Vegetation history and climate records of Colombian lowland areas: rain forest, savanna and intermontane ecosystems

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Environmental change in the Colombian subandean forest belt from 8 pollen records: the last 50 kyr.

M. Wille, H. Hooghiemstra, H. Behling, K. van der Borg, A.J. Negret (†)

Abstract

We present a reconstruction of forest history and climatic change based on 11 pollen records from 8 sites, all located in the lower montane forest belt of the northern Andes in Colombia. We compared records from the Popayán area in southern Colombia, Timbio (1750 m), Genagra (1750 m) and Pitalito (1300 m) and the new Piagua (1700 m) record, with the records from Lusitania (1500 m), Libano (1820 m), Pedro Palo (2000 m) and Ubaqué (2000 m) from central Colombia. The changes of the altitudinal position of the lower/upper montane (= subandean/Andean, S/At) forest belt transition were used to estimate temperature change for the last 50 kyr. We infer a LGM temperature drop of 6°-7°C at 1700 m, and a steeper LGM lapse rate of 0.76°C/100 m compared to today (ca. 0.6°C/100 m). Around 514 C kyr B.P. temperature at 1700 m was ca. 3°C lower than today. Until 214 C kyr B.P. temperature oscillated and gradually decreased. During the LGM, temperature was maximally ca. 6°-7°C lower than today. After the LGM temperature increased and ca. 1414 C kyr B.P. it was 2°-3°C lower than today (S/At at ca. 1800 m, 500 m below present elevation; Susacá interstadial). An unquantified cooling (Ciega stadial) followed. During ca. 12.3-11.714 C kyr B.P. the S/At shifted upslope to 2100 m indicating a temperature of 1°-2°C cooler than today (GUANTIVA interstadial). From 11.7-10.914 C kyr B.P. the S/At was at 1800 m indicating temperature was ca. 3°C lower than today and humid conditions prevailed (partly coinciding with the El Abra stadial). The period 10.9-914 C kyr B.P. was also cool, but drier. During 9-7.514 C kyr B.P. temperature was ca. 1°C warmer relative to today (mid Holocene hypsithermal).
last 5 kyr presence of cultivated plants demonstrate human colonization of the lower montane zone in Colombia.

5.1 Introduction

Our understanding of the Late Quaternary environmental change in the northern Andes of South America is mainly based on pollen records from sites between 2500 and 4400 m above sea-level (LAPD 1996). These records show a vertical migration of the main vegetation belts during the last glacial-interglacial cycle, mainly responding to temperature change. In palynological studies temperature reconstructions are mainly based on altitudinal shifts of the upper forest line, which corresponds to the 9.5°C annual isotherm, currently located at 3200 m. Van der Hammen and González (1963) and Hooghiemstra (1984) used a lapse rate (change in temperature with height) of 0.65°C/100 m in reconstructions from pollen sites at 2550 m. Based on analysis of meteorological data Witte (1994) calculated for the Colombian Andes a modern lapse rate of 0.55°-0.62°C/100 m which is close to the value of 0.64°C/100 m calculated by Thouret (1983) and by Florez (1986). Witte concluded that up to 3750 m modern lapse rates are well defined and stable, while at higher elevation lapse rates become unstable and temperatures depend more on local conditions (Witte 1994). On the basis of terrestrial evidence from pollen, lake-levels and geochemistry in the tropics Farrera et al. (1999) estimated that during the Last Glacial Maximum (LGM) at 18°14C kyr B.P. the average reduction in temperature was 2.5°-3°C at sea-level and ca. 6°C at 3000 m, thus demonstrating lower temperature with altitude during the last glacial period. However for the neotropics Farrera et al. (1999) showed a larger than average LGM sea-level temperature reduction of 5°-6°C. Bush et al. (2001) arrived on the basis of pollen data at a rough estimate for a LGM sea-level temperature drop of 5°C, on the basis of pollen data. There is also some impact of changes in precipitation on the altitudinal position of the upper forest line (see e.g. Van der Hammen and González 1963) and therefore, on temperature reconstructions. Recently it was shown that a low atmospheric pCO2 during the glacial period may have contributed to a lower forest line and, as a consequence, temperature estimates from high elevation sites may be considered as maximum values (Street-Perrott 1994; Street-Perrott et al. 1997; Boom et al. 2001). However, a straightforward quantitative estimation of the impact of precipitation and low atmospheric pCO2 on temperature reconstructions is not available and the debate quantifying the impact is still ongoing (Cowling and Sykes 1999, 2000; Williams et al. 2000).
The occurrence of night frost is an important factor that determines the transition between the subandean and Andean forest belts. Therefore, we assume that the effects of changing precipitation and atmospheric $pCO_2$ at mid-altitudes (1300-1700 m) have less impact on the altitudinal position of the forest belts than at high-altitude (> 2500 m) sites. We observe a significant discrepancy between estimates of the LGM temperature drop in northern South America for sea-level and high elevation, and between authors. Many pollen records from sites between 2500 and 3600 m have shown that temperature cooled some 8°-9°C (e.g. Hooghiemstra 1984; Mommersteeg 1998; Van 't Veer and Hooghiemstra 2000). This estimation is in contrast with recent estimates of the LGM temperature drop at sea-level of 4±2°C in Amazonia (Van der Hammen and Absy 1994), 6°C for Amazonia by Colinvaux et al. (2000), 4°-5°C in Brazil (Stute 1995), 5°-6°C for the neotropics (Farrer a et al. 1999). It was suggested that the present-day lapse rate of 0.65°C per 100 m was steeper under glacial conditions (Bakker 1990; see also Van der Hammen and Hooghiemstra 2000).

Objectives of this paper are to present a new pollen record from site Piagua at 1700 m and to synthesize pollen data from the altitudinal interval of 1300-2000 m to contribute from an almost unexplored altitudinal interval to the current debate of LGM cooling. Attention is paid to the sequence of temperature oscillations during the Late Glacial at 1700 m and we compare observed changes with the Late Glacial climate chronology established on pollen sites from higher elevation. Van der Hammen (1995) arrived at the following sequence of chronostratigraphic periods and most probable ages: Susaca interstadial (14-13.14°C kyr B.P.), Ciega stadial (13-12.5 14C kyr B.P.), Guantiva interstadial (12.5-11 14C kyr B.P.) and El Abrad stadial (11-10.15/9.5 14C kyr B.P.). We focus on Colombian data for maximum comparability and for the reason that estimates vary between distant areas (Farrer a et al. 1999). The regional environmental setting of site Piagua, presented in the following paragraph, is also valid for sites Genagra and Timbio, and as such relevant to appreciate the data synthesis. Another deficiency in our understanding of altitudinally migrating vegetation belts is to which degree vegetation belts were compressed during glacial conditions; a question that directly relates to past lapse rates and temperature depression. Van der Hammen (1981) focussed already on this aspect for the Andean forest belt and the different belts of paramo (a mountain vegetation consisting of mainly shrub, grasses, other herbs, cushion plants and mosses, which is found above the forest line), but a possible compression of the subandean forest belt during glacial conditions was never studied because pollen records were lacking. Based on the biomisation of Colombian pollen data Marchant et al. (submitted) showed clearly that during the mid and
late Holocene biome assignments changed at different altitudes in a different way, indicating that climatic change is not uniform for the different altitudinal zones in the Colombian Andes. As several new pollen records between 1300 and 1750 m recently became available, another objective of this paper is to provide for the first time an integrated reconstruction of changes in the altitudinal range and floral composition of the subandean forest belt. As the best records are located in southern Colombia, this paper is focussed on the area of Popayán, but comparisons with other subandean pollen records have been made. Changes in floral composition compared to present-day and also changes in the vegetational composition of the subandean forests will be evaluated.

5.2 Environmental setting of the pollen sites

The vegetation in the northern Andes shows a clear altitudinal zonation (e.g. Van der Hammen 1974; Hooghiemstra and Cleef 1984). In this paper we focus on the sites located in the subandean forest belt (= lower montane forest belt), at present day extending from 1000 to 2300 m elevation. Tropical lowland forest occurs at lower elevation (0-1000 m) and Andean forest (= upper montane forest) at higher elevation (2300-3200 m). The records represent various time intervals, as shown in the synthesis paragraph, but form together an almost complete composite record of the last 50 kyr.

Sites from Bogotá latitudes (between 3°49'N and 4°30'N; Fig. 5.1.):

(1) Site Lusitania (1500 m, 3°49'N, 76°34'W; Monsalve 1985) is located in the Western Cordillera of Central Colombia close to the Hacienda Lusitania in a marshy area at the bottom of the El Dorado Valley.

(2) Site Libano (1820 m, 4°30'N, 75°30'W; Salomons 1986) is located on a NNE exposed slope of the El Ruiz volcano in the Western Cordillera of Central Colombia and surrounded by strongly degraded forest. It represents the upper part of a thick soil-tephra sequence collected in a road-cut.

(3) Laguna Pedro Palo (2000 m, 4°30'N, 74°23'W; Hooghiemstra and Van der Hammen 1993) is located on the western slope of the Eastern Cordillera facing the Magdalena Valley.

(4) Laguna Ubaqué (2000 m, 4°30'N, 73°55'W, Berrio 1995) is located on the eastern slope of the Eastern Cordillera. The sediment sequence was collected at the border of the lake which is about 300 x 500 m in size. Under natural conditions the lake was located in the upper part of the subandean forest, but the area is totally deforested.
Fig. 5.1. Map showing the location of the pollen sites in the present subandeán (lower montane) forest belt. LIB = Libano, PP = Laguna Pedro Palo, UBA = Laguna Ubaqué, LUS = Lusitania, GEN = Pantano de Genagra, PIA = Pantano Piagua, TIM = Pantano Timbio. PIT = Pitalito. Patterns show altitudinal intervals.

Sites from Popayán latitudes (between 1°52’N and 2°28’N; Fig. 5.1.):
(5) Piagua (1700 m, 2°30’N, 76°30’W) is a small village about 10 km south of Popayán in the catchment area of the Patia River. The site is located at the southern edge of the village. It is a small swamplike area, about 100 x 100 m in size, in a depression which is crossed by a small shallow creek draining in a westerly direction. The catchment area of the depression is almost 1 km in diameter. Surrounding slopes are gentle and are part of a saddle like interandean high plateau. This plateau separates two drainage systems that originate southeast of Popayán: the Cauca river at about 3500 m, and the Patia and Timbio rivers at approximately 2500 m.

(6) Pantano Genagra (1750 m, 2°28’N, 76°37’W; Behling et al. 1998) is a swamp of 200 x 50 m in size, located in a small valley with steep slopes on the Hacienda Genagra, 5 km north of the city of Popayán. The site lies in the catchment area of the Cauca river.
(7) Site Timbio (1750 m, 2°24'N, 76°36'W; Wille et al. 2000) is located in a swampy area, about 60 m in diameter, located in a small depression and is part of the catchment area of the Patia river.

(8) Site Pitalito (1300 m, 1°52'N, 76°02'W; Bakker 1990) is located in a sediment filled basin in the southern Magdalena Valley between the Central and Eastern Corillera. Core Pitalito-11 was taken from a small grass yard near the southern basin margin. Core Pitalito-2 was taken from a swampy area in the northwestern part of the basin.

5.2.1 Modern vegetation of the Popayán area

The natural vegetation of the study area, including sites Piagua, Timbio, Genagra and Pitalito, is almost completely replaced by commercial forestry, coffee plantations and farmland. At present only small patches of forest, possibly representing secondary vegetation, occur along the rivers. Near Popayán the upper forest limit is at about 3400 m. An evaluation of the potential natural vegetation of this area, based on analysis of the legend units of the ecological map of Colombia (IGAC 1977), and floral inventory studies of remnants of forest, is presented elsewhere (Wille et al. 2000) and serves to help understand pollen records from this area. Here we summarise the altitudinal range and floral composition of the main forest types in the study area (Fig. 5.2.):

Humid low montane forest (1000-1400 m): Croton gossypiaefolius, Erythrina poeppigiana, Inga densiflora, Miconia rufescens/albicans, Myrsine guianensis, Nectandra sp.

Very humid low montane forest (1400-2000 m): Alchornea latifolia, Clusia sp., Erythrina sp., Inga sp., Miconia caudata/theaezeans, Myrica pubescens, Myrsine guianensis, Piper aduncum, Tabebuia chrysanthia.


Humid montane forest (2500-3000 m): Bocconia frutescens, Jamesonia sp., Laplacea sp., Myrica pubescens, Quercus humboldtii, Weinmannia sylvatica.
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The forest classes from the ecological map of Colombia are mainly based on ranges of modern precipitation, whereas the traditional zonation used in Fig. 5.2. is mainly based on temperature. Identification of the above mentioned forest types in the pollen diagrams, in particular the 'very humid montane forest between 2000 and 3000 m' is helpful to estimate changes in precipitation. This forest type has not been used to estimate the altitudinal distribution of main vegetation belts because Alchornea bogotensis, Clusia sp., Hyeronima sp., Myrica pubescens, Myrsine ferruginea, and Vismia baccifera are taken as evidence for the subandean forest belt, whereas Bocconia frutescens, Hedyosmum bonplandium, Podocarpus oleifolius, Quercus humboldtii, and Weinmannia pubescens are taken as evidence of the Andean forest belt.

5.2.2 Climatic conditions

The subandean forest belt in general is characterised by temperatures of 14° to 25°C; mean annual rainfall ranges from 1200 to 2900 mm. The climate station at Popayán airport (1730
Environmental change in the Colombian subandean forest belt

m) shows for the period of 1982 to 1995 an annual rainfall between 1580-3160 mm (average 2140 mm) with a relatively dry period from June to August. On average, the lowest temperatures are between 12° and 14°C whereas the highest temperatures are from 23° to 25°C. A longer precipitation record from Popayán, covering the period of 1955-1984, shows an average annual rainfall of 2060 mm with a dry period from June to September (Rangel 1991). The driest month during the year is July with an average rainfall of about 60 mm and the wettest month is November with some 340 mm precipitation. Seasonality in precipitation relates to the annual movements of the Intertropical Convergence Zone (ITCZ) cutting especially the Andean area into a northern and a southern part. From January to April the ITCZ is located at ca. 5°N and from July to October at ca. 10°N. The area north of these latitudes is influenced by the north-easterly trade winds causing relatively warm and dry conditions, whereas the part in the south is influenced by southerly or south-westerly winds bringing mostly clouds and rain. Additionally the three Cordilleras of the Andes form barriers for winds and clouds (Martyn 1992). Therefore the northern Andes are divided into regions with locally different climate regimes (e.g. up/down winds, cloud cover, precipitation). On longer time scales fluctuations in precipitation are forced by latitudinal changes of the Southern Oscillation (Martin et al. 1993) and latitudinal movements of the ITCZ due to precession forcing (Martin et al. 1997).

5.2.3 Human impact

Records of human occupation of the study area come from archeological sites. Gnecco (1999) found substantial evidence for a Late Glacial-early Holocene occupation in the valley of the Magdalena river and in the upper and middle Calima valley since 10 $^{14}$C kyr B.P. At site San Isidro, which is located about 50 km north of Popayán, human impact was also dated back to 10 $^{14}$C kyr B.P. (Gnecco and Mora 1997). Considering human impact on the Colombian vegetation more in general, Marchant et al. (submitted) shows in a biome reconstruction at 10 time slices from 6 $^{14}$C kyr B.P. to the present that the degraded vegetation category started at low elevations between 5-3 $^{14}$C kyr B.P., gradually increasing and expanding to higher elevations during the last 2.5 $^{14}$C kyr B.P. In our southern Colombian pollen records the first human occupation can be recognised at 4.3 $^{14}$C kyr B.P. in Pitalito (Bakker 1990), about 2.3 $^{14}$C kyr B.P. in Genagra (Behling et al. 1998), and at about 2.1 $^{14}$C kyr B.P. in Timbio (Wille et al. 2000).
5.3 Methods

5.3.1 Recovery and analysis of the new Piagua core

The 6-m-long sediment core from Piagua was drilled with a Dachnowsky sampler in the centre of the swamp. Sediment cores of 25 mm diameter were collected in 25 cm increments, wrapped in plastic foil and transported in PVC gutters. Connections between sediment increments were of good quality. Only the sediments between 0 to 60 cm were too soft to be recovered as a solid core; therefore this interval was sub-sampled in 10 cm intervals in the field after coring. The interval 377 to 349 cm was very wet and sandy and could not be recovered. Sandy sediments below 600 cm prevented further sediment recovery. In the laboratory the core was stored under cold (4°C) and dark conditions. Samples of 0.5 cm³ were taken at 5 cm intervals along the core for pollen analysis. The samples were treated with sodium pyrophosphate, acetolysis and heavy liquid separation with bromoform (Faegri and Iversen 1989). A tablet of exotic *Lycopodium* spores was added to each sample to calculate pollen concentration values. A minimum of 300 pollen grains were counted in each sample, excluding taxa representing aquatic and lake shore vegetation. Core Piagua revealed 127 different identified fossil pollen and spore types (Tab. 5.1.).

*Tab. 5.1. Identified fossil pollen and spore types in core Piagua. Taxa have been arranged after altitudinal and ecological preference. Taxa with an asterisk are included in the pollen sum.*

**Lower subandean trees and shrubs (1000 – 1800 m)** *

Acalypha
Bombacaceae
Menispermaceae
Moraceae/Urticaceae

**Upper subandean trees and shrubs (1800 – 2300 m)** *

Alnus
Bocconia
Clusia
Dodonaea

Ericaceae
Gunnera
Hedyosmum
Juglans

Myrica
Myrsine
Podocarpus
Symlocos
### Other subandean trees and shrubs (1000 – 2300 m)

<table>
<thead>
<tr>
<th>Drimys</th>
<th>Laplacea</th>
<th>Weinmannia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abutilon-type</td>
<td>Abutilon-type</td>
<td>Ilex</td>
</tr>
<tr>
<td>Alchornea</td>
<td>Ilex</td>
<td>Piper</td>
</tr>
<tr>
<td>Anacardiaceae</td>
<td>Lauraceae</td>
<td>Laplacea</td>
</tr>
<tr>
<td>Antidaphne</td>
<td>Loranthaceae</td>
<td>Weinmannia</td>
</tr>
<tr>
<td>Apocynaceae</td>
<td>Mabea-type</td>
<td></td>
</tr>
<tr>
<td>Arecaceae</td>
<td>Malpighiaceae</td>
<td></td>
</tr>
<tr>
<td>Bauhinia bicuspida-type</td>
<td>Malvaceae</td>
<td></td>
</tr>
<tr>
<td>Bignoniaceae</td>
<td>Melastomataceae</td>
<td>19 µm</td>
</tr>
<tr>
<td>Casearia-type</td>
<td>cf. Miconia (=}</td>
<td></td>
</tr>
<tr>
<td>Cecropia</td>
<td>Melastomataceae</td>
<td>19 µm</td>
</tr>
<tr>
<td>Cordia lanata-type</td>
<td>Meliaceae</td>
<td></td>
</tr>
<tr>
<td>Croton</td>
<td>Mimosaceae</td>
<td></td>
</tr>
<tr>
<td>Daphnopsis</td>
<td>Mimosaeae</td>
<td></td>
</tr>
<tr>
<td>Euphorbiaceae</td>
<td>Myrtaceae</td>
<td></td>
</tr>
<tr>
<td>Hyeronima</td>
<td>Oryctanthus</td>
<td></td>
</tr>
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### Herbs

<table>
<thead>
<tr>
<th>Acanthaceae</th>
<th>Brassicaceae</th>
<th>Papilionaceae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amaranthaceae/</td>
<td>Bromeliaceae</td>
<td>Plantago</td>
</tr>
<tr>
<td>Chenopodiaceae</td>
<td>Caryophyllaceae</td>
<td>Poaceae</td>
</tr>
<tr>
<td>Apiaceae</td>
<td>Convolulaceae</td>
<td>Polygala</td>
</tr>
<tr>
<td>Artemisia</td>
<td>Cucurbitaceae</td>
<td>Polygonum persicaria-type</td>
</tr>
<tr>
<td>Asteraceae (Asteroidae)</td>
<td>Cuphea</td>
<td>cf. Portulacaceae</td>
</tr>
<tr>
<td>Asteraceae (Cichorioideae)</td>
<td>Hypericum</td>
<td>Ranunculaceae</td>
</tr>
<tr>
<td>Begonia</td>
<td>Iridaceae</td>
<td>Spermacoce</td>
</tr>
<tr>
<td>Boraginaceae</td>
<td>Lamiaceae</td>
<td>Valeriana</td>
</tr>
<tr>
<td>Borreria</td>
<td>Lupinus</td>
<td>Vernonia-type</td>
</tr>
</tbody>
</table>

### Human impact indicators

<table>
<thead>
<tr>
<th>Ipomoea-type</th>
<th>Aquatic taxa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manihot</td>
<td>Sagittaria</td>
</tr>
<tr>
<td>Phaseolus-type</td>
<td>Selaginella</td>
</tr>
</tbody>
</table>

| Ludwigia | Typha |

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Tab. 5.1. (continued)

<table>
<thead>
<tr>
<th>Ferns</th>
<th>Tree ferns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zea mays</td>
<td>Hydrocotyle</td>
</tr>
<tr>
<td></td>
<td>Isoëtes</td>
</tr>
<tr>
<td><em>Anemia</em></td>
<td>Marsileaceae</td>
</tr>
<tr>
<td><em>Grammitis-type</em></td>
<td>Monolete psilate</td>
</tr>
<tr>
<td><em>Jamesonia-type</em></td>
<td>Monolete verrucate</td>
</tr>
<tr>
<td><em>Lophosoria quadripinnata</em></td>
<td>Osmunda-type</td>
</tr>
<tr>
<td><em>Lycopodium foveolate</em></td>
<td>Trilet echinate</td>
</tr>
<tr>
<td>(form type)</td>
<td>Trilet psilate</td>
</tr>
<tr>
<td><em>Lycopodium jussiaei-type</em></td>
<td>Trilet verrucate</td>
</tr>
</tbody>
</table>

For pollen and spore identification of all cores in the Popayán area we used the studies of Murillo and Bless (1974, 1978); Hooghiemstra (1984); Roubik and Moreno (1991); Graf (1992); Behling (1993); Herrera and Urrego (1996) and the reference collection of the Hugo de Vries Laboratory. For calculation and presentation of the data of sites Piagua, Timbio and Genagra, TILIA, TILIAGRAPH and CONISS software was used. Original counting data of the cores from site Pitalito were not available any more, therefore we had to use the data presentation as originally published, which is different from the new cores. The pollen percentage diagram shows only the most important taxa. Taxa of cores Piagua, Timbio and Genagra have been arranged into seven ecological groups: (1) upper subandean trees and shrubs, (2) lower subandean trees and shrubs, (3) other subandean trees and shrubs without clear altitudinal preference, (4) human impact indicators, (5) herbs, (6) aquatics, and (7) ferns. Taxa belonging to the groups 1 to 5 represent the regional vegetation and are included in the pollen sum. Rare taxa that occur mainly at higher elevation (in the Andean vegetation belt, such as *Drimys*), or mainly at lower elevation (in the tropical lowland vegetation, such as Bombacaceae) were placed into the nearest group of the subandean forest. Taxa that occur across the whole altitudinal range of the subandean belt, without clear altitudinal preference, were grouped into the category 'other subandean forest taxa'.

Eight 0.5 cm³ bulk samples were collected for AMS $^{14}$C dating at depths where significant changes in the pollen record occurred. Samples were cleaned of roots and dated at the Van de Graaff Laboratory of the University of Utrecht (Van der Borg et al. 1987).
5.3.2 Interpretation and comparison of pollen records

Interpretation of pollen records is based on studies of the modern pollen rain along altitudinal transects in Central Colombia by Grabandt (1980), Melief (1985), Witte (1994). A synthesis of modern pollen rain at Bogotá latitudes (Fig. 5.3.) shows the direct relationship with the altitudinal distribution of the main floral elements (Cleef and Hooghiemstra 1984; Mommersteeg 1998). The altitudinal vegetation distribution in the Popayán area is similar and differs only in detail (Fig. 5.2.). In the palaeotemperature reconstructions we used a lapse rate of 0.6°C temperature decrease per 100 m upslope shift.
Fig. 5.3. Altitudinal distribution of modern pollen rain in the Eastern and Central Cordillera at Bogotá latitudes. nges in pollen representation in surface samples are shown in altitudinal intervals of 100 m. Synthesis based on data presented in Grabandi (1980), Melief (1985), and Salomons (1986). Only a selection of the most important pollen producers is shown. The present-day altitudinal range of the taxa is shaded. (After Van 't Veer and Hooghiemstra 2000)
5.4 Results

5.4.1 Stratigraphy of core Piagua

The stratigraphy of the sediment sequence is summarised as follows:

- 0 - 175 cm dark brown organic rich soft clay, plant remains, rootlets between 0 – 125 cm
- 175 - 289.5 cm dark brown clay with dark grey loamy fraction
- 289.5 - 292 cm brown sand with organic rich components
- 292 - 349 cm brown-grey clay
- 349 - 377 cm sediments not recovered
- 377 - 425 cm light brown-grey clay
- 425 - 500 cm dark grey clay
- 500 - 550 cm dark brown clay
- 550 - 600 cm dark brown clay, downward increasing amounts of sand

5.4.2 Time control of core Piagua and other subandean forest records

The $^{14}$C ages of core Piagua belong to three different time intervals (Tab. 5.2.). The lowermost sample at 599 cm dates back to Middle Pleniglacial time. The lowermost 50 cm of sediments are increasingly sandy: this points to riverine activity during the last glacial. Organic rich sediments of Middle Pleniglacial time (also found in the cores of Genagra and Timbio) may have been removed from this depression during the later part of the glacial and remnants may have been dated in this sample. The high percentages of upper subandean forest elements in the lowermost sample, also point to cooler conditions as in the adjacent part of the record and support a glacial age of these sediments. Therefore, we consider the lowermost radiocarbon sample as being contaminated. As also the lowermost two pollen samples are at significant variance with the remaining part of pollen zone PIA-1 we also discarded these pollen assemblages. The following core interval shows four radiocarbon dates of Late Glacial and early Holocene age. The depth vs. age profile of Piagua (Fig. 5.4.) shows a linear relationship for the period of 14 to 7.5 $^{14}$C kyr B.P. The transition to the uppermost core interval with three samples of late Holocene age is formed by a 2.5-cm-thick sand layer which has a minimum age of 1923±43 $^{14}$C yr B.P. In the upper core interval
the depth vs. age profile shows also a constant sedimentation rate during the last 1.9 $^{14}$C kyr B.P. A hiatus in the sedimentary record of core Piagua from 7.5 to 1.9 $^{14}$C kyr B.P. is obvious.

![Graph](image.png)

*Fig. 5.4. Depth vs. age profile of sediment core Piagua, southern Colombia.*

Based on CONISS cluster analysis, and supported by marked changes in the pollen assemblages, five pollen zones were recognised: PIA-1 (595-472 cm, 26 samples), PIA-2 (472-342.5 cm, 24 samples), PIA-3 (342.5-292.5 cm, 12 samples), PIA-4 292.5-92.5 cm, 45 samples), and PIA-5 (92.5-0 cm, 14 samples)

*Tab. 5.2. Absolute time control of the sediment cores from the Popayán area: core Piagua (PIA), core Genagra (GEN), core Timbio (TIM), core Pitalito-2 (PIT-2), and core Pitalito-11 (PIT-11).*

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Col-No.</th>
<th>UtC-No.</th>
<th>$^{14}$C yr B.P.</th>
<th>δ $^{13}$C</th>
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</thead>
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<td>Piagua</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>1145</td>
<td>7549</td>
<td>650±80</td>
<td>-24.7</td>
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<tr>
<td>197</td>
<td>1123</td>
<td>5844</td>
<td>1213±35</td>
<td>-21.5</td>
</tr>
<tr>
<td>291</td>
<td>1146</td>
<td>7550</td>
<td>1923±43</td>
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</tr>
<tr>
<td>310</td>
<td>1124</td>
<td>5845</td>
<td>7996±49</td>
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</tr>
<tr>
<td>386</td>
<td>1147</td>
<td>7551</td>
<td>10 340±60</td>
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<tr>
<td>462</td>
<td>1148</td>
<td>7600</td>
<td>12 960±130</td>
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<td>1073</td>
<td>4967</td>
<td>40 900+900-1000</td>
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<tr>
<td>Genagra</td>
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<tr>
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<td>1058</td>
<td>4961</td>
<td>56 000-9000/+4000</td>
<td>-29.4</td>
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</tbody>
</table>
The pollen records from South Colombia have satisfactory time control. Whereas record Genagra include radiocarbon ages older than 50 $^{14}$C kyr B.P., time control of record PIT-11 provides also radiocarbon ages of 45.5 $^{14}$C kyr B.P. and 31.5 $^{14}$C kyr B.P. The interval around the LGM is represented in the pollen records from Timbio and Pitalito. The Late Glacial is shown in the pollen records Timbio and Piagua, whereas the early to mid-Holocene interval is only represented in the younger record from Pitalito (PIT-2). The last about 2 $^{14}$C kyr B.P. are represented in all records and time control of this period is based on six radiocarbon ages in total.

The subandean pollen records from Central Colombia have less satisfactory time control. Three time intervals are represented in the Lusitania record. The lower part of the core includes three ages around 39 $^{14}$C kyr B.P. In the upper part of the Lusitania core, two radiocarbon ages at 30 cm from each other show 14.58 $^{14}$C kyr B.P. and 5.15 $^{14}$C kyr B.P.; this difference in age and marked difference in the lithology is indicative of a gap in the record. The pollen records of Pedro Palo and Libano include radiocarbon dates from the base of the records showing Late Glacial ages. The youngest record of the Pedro Palo (PP-II) site is undated. One radiocarbon date at the base of core Ubaqué shows the pollen record represents the last 3.5 $^{14}$C kyr B.P.

<table>
<thead>
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<th>Tab. 5.2.</th>
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<td>550</td>
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</tr>
<tr>
<td>690</td>
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<td>891-895</td>
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<td>1271-1275</td>
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</table>

The pollen records from South Colombia have satisfactory time control. Whereas record Genagra include radiocarbon ages older than 50 $^{14}$C kyr B.P., time control of record PIT-11 provides also radiocarbon ages of 45.5 $^{14}$C kyr B.P. and 31.5 $^{14}$C kyr B.P. The interval around the LGM is represented in the pollen records from Timbio and Pitalito. The Late Glacial is shown in the pollen records Timbio and Piagua, whereas the early to mid-Holocene interval is only represented in the younger record from Pitalito (PIT-2). The last about 2 $^{14}$C kyr B.P. are represented in all records and time control of this period is based on six radiocarbon ages in total.

The subandean pollen records from Central Colombia have less satisfactory time control. Three time intervals are represented in the Lusitania record. The lower part of the core includes three ages around 39 $^{14}$C kyr B.P. In the upper part of the Lusitania core, two radiocarbon ages at 30 cm from each other show 14.58 $^{14}$C kyr B.P. and 5.15 $^{14}$C kyr B.P.; this difference in age and marked difference in the lithology is indicative of a gap in the record. The pollen records of Pedro Palo and Libano include radiocarbon dates from the base of the records showing Late Glacial ages. The youngest record of the Pedro Palo (PP-II) site is undated. One radiocarbon date at the base of core Ubaqué shows the pollen record represents the last 3.5 $^{14}$C kyr B.P.
5.5 Late Glacial and Holocene environmental change at Piagua (Figs. 5.5, 5.6, appendix)

The period of 15.5 to 13.1 $^{14}$C kyr B.P. (zone PIA-1, 595 - 472 cm)

The oldest interval represents the period of ca. 15.5 $^{14}$C kyr B.P. (extrapolated age for 590 cm using a linear accumulation rate) to 13.1 $^{14}$C kyr B.P. During the period from 15.5 to 14.8 $^{14}$C kyr B.P., *Quercus*-dominated forest was abundant around the site at 1700 m. At present *Quercus* forest is common between 1550 and 2400 m. Also upper subandeian/Andean forest with a significant contribution of *Weinmannia*, *Hedyosmum* and *Myrsine* was present around the site. Between 14.8 to 14 $^{14}$C kyr B.P., *Quercus* became less dominant and Andean taxa like *Weinmannia* and *Miconia* became more abundant. The change in forest composition points to cooling. For the interval 15.5-14 $^{14}$C kyr B.P., we estimate that the subandeian to Andean forest belt transition (S/At) was located at 1500/1600 m. That is 800-700 m lower than today which points to temperatures 4°-5°C lower than today using the 0.6°C/100 m lapse rate.

From 14 to 13.1 $^{14}$C kyr B.P., *Quercus* and *Weinmannia* forest communities were replaced by *Alchornea* dominated forest (present-day altitudinal range: 1350-1750 m) whereas the contribution of *Miconia* did not change. Lower subandeian forest with Moraceae/Urticaceae and *Acalypha* reached nearer to site Piagua which was probably surrounded by uppermost subandeian forest. We interpret this change as an upslope shift of the S/At from 1500/1600 m to about 1800 m and temperature must have increased by ca. 1.5°C to a level of some 3°C lower than today. The temperature increase during this period is called the Susacá interstadial and represents the start of the Late Glacial period which was dated in other Colombian pollen records to 14 $^{14}$C kyr B.P. (Van der Hammen 1995, Thouret et al. 1997).

Apart from some Cyperaceae and *Selaginella*, aquatic vegetation was rare indicating open water conditions. Poor local vegetation, and as a consequence low input of organic material, is supported by the presence of grey sediments, mixed with dark brown sediments that apparently received a temporary supply of organic material from the surrounding forested area.

The period of 13.1 to 10 $^{14}$C kyr B.P. (zone PIA-2, 472 - 342.5 cm)

During the period 13.1 to 10 $^{14}$C kyr B.P. *Alchornea* disappeared as a dominating tree, and other arboreal taxa of the subandeian forest belt, such as *Quercus*, *Ilex* and Euphorbiaceae
mainly made up the forest. Herbaceous vegetation became abundant, mostly represented by Poaceae and Asteraceae.

For the period from 13.1 to 12.3 $^{14}$C kyr B.P., we are not confident to reconstruct the forest composition because of the relatively high number of unknown pollen grains. Most of the unknown pollen grains are tricolporate and reticulate to microreticulate, which are common in families such as Leguminosae and Rubiaceae with many arboreal genera represented in the subandean and Andean forest belts. It is also possible that this relatively high number of unknown pollen grains might represent a yet unknown forest community; but assuming an unknown forest type with no modern analogue that occurred only for a few hundred years and disappeared again is doubtful. The forest seems mainly made up of Quercus, Ilex, Hedyosmum and Euphorbiaceae, taxa that are indicative of forest types of the subandean as well as the Andean forest belt. Alchornea and Miconia disappeared almost completely. In our opinion the forest composition is not sufficiently indicative of a temperature range. The abundance of Poaceae and Asteraceae points to more open forest. Presence of herbs, Lycopodium (with foveolate spores) and shrubs (Hypericum and Asteraceae) that nowadays occur close to the upper forest line, could also suggest that the width of the forest belt was significantly reduced during this period, a phenomenon also reported for the region around Laguna Pedro Palo (Hooghiemstra and Van der Hammen 1993). Although the temperature in this period was probably lower than before, we cannot make a quantitative estimation on the basis of core Piagua. Other records further north in the Central Cordillera show a distinct cooling during this period known as the Ciega stadial (Van der Hammen 1995).

From 12.3 to 11.7 $^{14}$C kyr B.P., lower subandean forest taxa like Acalypha and Moraceae/Urticaceae were abundant and formed with Cecropia and Myrtaceae a forest type that points to a distinct warming. We estimate that the S/At shifted to about 2100 m and the temperature was approximately 1°-2°C cooler than today. This period corresponds to the Guantiva interstadial.

Between 11.7 and 10.9 $^{14}$C kyr B.P. the forest composition changed again. At the beginning of this interval, Acalypha, Cecropia and Moraceae/Urticaceae (lower subandean forest taxa) disappeared almost completely and were replaced by trees of the upper subandean and Andean forest belt such as Miconia, Quercus and Weinmannia. We estimate that the S/At shifted downslope to ca. 1800 m indicating temperatures of about 3°C lower than today. If this cold interval corresponds to the El Abra stadial, it is noted here that cooling started ca. 700 years earlier than in records from higher elevation (Van der Hammen and Hooghiemstra
Environmenta l chang e  in  th e  Colombia n  subandea n  fores t bel t

1995). Nevertheless, this discrepancy may just be a result of the lack of precise dating control (see the final section).

From 10.9 to 9 $^{14}$C kyr B.P., other subandean forest taxa like *Myrsine* and *Ilex* became more abundant. During the same interval, the occurrence of Chenopodiaceae, Malvaceae and *Abutilon*-type indicate drier conditions than before. We estimate the S/At at the same elevation, but the climate was drier than before. A change to drier conditions from 10.5 to 9 $^{14}$C kyr B.P. was also observed by Van’t Veer et al. (2000) for the area of Bogotá.

The period of 9 to 7.5 $^{14}$C kyr B.P. (zone PIA-3, 342.5 - 292.5 cm)

From 9 to 7.5 $^{14}$C kyr B.P., the forest composition differs significantly from that before and represents the situation during the beginning of the Holocene. The forest was made up by taxa characteristic of low elevation like Moraceae/Urticaceae, *Acalypha* and the dry lowland element *Zanthoxylon* (only occurring at this time). *Quercus* disappeared as an important forest element during the later part of this period. During the last part of this time interval, *Cecropia* was dominant in the forest. The S/At is estimated at about 2400 m, pointing to temperatures of about 0.5° to 1°C above modern values, but the climate was probably drier than today. Although *Cecropia* is often seen as an indicator for disturbed forest, we assume that *Cecropia* reflects here the natural forest composition. This view is supported by the low frequency of herb vegetation. We assume that the sediment hiatus from 7.5 to about 2 $^{14}$C kyr B.P. is related to incision by the small stream into previously accumulated early and middle Holocene sediments.

The period of 1920 to 670 $^{14}$C yr B.P. (zone PIA-4, 292.5 - 92.5 cm)

The first organic rich sediments on top of the 2.5-cm-thick sand layer were dated to 1923±43 $^{14}$C yr B.P. indicating that the period of 7.5 to ca. 1.9 $^{14}$C kyr B.P. is not represented in the sediment record. During the last 1.9 $^{14}$C kyr B.P. the vegetation was strongly affected by human disturbance as indicated by pollen grains from crops like *Zea mays*, *Phaseolus* and *Ipomoea*. Abundant *Zea mays* has been registered during the period 890 to 790 $^{14}$C yr B.P., indicating a cultural phase. The very low percentages of tree pollen indicate that since 1.9 $^{14}$C kyr B.P. the area must have been deforested and changed into a cultural landscape. Therefore, the natural vegetation cannot be inferred, preventing any conclusion about the climatic conditions of the last 1.9 $^{14}$C kyr B.P.
The period of 670 \(^{14}\)C yr B.P. to modern (zone PIA-5, 92.5 - 0 cm)

After 670 \(^{14}\)C yr B.P. there is no evidence of crop plants and the area of Piagua started to recover with secondary forest in which Melastomataceae and *Cecropia* are important. For the first time in this record, taxa characteristic of swampy conditions became abundant (Cyperaceae and *Typha*) suggesting that open lake conditions changed into swamp conditions. This is supported by the lithological column, showing dark brown organic rich sediments and Cyperaceous rootlets since ca. 1.1 \(^{14}\)C kyr B.P. (175 cm core depth).

5.6 Synthesis of environmental change from subandean forest belt sites; comparison of Popayán and Bogotá latitudes

Pollen records from Genagra, Piagua, Timbio and Pitalito from the Popayán area are used for a synthesis of vegetational and climatic change between 1300 and 1700 m. Records were graphed along a linear time scale (Fig. 5.7.). The reconstructions are given for periods that follow from the chronology of these four pollen records. Climatic conditions in the Pitalito basin are slightly warmer and drier than in Popayán, but the close distance and comparable setting and elevation make a comparison useful. A summary of the temperature and vegetational shifts during the investigated periods is shown in Fig. 5.8.

Period of >50-30 \(^{14}\)C kyr B.P.

Before 52 \(^{14}\)C kyr B.P. Bakker (1990) estimated a temperature some 7°C lower than today, inferred from the altitudinal position of the upper montane forest belt in which taxa like *Hedyosmum*, *Myrsine* and *Weinmannia* were dominant. Glacial conditions have also been found in the Genagra record (Behling et al., 1998) for the time around 50 \(^{14}\)C kyr B.P. for which period the same forest taxa were registered. Between 52 and 45 \(^{14}\)C kyr B.P. Bakker (1990) found forest taxa like Menisspermaceae, *Hieronima* and Arecaceae that are indicative of forest types at lower elevations. He inferred increasing temperatures to a level of about 4°-2°C lower than today. From 45 to 38 \(^{14}\)C kyr B.P. Andean forest taxa increased again indicating that the S/At shifted to ca. 1500 m, pointing to more humid conditions and temperatures of about 5°-6°C lower than today (we disagree with Bakker who inferred for this period a temperature drop of ca. 7°C). From 38 to 32 \(^{14}\)C kyr B.P., subandean forest taxa, like Myrtaceae and Urticaceae, became more abundant indicating drier conditions at site Pitalito. The S/At is estimated at ca. 1400 m and temperatures 5°-6°C lower than today were inferred.
Fig. 5.7. Composite pollen record on a linear time scale of southern Colombian sites located in the present subandean (= lower montane) forest belt. Ecological groups in core Genagra (1750 m, Behling et al. 1998), core Timbio (1750 m, Wille et al. 2000) and core Piagua (1700 m, this paper) are shown in uniform legend units. Ecological groups recognised in cores Pitalito-2 (upper part) and Pitalito-11 (lower part) (1300 m, Bakker 1990) are slightly different by lack of a possibility to recalculate the original data (Adapted after the original papers).
At site Lusitania, Quercus-dominated forest was found between 40 and 6 \(^{14}\)C kyr B.P. In contrast to our study area, where Quercus is a common tree in the subandean and Andean forest belts, in central and northern Colombia Quercus is most common in the Andean and high-Andean forest belts. Thus, abundance of Quercus-dominated forest at 1500 m at site Lusitania is indicative of lower temperatures than a similar situation in our study area when modern altitudinal distributions are used. We observe that during this period the altitudinal interval of 1500-1700 m in central and southern Colombia was characterised by different forest types, but for both locations temperatures about 5°-7°C lower than today can be inferred.

**Period of 30 to 23 \(^{14}\)C kyr B.P.**

Between 32 and 24 \(^{14}\)C kyr B.P., forest taxa like *Hedyosmum, Myrsine* and *Weinmannia* were dominant at Pitalito. These taxa were also important in the oldest part of the Timbio record which is of the same age. These taxa represent a forest community that grows today at higher elevation in the Andean forest belt under moist conditions. Bakker (1990) suggested for this period a temperature decline in Pitalito to some 8°C below present level, but we estimate the S/At at an elevation of 1400 - 1300 m and infer a temperature drop of ca. 6 -7°C. Regarding the difference in moisture this corresponds well to the inferred temperature drop of approximately 6°C at site Timbio. Today this forest type grows only on moist slopes in the Pitalito area. It is likely that this forest community was distributed further downslope during this time interval due to different humidity.

**Period of 23 to 18 \(^{14}\)C kyr B.P.**

From 24 to 20 \(^{14}\)C kyr B.P., forests in the Pitalito basin were dominated by *Quercus* and *Weinmannia* associated with *Hedyosmum, Hyeronima, Ilex*, and Myrtaceae A comparable forest community grows nowadays at around 2600 m, so at about 1300 m higher elevation where temperature is 8°C lower. Around 19 \(^{14}\)C kyr B.P., in the area of Pitalito forest communities with *Myrica* and *Weinmannia* were dominant (*Alnus* was mainly a local element in the depression); the present-day distribution is around 3000 m which indicates an ongoing trend to very cold and dry conditions. For this period Bakker (1990) reconstructed for site Pitalito a temperature about 10°C lower than today, but we estimate the S/At at ca. 1300 m and infer in Pitalito a maximum temperature of 6°-7°C below present level.
Between 23.8 and 16.6 \(^{14}\)C kyr B.P. the Timbio record shows a forest made up of *Weinmannia*, Melastomataceae, and Myrtaceae indicating first moister and later drier conditions; the inferred temperature was about 5°-7°C cooler than today.

Site Lusitania shows that *Quercus* was dominant during this period; therefore this site was located in the Andean forest belt and temperatures of 5°-7°C lower than today have been inferred.

Period of 18 to 13 \(^{14}\)C kyr B.P.

In the older part of this period Timbio records forest taxa, such as *Bacconia*, *Symlocos* and *Laplacea* which grow under modern conditions near the upper forest limit. The Piagua record starts at approximately 15.5 \(^{14}\)C kyr B.P. and during this period also shows 'high Andean' taxa, pointing to a downslope migration of the Andean forest belt of about 700 m. This is indicative of a temperature depression of 4°-5°C compared to today.

From 14.2 to 13.1 \(^{14}\)C kyr B.P., the Piagua record shows an upslope migration of the S/At from about 1500 to 1800 m pointing to temperatures of some 2°-3°C lower than today. This temperature increase corresponds to the 'Susacá interstadial' (Van der Hammen and González 1960). Our estimation of its start corresponds to the age of 14 \(^{14}\)C kyr B.P. reported by Van der Hammen (1995). The Libano pollen record is not well dated but one radiocarbon date, marking the first interstadial of the Late Glacial period, provides an age of 13 630±120 \(^{14}\)C yr B.P. During this time the area around the site was covered with Andean *Quercus* forest. According to Salomons (1986), the Andean forest belt at this time was located more than 500 m downslope compared to today. This is indicative of a temperature of at least 3°C lower than today and within the temperature range reconstructed from Piagua.

Period of 13 to 9 \(^{14}\)C kyr B.P.

The period of 13.1 to 12.3 \(^{14}\)C kyr B.P. is represented in cores Timbio (but possibly disturbed) and Piagua. An increase in timberline shrubs and a decrease of lower montane tree taxa (*Alchormea*) is indicative of cooler conditions which we interpret as reflecting the 'Ciega stadal' (Van der Hammen 1995). As discussed in the previous section we are not confident to make more precise statements about the forest composition as the number of unknown pollen types in the Piagua record is relatively high; neither do we try to estimate the temperature depression during this stadial. The sediment sequence of site Lusitania shows a stratigraphical discontinuity during this time which may suggest a hiatus. During this period the Andean
forest belt was almost absent in site Pedro Palo (Hooghiemstra and Van der Hammen 1993; Boom et al. 2001), also preventing an estimation of the temperature depression.

Around 12 $^{14}$C ky r B.P. the records of Piagua and Pedro Palo show a short warm interval indicated by abundant subandean forest taxa among which Acalypha, Cecropia and Moraceae/Urticaceae are dominant. This period corresponds to the 'Guantiva interstadial' (Van der Hammen and González 1963), dated in high elevation pollen records from 12.5 to 11 $^{14}$C ky r B.P. We estimate the S/At at ca. 2100 m and infer a temperature of only 1°-2°C lower than today at 1700 m. This period lasted till 11 $^{14}$C ky r B.P. at site Pedro Palo, until 10.8 $^{14}$C ky r B.P. in core Fuquene-2 (Van Geel and Van der Hammen, 1973) and until 11 210±90 $^{14}$C ky r B.P. in core El Abra-B3 (Schreve-Brinkman 1978), whereas it ended in record Piagua at 11.7 $^{14}$C ky r B.P. (see discussion) for this period.

The warm 'Guantiva interstadial' is followed by another cold phase called the 'El Abra stadial'. Although the El Abra stadial lasted from 11 to 10 $^{14}$C ky r B.P. according to Van der Hammen and Hooghiemstra (1995), it is likely that this cool period extended beyond the Late Glacial chronzone (Mangerud et al., 1974) and continued into the beginning of the Holocene. In record Pedro Palo this period was dated from 11 to 10.15 $^{14}$C ky r B.P. and in the Piagua record from 11.7 to 9 $^{14}$C ky r B.P. Both records show during this cold period a downslope shift of the Andean forest belt. In the Piagua record the S/At dropped about 300 m and in record Pedro Palo the upper forest limit dropped about 500 m. This is equivalent to a temperature about 3°C lower than today at 1700 m but about 5°C lower than today at 2500-3000 m (Van der Hammen and Hooghiemstra 1995) and suggests a reduced altitudinal extent of the Andean forest belt during this period. The period from 10.9 to 9 $^{14}$C ky r B.P. in record Piagua is characterised by cool and dry conditions, suggesting the climatic conditions during the El Abra stadial were in the beginning mainly cool and later mainly dry.

A similar change was also found by Van’t Veer et al. (2000) in a re-evaluation of pollen records from the area of Bogotá: he found dry climatic conditions during the period from 10.5 to ca. 9 $^{14}$C ky r B.P.

Period of 9 to 4 $^{14}$C ky r B.P.

From 9 to 7.5 $^{14}$C ky r B.P. the Piagua site is surrounded by subandean forest, dominated by Moraceae/Urticaceae and Acalypha. The pollen record of Pitalito shows a similar transition from cool Late Glacial to warm Holocene conditions. Around 7.3 $^{14}$C ky r B.P. temperature was probably comparable to present-day values. From 7.2 to 5 $^{14}$C ky r B.P. the Pitalito and
Pedro Palo records show that climate was about 1°C warmer, and more humid compared to today, a value supported by the synthesis of mid and late Holocene Colombian biomes (Marchant et al. submitted).

The earliest record of *Zea mays*, which reflects human settlements and agriculture, is present at site Lusitania already before 5 ¹⁴C kyr B.P. Around 5 ¹⁴C kyr B.P. the Lusitania site shows an important agricultural phase. At the Ubaqué site the earliest human impact was recognised 3.5 ¹⁴C kyr B.P. (Berrio 1995). The first occurrence of *Zea mays* in the Pitalito basin has been registered at 4.3 ¹⁴C kyr B.P. The first agricultural phase in the area of Popayán seems to occur at about the same time.

Period of 4 ¹⁴C kyr B.P. to recent

The pollen records of Genagra, Piagua and Timbio start again around 2 ¹⁴C kyr B.P. and all reflect a vegetation strongly affected by man as a result of deforestation and agriculture. The area of Popayán has been covered by secondary vegetation for at least 2000 years. After 670 ¹⁴C yr B.P. the presence of crop plants diminished and site Piagua then shows abundant secondary forest, pointing to a significant reduction of human activity. Human impact decreased around 900 ¹⁴C yr B.P. in the area of site Timbio, and around 780 ¹⁴C yr B.P. in the area of site Genagra. There is evidence for agriculture in the Pitalito basin since around 450 ¹⁴C yr B.P.

5.7. Discussion and conclusions

This paper integrates evidence for the last 50 ¹⁴C kyr B.P. from pollen records between 1300 and 2000 m elevation; the South Colombian sites do have the best time control and show most detail. A general temperature record for 1700 m is shown in Fig. 5.8. After around 50 ¹⁴C kyr B.P. temperature was relatively mild and at 1700 m about 3°C lower than today. Around 40 ¹⁴C kyr B.P. temperature was only slightly warmer than at the LGM. Between 40 and 32 ¹⁴C kyr B.P., temperatures increased again and were about 5°-6 °C cooler than today. After 32 ¹⁴C kyr B.P., temperatures at 1700 m gradually decreased and reached at the LGM values of about 6° to 7°C lower than today. These LGM values at 1700 m are less than the estimated LGM temperature drop of 8°-9°C at 2500-3000 m (e.g. Van der Hammen and González 1963; Hooghiemstra 1984; Mommersteeg 1998; Van 't Veer and Hooghiemstra 2000), but higher than the estimated LGM temperature drop of 4°-6°C at sea-level (e.g. Bush et al. 1990, 2001;
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Stute et al. 1995; Farrera et al. 1999) and substantiate a steeper glacial lapse rate. After the LGM, temperatures continuously increased until about 14\(^{14}\)C kyr B.P. and reached an annual mean of about 15°C at 1700 m, about 3°C lower than today. From 14 to 9 \(^{14}\)C kyr B.P. the lower montane forest belt shows altitudinal shifts that mainly reflect the well known Late Glacial temperature oscillations: the 'Susacá interstadial', 'Ciega stadal', 'Guantiva interstadial' and 'El Abra stadial' according to Colombian chronosтратigraphy (Van der Hammen 1995). The El 'Abra stadal', claimed by Van der Hammen and Hooghiemstra (1996) to be the equivalent of the Younger Dryas stadal of the North Atlantic area, shows temperatures of about 3°C cooler than today. We recognise drier climatic conditions during the second part of the El Abra stadial; such a wet to dry climatic transition has also been found in high Andean records near Bogotá (Van 't Veer et al. 2000). Although some 45 radiocarbon dates are available for the sequence of climate oscillations during the Guantiva interstadial-El Abra stadal-early Holocene (Van der Hammen and Hooghiemstra 1995), bracketing radiocarbon dates are not available for Colombian records and precise dating of the rapid climatic oscillations during the Late Glacial is still lacking. Discrepancies between records are due to linear interpolations of available radiocarbon ages. Additionally, lakes may lose previously accumulated sediments by river incisions during dry episodes with low lake-levels. We conclude that the Late Glacial climate oscillations, as known from high-elevation records, are recognised in the subandean forest belt. The beginning of the Holocene, until around 7 \(^{14}\)C kyr B.P., is characterised by a transition to warmer temperatures. From 7 to 5 \(^{14}\)C kyr B.P. temperature was about 0.5°-1°C warmer than today. During the last 4.5 \(^{14}\)C kyr B.P. pollen records at many places are affected by human activity (agriculture and deforestation, see also Marchant et al. submitted), and are not suitable for inferring natural environmental change.

Although changes in humidity are registered in our subandean pollen records with less temporal resolution than in the records from higher elevation, we compare our results with the records of moisture reconstruction from site Fuquene-2 (Van Geel and Van der Hammen 1973; representing the last ca. 32 \(^{14}\)C kyr B.P.), and in particular site Fuquene-7 (Mommersteeg 1998) that represents the total time range of the present paper.
Fig. 5.8. Top: estimated altitudinal shifts of the subandean/Andean forest belt transition (S/At) and inferred palaeotemperatures at 1700 m elevation (deviation to modern values) during the last 50 \(^{14}\)C yr B.P. Temperature bars show values reconstructed for time intervals discussed in the text. Bottom: Pollen records located in the present subandean forest belt used in this synthesis: dotted lines show the time intervals represented by the cores, 'x' indicate the position of radiocarbon dates, '>' indicate the position of finite radiocarbon dates (older than 50 \(^{14}\)C yr B.P). Vertical lines indicate the time intervals discussed in the text. LUS = Lusitania, LIB = Libano, UBA = Ubaqué, PP = Pedro Palo, GEN = Genagra, TIM = Timbio, PIA = Piagua, PIT = Pitalito.

Mommersteeg calculated a 'dryness index' based on a summation of the normalised curves of Cyperaceae, marsh and aquatic elements (Mommersteeg 1998, p. 54); in fact a high dryness index reflects low water level stands in lake Fuquene. Only relative changes of the curve of
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the dryness index are considered as, in general, cold climatic episodes have high lake level stands due to lower evaporation than under warmer climatic conditions. Between 45 and 38 $^{14}$C kyr B.P. inferred increasing humidity around 1700 m is supported by the dryness index of core Fuquene-7. Drier conditions inferred from site Pitalito between 38 and 32 $^{14}$C kyr B.P. are also recorded in Fuquene. Between 32 and 24 $^{14}$C kyr B.P. the Popayán records, as well as the Fuquene record, document increasing climatic humidity, changing in both areas to dry conditions in the period of 24 to 20 $^{14}$C kyr B.P. around the LGM. Our mid-elevation pollen records are not conclusive for the period between 18 and 11 $^{14}$C kyr B.P., but dry conditions during the second part of the El Abra stadial (10.0 to ca. 9 $^{14}$C kyr B.P.), and more humid conditions during the period from 7.2 to 5 $^{14}$C kyr B.P. are supported by the dryness index of core Fuquene-2. We conclude that changes in climatic humidity, as registered in two different areas (at Bogotá and Popayán latitudes), and at two different elevations (around 2500-3000 m and around 1300 to 2000 m), match well and appear representative for a larger area of Colombia. A more thorough comparison between Colombian records of climatic humidity will be presented elsewhere.

Martin et al. (1997) postulated a mechanism to explain the antiphase in climatic moisture north and south of the Amazon basin during the last 12 $^{14}$C kyr B.P. He showed that opposite trends in the lake level histories of Lake Valencia (Venezuela) and Lake Titicaca (Bolivia) can be explained by precession-forced shifts of the ITCZ. Indeed, frequency analysis of the Funza-1 data set (Hooghiemstra et al. 1993), and analysis of core Fuquene-7 (Mommersteeg 1998) both showed the impact of the precession cycle of orbital forcing on changes in climatic humidity. In the Funza-1 core cyclic change in humidity was reflected in cyclic changes of the width of the subparamo vegetation belt. In the Fuquene-7 core cyclic changes in humidity were shown by the relation between maximum percentages of *Alnus* (indicating low lake levels) and minima in the precession (Mommersteeg 1998, p. 36, 72). The present record of climatic moisture from mid-elevation Colombian sites, showing relatively dry conditions around 10, 20, and 32 $^{14}$C kyr B.P. is in harmony with the climatic moisture record observed in Fuquene (Mommersteeg 1998), and possibly also in harmony to the record of Lake Pata in northeastern Amazonia (Colinvaux et al. 1996) where some expansion of dry vegetation elements, such as Gramineae and *Borreria*, can be noticed.

In Fig. 5.9. we summarise the altitudinal distribution of main vegetation belts along a cross section through the Colombian Andes at Popayán latitude for the present and the LGM. The plot for modern conditions shows a lapse rate of ca. 0.6°C/100 m. The plot for LGM
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conditions shows a calculated lapse rate of 0.76°C/100 m and strongly suggests a steeper temperature gradient than today's. The dry LGM atmosphere must be responsible for the higher lapse rate. At this moment it is uncertain in what ways a steeper LGM lapse rate may affect temperature reconstructions for neotropical mountains. When the LGM altitudinal position of the upper forest line has been inferred from a pollen diagram, application of a steeper lapse rate results in a higher estimated temperature drop whereas the effect of a lower atmospheric $p$CO$_2$ has an opposite effect. Both variables are quantitatively poorly understood and need further attention.

Fig. 5.9. Altitudinal distribution of main vegetation belts along a cross section through the volcano Purace in the Colombian Andes at Popayán latitude for time slices at present-day (A) and at the Last Glacial Maximum (B). Fig. 5.9A: modern altitudinal vegetation distribution (after Van der Hammen 1974), and measured modern mean annual temperatures of 16 sites plotted against altitude. Fig. 5.9B: Last Glacial Maximum altitudinal vegetation distribution as summarised from sites Timbio and Pitalito (this study), and the reconstructed mean annual LGM temperatures for 16 sites plotted against altitude. Modern conditions shows a lapse rate of ca. 0.6°C/100 m, whereas the reconstructed LGM lapse rate is 0.76°C/100 m. Sites: 1 = La Ciega (3510 m, Van der Hammen et al. 1989/81); 2 = Alsacia (3100 m, Melief 1985); 3 a = TPN40 (2940 m, Salomons 1986), 3 b = TPN21 (2940 m, Salomons 1986); 4 a = Fuquene 2 (2580 m, Van Geel, Van der Hammen 1973), 4 b = El Abra (2570 m, Schreve-Brinkmann 1977), 4 c = CUX (ca. 2550 m, Van der Hammen, Gonzalez 1963); 5 = Merenberg (2500 m, Piñeros-Soler 1988); 6 = Otoño-Manizales Enea (2250 m, Cleef et al. 1995); 7 = Pedro Palo (2000 m, Hooghiemstra, Van der Hammen 1993); 8 = Libano (1820 m, Salomons 1986); 9 = El Dorado (1500 m, Monsalve 1985); 10 = Pitalito (1300 m, Bakker 1990); 11 = Mera (1100 m, Liu, Colinvaux 1985); 12 = La Yeguada (650 m, Piperno et al. 1990); 13 a = Timbio (1750 m, Wille et al. 2000), 13 b = Genagra (Behling et al. 1998), 13 c = Piagua (this study).
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