000). At the end of a La Niña event (June to August), a higher frequency of cold trades and convective rainfall on the afternoon but frequently clear nights occur. Hence, rainfall data from Micacocha reveal a significant surplus of precipitation during the peak of La Niña (January to March) which is followed by a dry period during April to August 1999 (Fig. 14) when –0.5 m soil temperatures reach their minimum. As a result, the observed decrease of the –0.5 m soil temperature and the temperature difference

Table 7: Mean daily –0.1 m soil temperature (9:00–18:00 LT) for the forest sites

Tagesmittel der Bodentemperatur in 10 cm Tiefe zwischen 9:00 und 18:00 Uhr Ortszeit an zwei Waldstandorten

Logger Sites	Date	*Soil Temperature* [°C]
L1	03.12.99	7.03
L1	07.16.00	4.38
L6	03.15.99	5.50
L6	07.17.00	3.39

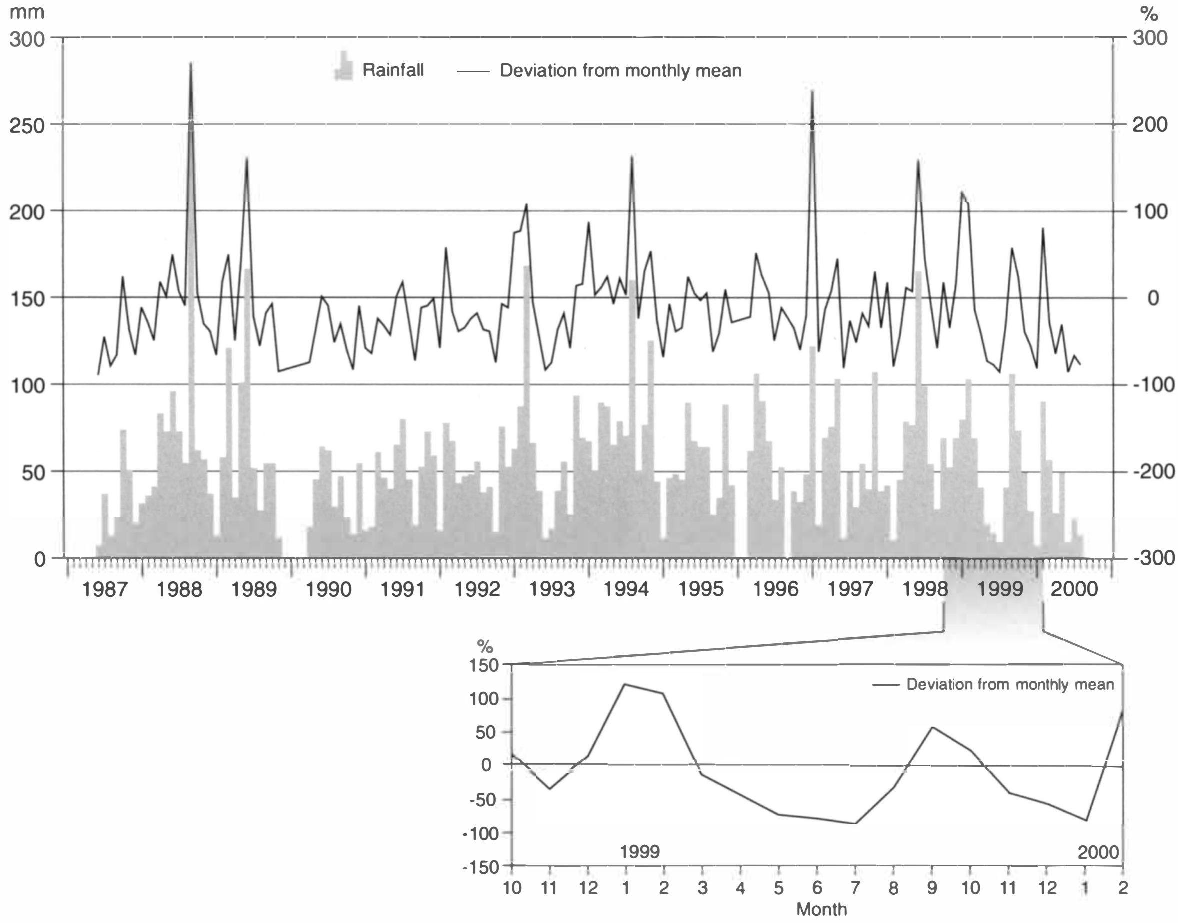

Fig. 14: Precipitation at Micacocha (4000 m asl) and deviation from monthly mean (period 1987–2000) (data: INAMHI)
Niederschläge und ihre Abweichung von mittleren Monatswerten an der Station Micacocha (4000 m ü. NN) für die Periode 1987–2000 (Daten: INAMHI)

between forest and bunchgrass is probably due to the following scenario. Exceptional rainfall from December 1998 to March 1999 is the initial trigger of the soil temperature depression by soaking the deeper, normally dry horizons of the soils under both forest and bunchgrass. A study in the high Andes of Chile has proven that such a change in soil moisture provides a better heat conduction between soil surface and deeper soil levels (–0.5 m) (SCHMIDT 1999). Because cloudiness is significantly increased during the peak of a La Niña situation, this cannot lead to a better heat transfer to deeper soil layers due to a lack of solar radiation. In the dissipation stage (April to August 1999) however, the increased frequency of cold and turbulent trades cause an increased transfer of heat from the soil surface to the atmosphere. On the other hand, nocturnal radiation during clear nights in combination with the foregoing soaking of deeper soil levels can become more effective to initiate an increased heat flux from the deeper layers (–0.5 m) towards the soil surface. The combination of the described mechanisms is finally responsible for the decrease of the –0.5 m soil temperature in August at all sites. Obviously, nocturnal radiation losses are more enhanced for most bunchgrass sites due to a lacking insulation by the mossy and peat-like organic matter as well as the absence of sheltering canopies against nocturnal radiation. Therefore, the decrease of the –0.5 m soil temperature during the La Niña as well as other cold phases is generally stronger for bunchgrass sites than for forest soils.

In conclusion, the thermal level of soils at a depth of –0.5 m at the upper tree line of the Páramo of Papallacta is significantly lower with a mean temperature of 4.8 °C than the reported values of 6–8.5 °C (MIEHE a. MIEHE 1994). Tree growth is therefore possible throughout the year under generally colder conditions up to

4100 m asl. The same seems to be true for the root zone (–0.1 m) temperature. However, KÖRNER (1998 b) found evidence for similar conditions at the upper tree line in Mexico. He observed average –0.1 m soil temperatures of 5.4 and 4.8°C for *Pinus* forests at the Iztacihuatl (3970 m asl) and the Pico de Orizaba (4020 m asl), respectively.

Especially the small difference between the –0.5 m soil temperatures of forest and bunchgrass sites in the Páramo of Papallacta, which is proven to be mainly due to the better insulation on the forest ground by a well developed organic layer, is of great importance for the discussion of the potential position of the upper timberline in the study area. It agrees with the hypothesis which is given in LÆGAARD (1992) and LAUER et al. (2001) that the Grass-Páramo is mainly man-made and that its thermal conditions are suitable for tree growth up to 4100 m asl. Therefore, the extended patches of *Polylepis* forest, which presently form the upper tree line at this altitude, mark the potential upper timberline of the study area.

It should be stressed that the presented relations between soil heat flux, soil and air temperature, soil moisture, solar radiation and other climatic and edaphic parameters determine the growth conditions in a humid Páramo. As a consequence of the current momentary case studies, extensive measurements and modelling of SVAT fluxes (Soil Vegetation Atmosphere Transfer) in- and outside the forest patches are required in future for a better understanding of the thermal behaviour of soils at the upper tree line and to make the results more comparable to other regions. These studies should be particularly focussed on the interaction of wind field, air temperature, turbulence and soil climate within the forest patches in the course of the year. The modification of soil climate within forest patches due to a varying soil moisture regime again seems to be a key feature in the understanding of the thermal growth conditions which, unfortunately, is to the present day not well known. Hence, the influence of soil moisture on the thermal properties of soils in the study area needs further attention in future studies. The complex relation between soil, atmosphere and vegetation has finally to be de-mystified by means of a suitable and realistic SVAT model which must be driven by a comprehensive set of *in-situ* measurements.

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Beilage II zu ERDKUNDE 55,3 Beitrag Bendix/Rafiqpoor

Vegetationskarte im Umfeld des Antisana
Mapa de vegetación en alrededor del Antisana
Vegetation map in the area around the Antisana

Páramo de Papallacta

Ostkordillere Ecuador *Cordillera Oriental del Ecuador* Eastern Cordillera of Ecuador

Geländeaufnahmen und Fotointerpretation: Wilhelm Lauer und M. Daud Rafiqpoor
Alzado topográfico y interpretación de aerofotos: Wilhelm Lauer y M. Daud Rafiqpoor
Geographical mapping out and photointerpretation: Wilhelm Lauer and M. Daud Rafiqpoor

Wälder *Bosques* Forests ········ **< 3700m**

- ▥ *Alnus acuminata* -Bestand am Rio Papallacta ········ < 3100m
  Arbolado de Alnus acuminata a la orillas del Río Papallacta
  Stand of *Alnus acuminata* at Río Papallacta
- ▥ Hochmontaner Wald des Verbandes ›Miconion‹ ········ 2200–3100m
  Bosque alto montanos de la Comunidad ›Miconion‹
  High montane forest of the Community ›Miconion‹
- 🟦 Ceja-Nebelwald des Verbandes ›Tournefortion‹ ········ 3100–3550m
  Bosque nublado de la Ceja de la montaña de la Comunidad ›Tournefortion‹
  Ceja-elfin forest of the Community ›Tournefortion‹
- ▥ Lichter Bestand des Verbandes ›Tournefortion‹
  Arbolado disperso de la Comunidad ›Tournefortion‹
  Dispers woodland of the Community ›Tournefortion‹
- 🟦 Ceja-Übergangswald der Assoziation *Miconietum salicifoliae* mit *Escallonia myrtilloides* ········ 3500–3700m
  Bosque nublado transicional de la Asociación Miconietum salicifoliae con Escallonia myrtilloides
  Ceja-transation forest of the Association *Miconietum salicifoliae* with *Escallonia myrtilloides*
- ▥ Lichter Bestand der Assoziation *Miconietum salicifoliae*
  Arbolado disperso de la Asociacion Miconietum salicifoliae
  Dispers woodland of the Association *Miconietum salicifoliae*
- 🟦 Ceja-Wald des Verbandes ›Oreopanaxion‹ ········ 3000–3700m
  Bosque nublado de la Comunidad ›Oreopanaxion‹
  Elfin-Forest of the Community ›Oreopanaxion‹
- ▥ Lichter Bestand des Verbandes ›Oreopanaxion‹
  Arbolado disperso de la Comunidad ›Oreopanaxion‹
  Dispers woodland of the Community ›Oreopanaxion‹

Trockenbuschformation *Matorrales* Shrublands ········ **2400–3000m**

- 🟧 Xerophytische Gebüsche des Verbandes ›Byttnerion‹ mit *Mimosa albida* ········ 2400–2700m
  Matorral xerofítico de la Comunidad ›Byttnerion‹ con Mimosa albida
  Xerophytic shrubland of the Community ›Byttnerion‹ with *Mimosa albida*
- ▥ Lichter Bestand des Verbandes ›Byttnerion‹ mit *Mimosa albida*
  Matorral disperso de la Comunidad ›Byttnerion‹ con Mimosa albida
  Dispers shrublands of the Community ›Byttnerion‹ with *Mimosa albida*
- 🟧 Xerophytische Gebüsche des Verbandes ›Byttnerion‹ mit *Duranta triacantha* 2700–3000m
  Matorral xerofítico de la Comunidad Byttnerion‹ con Duranta triacantha
  Xerophytic shrubland of the Community ›Byttnerion‹ with *Duranta triacantha*
- ▥ Lichter Bestand des Verbandes ›Byttnerion‹ mit *Duranta triacantha*
  Matorral disperso de la Comunidad ›Byttnerion‹ con Duranta triacantha
  Dispers shrubland of the Community ›Byttnerion‹ with *Duranta triacantha*
- ▨ Übergangszone von ›Byttnerion‹ und ›Oreopanaxion‹ ········ 3000–3200m
  Zona de transición de ›Byttnerion‹ a ›Oreopanaxion‹
  Transation zone of ›Byttnerion‹ and ›Oreopanaxion‹

Forste *Reforestación* Afforestation ········ **2400–3000m**

- 🟩 *Eucalyptus globolus* -Forst
  Reforestación de Eucalyptus globolus Afforestation of *Eucalyptus globolus*
- ▥ Lichter *Eucalyptus globolus* -Forst
  Arbolado disperso de Eucalyptus globolus Dispers woodland of *Eucalyptus globolus*

Polylepis Gehölze *Arbolados de Polylepis* Polylepis woodlands ········ **3550–4100m**

- 🟩 Reiner *Polylepis pauta* -Bestand
  Arbolado puro de Polylepis pauta Pure *Polylepis pauta* woodland
- ▥ Lichter *Polylepis pauta* -Bestand
  Arbolado disperso de Polylepis pauta Dispers *Polylepis pauta* woodland
- 🟩 *Polylepis pauta* -Mischbestand
  Arbolado mixto de Polylepis pauta *Polylepis pauta* mixed woodland
- ▥ Lichter *Polylepis pauta* -Mischbestand
  Arbolado disperso mixto de Polylepis pauta Dispers *Polylepis pauta* mixed woodland
- 🟩 Reiner *Polylepis incana* -Bestand
  Arbolado puro de Polylepis incana Pure *Polylepis incana* woodland
- ▥ Lichter *Polylepis incana* -Bestand
  Arbolado disperso de Polylepis incana Dispers *Polylepis incana* woodland
- 🟩 *Polylepis incana* -Mischbestand
  Arbolado mixto de Polylepis incana *Polylepis incana* mixed woodland
- ▥ Lichter *Polylepis incana* -Mischbestand
  Arbolado disperso mixto de Polylepis incana Dispers *Polylepis incana* mixed woodland

Páramo *Páramo* Páramo ········ **3600–4700m**

- 🟪 Polster-Páramo der Assoziation *Wernerietum crassae* ········ 4200–4700m
  Páramo de plantas almohadelladas de la Asociación Wernerietum crassae
  Cushion plant páramo of the Association *Wernerietum crassae*
- ⬜ Niederstrauch-Subpáramo des Verbandes ›Loricarion‹ ········ 4100–4200m
  Páramo arbustivo de la Comunidad ›Loricarion‹
  Dwarft shrub subpáramo of the Community ›Loricarion‹

Graspáramo *Páramo* Bunchgrass-Páramo

- ⬜ Assoziation *Festucetum subulifoliae* mit /*con*/with *Puya clava-hercules* ········ 3800–4200m
- 🟨 Assoziation *Festucetum procerae* ········ 3600–3800m
- *Cortaderia nitida* -Bestand
  Monotónes de Cortaderia nitida Assemblys of *Cortaderia nitida*

Moore *Pantanos* Swamps

- ▤ *Distichia-Plantago* -Polstermoor ········ > 4000m
  Pantano de Distichia-Plantago Swamp of *Distichia-Plantago*
- ▤ *Juncus-Carex* -Moor ········ < 4000m
  Pantano de Juncus-Carex Swamp of *Juncus-Carex*

Felsflur *Vegetación de roquedal* Rocky vegetation

- *Echeveria-Puya glomerifera* -Felsflur
  Vegetación de roquedal de Echeveria-Puya glomerifera
  Rocky vegetation of *Echeveria-Puya glomerifera*

Ackerunkrautfluren *Cultivos agrícolas* Agricultural weeds ········ **2400–3800m**

An Stelle des Verbandes/der Assoziation *en lugar de Comunidad/Asociación* in stead of Community/Association

- ›Byttnerion‹ mit /*con*/with *Mimosa albida*
- ›Byttnerion‹ mit /*con*/with *Duranta triacantha*
- ›Oreopanaxion‹
- ›Tournefortion‹ mit /*con*/with *Miconietum salicifoliae* + *Escallonia myrtilloides*
- ›Miconion‹

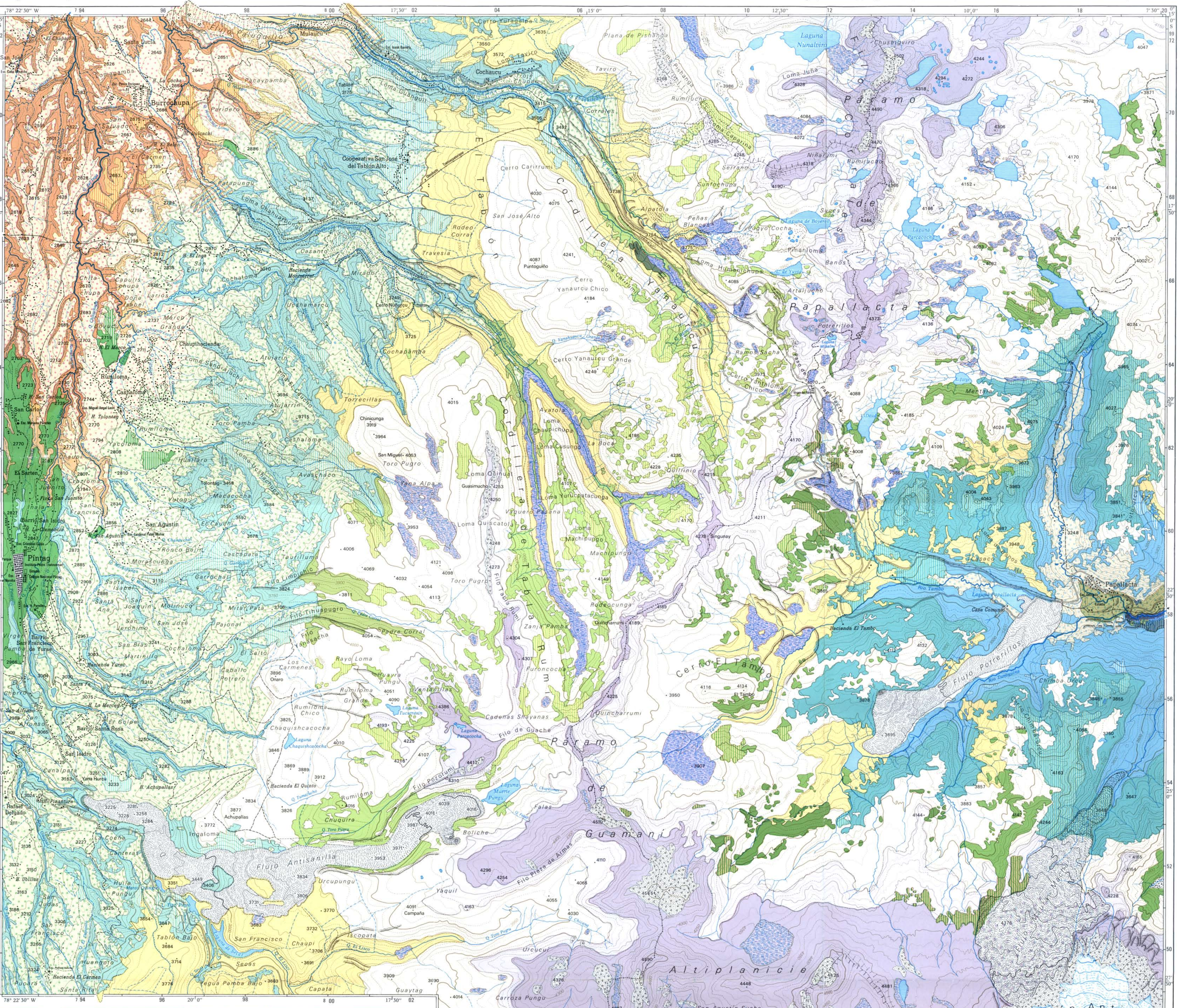
Topographische Merkmale *Rasgos topográficos* Topographical features

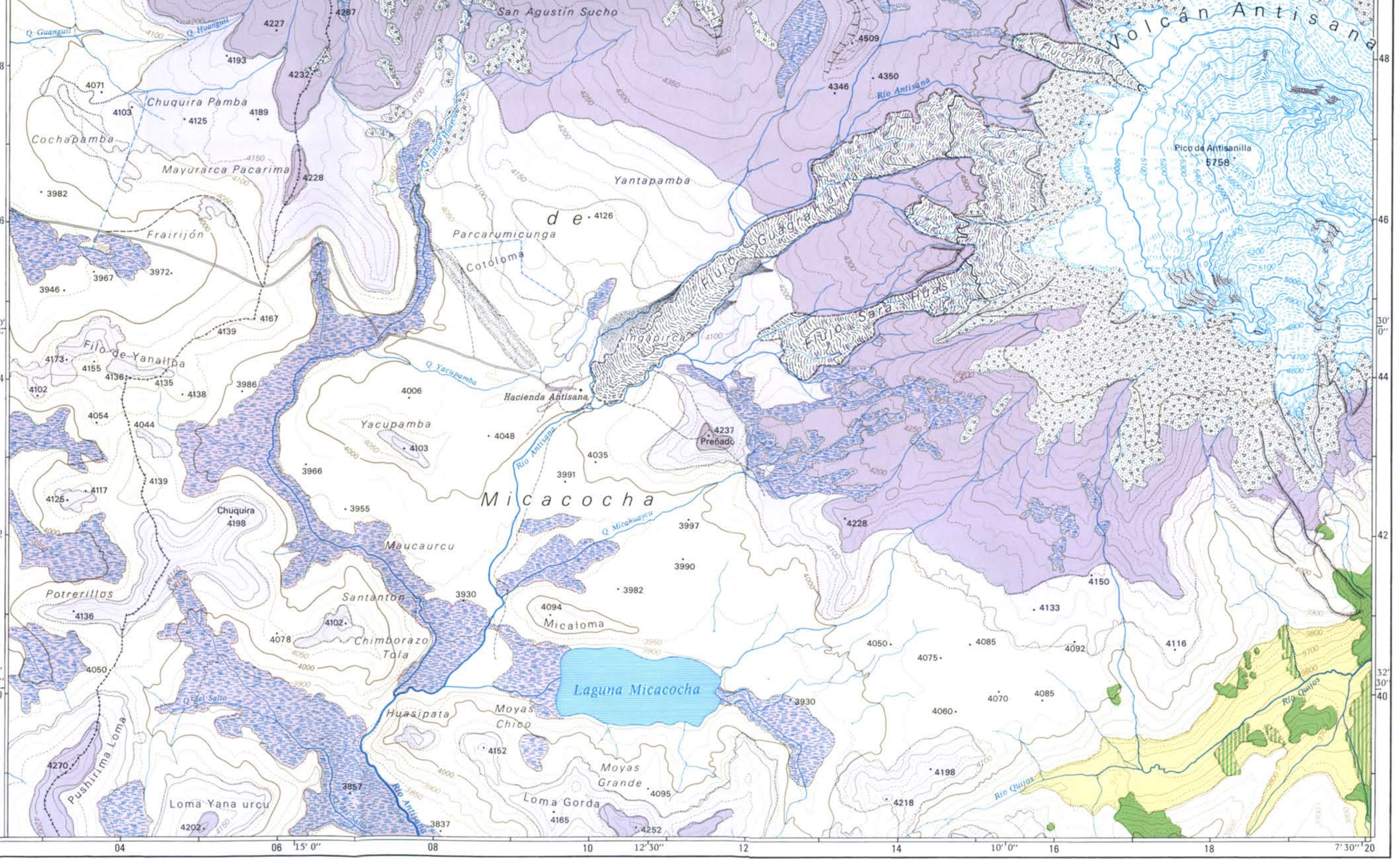
- teilweise bewachsener Lavastrom
  parcialmente con capa de vegetación partly with vegetation cover
- ⬜ nicht bewachsene Flächen
  sin capa de vegetación without vegetation cover
- ⬜ Schnee und Eis
  Nieve y hielo Snow and ice
- Gletscher *Glaciar* Glacier
- Felsen *Roca madre* Bedrock
- Caldera *Caldera* Caldera
- Älterer Lavastrom
  Flujo de lava (antiguo) Stream of lava (ancient)
- Jüngerer Lavastrom
  Flujo de lava (joven) Stream of lava (more recent)
- Hauptwasserscheide
  Divisiora mayor de agua Main watershed
- Frostschutt
  Escumbros producido por helada
  Frost debris
- Moränenrücken
  Morrenas Moraine
- Schwemmfächer
  Cono de dejección Aluvial fan
- Sand *Arena* Sand
- Alluvionen *Aluviones* Alluvium
- Kante *Borde* Edge
- Quelle *Fuente* Spring
- Thermalquellen
  Aguas termáles Hot springs

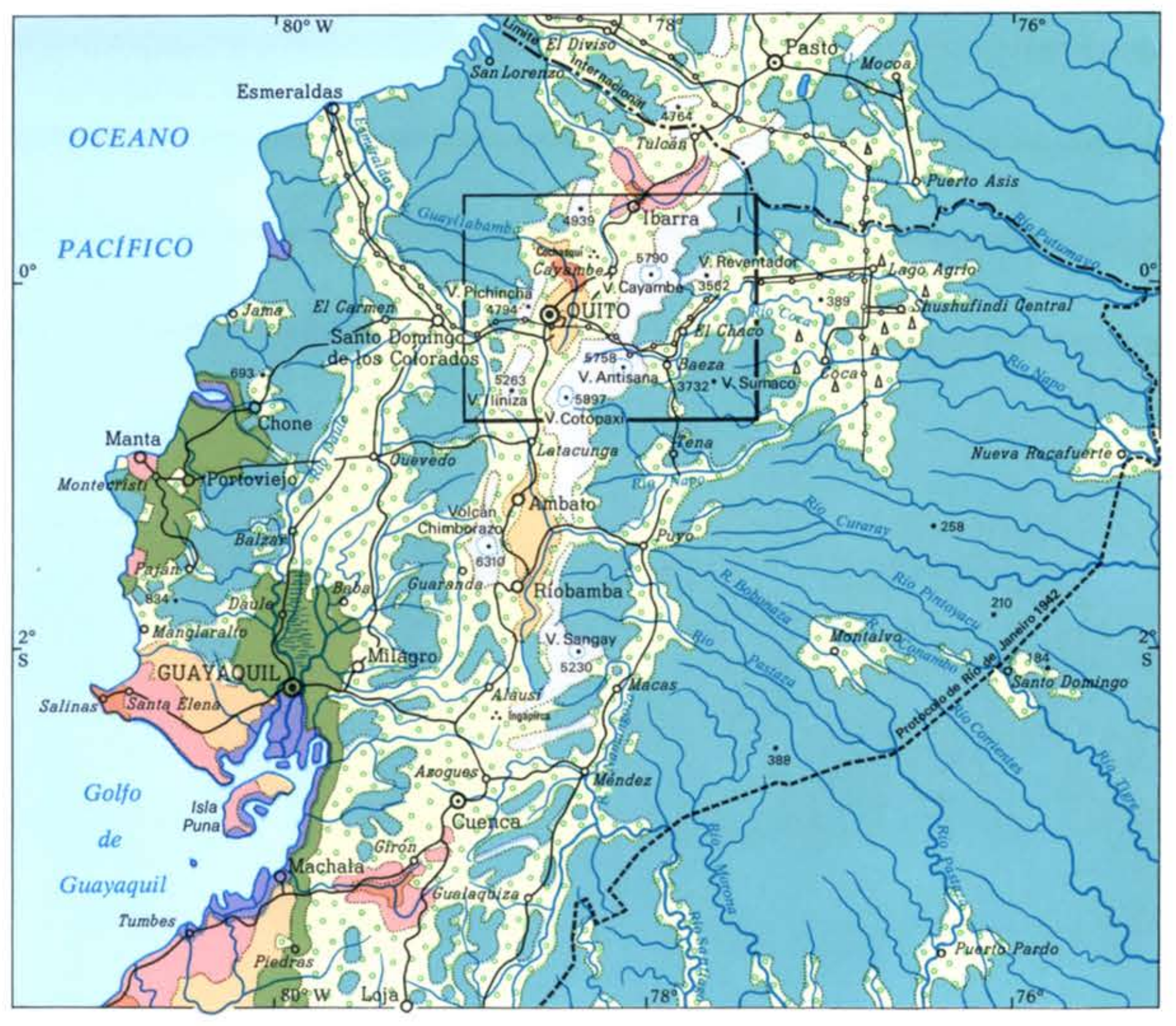
1 0,5 0 1 2 3 4 km
1 : 50000

Luftbilder/Fotos aereas/Air photographs 1 : 60 000: I. G. M., Quito, 1977–1979
Topographische Karten/Mapas topográficos/Topographical maps: I. G. M., Quito,
Blätter/Hojas/Sheets: 1 : 25 000: Papallacta, Nunalviro, Burrochupa, La Cocha, Píntag, Sincholagua, Antisana, Laguna Micacocha.
1 : 50 000: Papallacta, Oyacachi, Sangolquí, Píntag.

Kartographie: Geographische Institute der Universität Bonn, D. Gladenbeck
Druck: Landesvermessungsamt Nordrhein-Westfalen, 2000







- Gletscher *Glaciar* Glacier
- ⬜ Páramo *Páramo* Páramo
- 🟦 Tropischer Regen- und Bergwald (Höhenwald)
  Bosque tropical húmedo y bosque húmedo de altura
  Tropical rainforest and montane humid forest
- 🟩 Überschwemmungssavanne
  Sabana de inundación Inundation savanna
- Sumpf, Überschwemmungsgebiet
  Pantano, zona de inundación
  Swamp, zone of inundation
- 🟨 Trockensavanne
  Sabana arida Dry savanna
- Dornbusch
  Monte espinoso Thornbush
- 🟧 Halbwüste
  Semidesierto Semidesert
- Mangroven
  Manglares Mangrove swamp
- Agrarland
  Superficie agrícola útil
  Cultivated area
- ◉ Stadt mit mehr als 1 Mill. Einwohnern
  Ciudad de más de 1 000 000 habitantes
  Town over 1 000 000 inhabitants
- ⊙ Stadt mit 200000 - 400000 Einwohnern
  Ciudad de 200 000–400 000 habitantes
  Town with 200 000–400 000 inhabitants
- ○ Stadt mit 80 000–200 000 Einwohnern
  Ciudad de 80 000–200 000 habitantes
  Town with 80 000–200 000 inhabitants
- ∘ Ort unter 80000 Einwohnern
  Villa de menos de 80 000 habitantes
  Village less than 80 000 inhabitants
- ∴ Historische Stätte
  Sitio histórico
  Historical place
- Straße
  Carretera
  Road
- Ölleitung
  Oleoducto
  Pipeline
- ∆ Ölfeld
  Pozo de petroléo
  Oilfield

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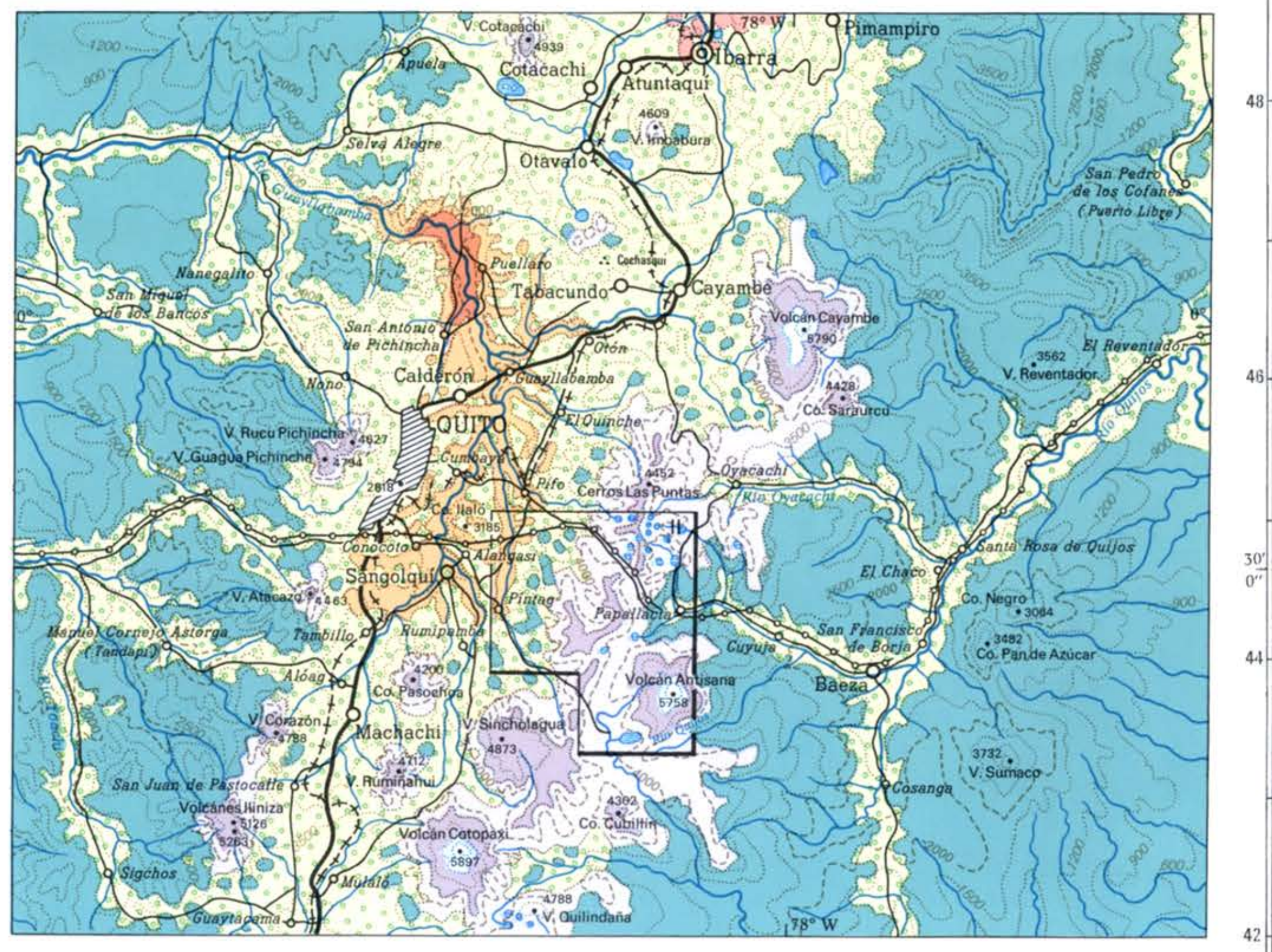
1 : 4 500 000

I Lage des Kartenblattes 1 : 1 000 000
Situación del mapa 1 : 1 000 000 Situation of the map 1 : 1 000 000



- Gletscher *Glaciar* Glacier
- 🟪 Polster–Páramo
  Páramo de plantas almohadelladas
  Cushion plant páramo
- ⬜ Graspáramo
  Páramo Bunchgrass-Páramo
- 🟦 Tropischer Regen- und Bergwald (Höhenwald)
  Bosque tropical húmedo y bosque húmedo de altura
  Tropical rain forest and montane humid forest
- 🟨 Trockensavanne
  Sabana arida Dry savanna
- Dornbusch
  Monte espinoso Thornbush
- 🟧 Halbwüste
  Semidesierto Semidesert
- Agrarland
  Superficie agrícola útil
  Cultivated area
- Stadt mit mehr als 1 Mill. Einwohnern
  Ciudad de mas de 1 000 000 habitantes
  Town over 1 000 000 inhabitants
- ◎ Stadt mit 80000 - 150000 Einwohnern
  Ciudad de 80 000–150 000 habitantes
  Town with 80 000–150 000 inhabitants
- ○ Ort mit 10000 - 50000 Einwohnern
  Villa de 10 000–50 000 habitantes
  Village with 10 000–50 000 inhabitants
- ∘ Ort unter 10000 Einwohnern
  Villa de menos de 10 000 habitantes
  Village less than 10 000 inhabitants
- Panamericana
  Panamericana Panamericana
- Sonstige Straßen
  Otras carreteras Other roads
- +++ Eisenbahnlinie (stillgelegt)
  Ferrocaril (paralizado)
  Railway (abandoned)
- Ölleitung
  Oleoducto Pipeline
- ∴ Historische Stätte
  Sitio histórico Historical place

10 5 0 10 20 30 40 50 60 km
1 : 1 000 000

II Lage des Kartenblattes 1 : 50000
Situación del mapa 1 : 50 000 Situation of the map 1 : 50 000

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