PHYTOGEOGRAPHIC DIVISIONS, CLIMATE CHANGE AND PLANT DIEBACK ALONG THE COASTAL DESERT OF NORTHERN CHILE

Natalie Schulz, Patricio Aceituno and Michael Richter

With 10 figures and 3 tables
Received 14. July 2010 · Accepted 02. May 2011

Summary: Along the hyper-arid Chilean coastal desert between 30°S and 18°S the Loma vegetation undergoes a gradual transition from open shrubland to small isolated areas of a scarce plant cover. Floristic and physiognomic features allow a differentiation of five Loma formations, each of them characterized by a distinctive spectrum of plant communities. However, particularly in the northern section of the investigation area, numerous indications point to a strong vegetation decline including a deterioration of plant cover, reduction of the vitality of various taxa, probably also a local loss of some perennial species, and even a dieback of specific populations. These signs of a retrogression, which coincide with a regional disappearance of Guanaco herds in the coastal area between 20°S and 23°30'S, became apparent in the second half of the past century and were most likely provoked by recent climate change in the arid coastal region. Especially the decrease of rainfall frequency might have negative implications for the regeneration and preservation of plants. In addition, a strong reduction of cloudiness in the northernmost section affects plant growth due to further limitations in the water disposability. A projected sustained decline of rainfall is expected to continue endangering the surprisingly high floristic diversity of the sensitive ecosystem complexes in the coastal desert.

Zusammenfassung: Entlang der perariden chilenischen Küstenwüste von 30°S bis 18°S verändert sich die Loma-Vegetation von offenen Strauchbeständen hin zu isolierten Pflanzenvorkommen geringer Deckung. Floristische und physiognomische Kriterien erlauben eine Untergliederung in fünf Abschnitte, die sich jeweils durch ein eigenes Spektrum an Pflanzengesellschaften auszeichnen. Allerdings belegen im Norden des Untersuchungsgebietes zahlreiche Merkmale eine Verminderung der Vitalität einzelner Sippen, den lokalen Verlust einiger perenner Taxa und sogar den Niedergang ganzer Populationen einzelner Arten. Dieser Vegetationsrückgang, der mit den Verlust von Guanaco-Herden aus der Küstenregion zwischen 20°S und 23°30'S einhergeht, zeichnet sich vor allem seit der zweiten Hälfte des letzten Jahrhunderts ab und ist mit großer Wahrscheinlichkeit auf Veränderungen im Klima der ariden Region zurückzuführen. Insbesondere die Abnahme der ohnehin bescheidenen Regenhäufigkeit dürfte sich negativ auf die Regeneration und den Erhalt der Pflanzen auswirken. Zudem beeinflusst ein Rückgang der Bewölkung im Norden der chilenischen Küstenwüste die Lebensbedingungen der Vegetation aufgrund weiterer Beschränkungen im Wasserhaushalt negativ. Die absehbare weitere Abnahme der Niederschläge wird die überraschend große Pflanzendiversität des höchst sensiblen Loma-Ökosystem-Komplexes auch in Zukunft bedrohen

Keywords: Loma formations, floristic composure, plant dieback, fog, decreasing rainfalls

1 Introduction

For some 15 years, reports on a regionally dramatic plant dieback have called attention to a damage of the unique ecosystems in the northern part of the coastal Atacama Desert (18°S-30°S), known as one of the world's driest regions. Although characterized by hyper-arid conditions, it locally sustains exuberant *Loma* vegetation, which harbours a surprisingly high amount of endemic vascular plant species. Despite rain scarcity and harsh environmental conditions, it succeeds in subsisting on the windward escarpment of the coastal cordillera, benefiting from frequent fogs.

Meanwhile, an increasing number of indications point to a decline of the Loma vegetation in the northern part of the desert, probably associated with the loss of some species (e.g., Follmann 1995; Richter 1995; Rundel et al. 1997; Dillon and Hoffmann 1997; Grau 2000; Muñoz-Schick et al. 2001; Pinto et al. 2001; Pinto and Kirberg 2005; Pinto 2007). Although some aspects of the vegetation decline has already been approached in a few studies on the current conservation status of some cactus species (Belmonte et al. 1998; Pinto and Kirberg 2005; Pinto 2007), the actual dimensions and origins of the deterioration processes remain so far unknown. Some authors have postulated increasing aridity in recent decades as a probable cause of the vegetation decline (e.g., Richter 1995; Rundel et al. 1997; Pinto and Kirberg 2005). However, the lack of studies on recent climate evo-

DOI: 10.3112/erdkunde.2011.02.05 ISSN 0014-0015 http://www.erdkunde.uni-bonn.de

lution in this region, particularly on precipitation, cloudiness and fog development, has made the corroboration of this assumption difficult so far.

More detailed research on driving forces of the vegetation decline constitutes an important task, particularly considering the singularity and high sensibility of the Loma ecosystems. In this context, the objective of our study is to assess vegetation changes in the arid coastal region in the recent past. Furthermore, detailed analyses of climate development during the past century may provide evidence for possible climate effects on vegetation retrogression. This paper focuses on spatial patterns of vegetation in order to elaborate a comparative framework of the plant formations and communities based on detailed previous and own studies of Chilean Lomas (i); on indices and evidence of recent vegetation changes compiled from various sources (ii); and finally on analyses of climate variations in the recent past (iii), which are expected to contribute to the discussion on possible triggers of this vegetation decline.

2 Data and methods

Vegetation sampling was carried out in 15 Loma localities between 20°S and 30°S (2005, 2006, and 2009). In each area, plant cover was studied along one to three transects situated mostly on southern, south-western or western sea-facing slopes, which usually receive moisture by stratocumulus clouds (detailed information in Schulz 2009). Floristic lists were compiled for each one of the studied Loma localities and additionally for 14 further localities using information from different sources (for localities see Fig.1). They include data from own field trips and those recorded in former vegetation studies and botanical collections (the latter from databases of three important Chilean herbaria: Santiago (SGO), Concepción (CONC), and La Serena (HULS). Floristic data from 29 Loma localities were used for cluster analyses in order to differentiate the Loma vegetation. A hierarchical agglomerative clustering was done as presence-absence analysis of the total number of registered perennial native plants. The Sørensen index was used as an algorithm for the calculation of similarity and average group linkage as distance between the clusters. The species nomenclature follows Hoffmann and Walter (2004) for Cactaceae and Squeo et al. (2008), Marticorena et al. (1998 and 2001) for further families.

With regard to difficulties in the application of quantitative methods to analyse vegetation changes within the investigation areas, we opted for a qualitative approach, since no vegetation releveés prior to 1972 were available. Due to insufficient spatial resolution and temporal coverage, satellite and areal images are inappropriate for detecting changes in the desert vegetation considered here. Hence, previous floristic publications and further sources were revised to assess indications on the previous floristic composition and state of plant cover. Since botanical research in some of the areas has been conducted continuously throughout the past nine decades, comparisons of floristic lists allow a detection of general tendencies during the recent vegetation history.

Trend analyses were performed for precipitation and total cloud cover. Analyses of tendencies in fog, a further important ecological factor in the study area, could not be included due to a series of difficulties associated with trend analyses of fog. Firstly, there are no suitable observational fog data series, since meteorological stations in the study area are situated mostly in the proximity of airports, at lower, widely fog-free sites. Secondly, reliable continuous fog data derivable from fog precipitation measurements or satellite images cover a relatively short period since 1997 and 1980 respectively. For the purposes of this study it is, however, crucial to assess longer trends from at least the mid-20th century or longer. And finally, tendencies identified for specific sites are not easily transferable to larger coastal zones, as fog characteristics vary highly along the northern Chilean coast depending on the ocean proximity, altitude, local relief, exposure of the coastal ranges (Larrain et al. 2002), as well as orographic fog influence and other factors not studied so far. Nevertheless, some general conclusions about advection fog tendencies can be derived from stratocumulus trends, given the fact that the formation and persistence of advection fog are highly influenced by the presence of this type of clouds (Cereceda et al. 2002; Garreaud et al. 2008).

To evaluate long-term changes of precipitation and cloudiness regimes, series of annual and monthly means from four coastal stations (Arica, Iquique, Antofagasta, La Serena) and one station nearby the coast (Copiapó, s. Fig.1) were compiled from meteorological annals published by the Chilean Meteorological Service (DMC). Also, daily precipitation values were provided by the DMC. Few data gaps in the rainfall series are completed by information obtained from Almeyda (1948), who extracted the missing data from original reports of the respective sites. All climatic stations considered here are located below the zone of direct fog influence.

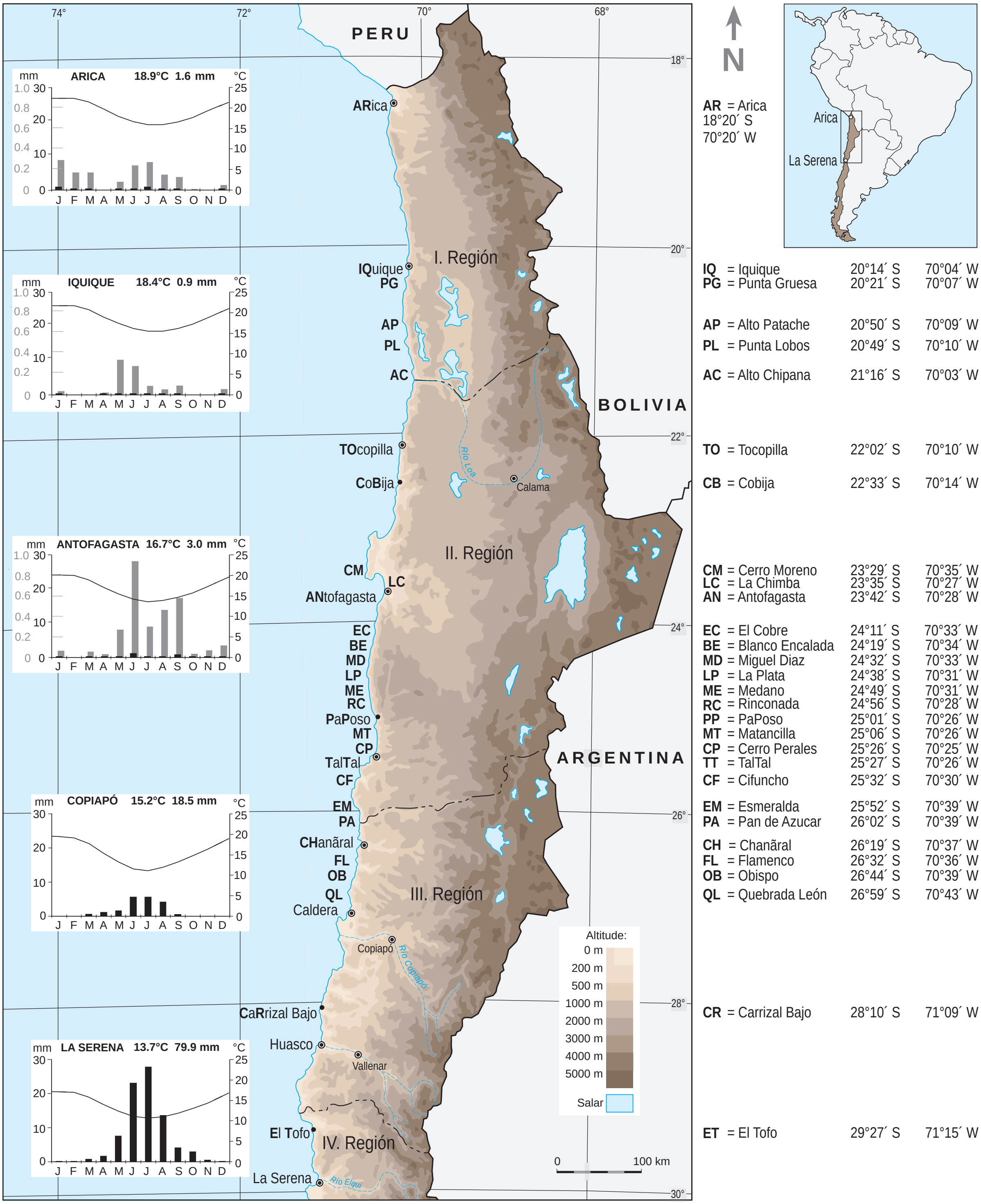

Fig. 1: Study area. Monthly precipitation and temperature means on the basis of data from 1971–2000 (note two scales for precipitation). Localities considered by the floristic analysis (data from own collections and/or other studies) are indicated in and at the right of the map

Apart from Arica, which does not show any correlation with precipitation series of other stations, all rainfall series were submitted to a relative homogeneity test according to ALEXANDERSSON (1986). Despite the fact that all stations were relocated at least once during the last century, this test did not reveal any significant inhomogeneity. Data of total cloud cover observations are compiled for the period 1950-2008. Since the interannual variability of cloudiness at all verified stations is widely coherent and the observation methodology has not changed during the past decades, no homogeneity tests were performed. The annual and seasonal frequency of cloudy days (mean daily cloud cover in oktas ≥ 6/8) and cloudless days (mean daily cloud cover ≤ 2/8) were derived from the meteorological annals of the DMC.

3 Geo-ecological resources of the study area

Along its entire length, the narrow coastal strip of northern Chile is bordered by a mostly steep mountain escarpment of up to 3000 m a.s.l. elevation, which rises like a wall from the seaside in its northern section, while it is dissected by numerous dry valleys in the southern part of the research area. Usually, the slopes bottom out gently into sedimentary fans of fluvial deposits and debris flows on a narrow shoreline (marine terraces) of some hundred meters up to few kilometres wide (Fig. 2).

The coastal desert of northern Chile is part of the stretched extremely arid zone extending along the western rim of South America, primarily influenced by steady subsidence processes in the domain of the Southeast Pacific subtropical anticyclone (e.g., Garreaud 2009). The climate is characterized by a moderate temperature regime, high atmospheric humidity (annual average: 65 - 80%) and rare rainfalls (Fig.1). Annual precipitation ranges from approx. 1 mm in the northernmost part (Iquique, Arica) to about 80 mm in the south of the arid section. Occasional rainfall episodes occur mainly during austral winter (May to September) and are mostly associated with northeastward moving extratropical low-pressure systems (Richter et al. 1993; Garreaud and Ruttlant 1996; Fuenzalida et al. 2005). In the northernmost part of the area around Arica (18ºS) episodic summer rains also occur.

A quasi-persistent climatic feature of the arid coastal region is the presence of high fog (*camanchaca*). It develops best during the cold season, resulting mostly from an adjacent stratocumulus cloud deck in the upper part of the marine boundary layer below a pronounced temperature inversion (Fig. 2 left). Apart from advection fog, locally orographic (upslope) fog can develop as well (Cereceda et al. 2002). A sharp temperature increase within the inversion layer inhibits the vertical development of stratocumuli. Depending on the season and latitude, they are confined to a belt between 300-600 m a.s.l. and 800-1200 m a.s.l. (Garreaud et al. 2008). The steep coastal mountain chain largely impedes cloud movement inland.

The high frequency and strong intensity of fogs represent a decisive ecological factor, since they ensure the existence and survival of the Loma vegetation along the hyperarid Peruvian and northern Chilean coast (Richter 1981). Dense fog deck protects plant cover from direct solar radiation and desiccation and along with relatively low temperatures and high atmospheric humidity it also reduces evapotranspiration rates. Since many plants can strip moisture from fog (Fig. 3), it further acts as an important water resource for certain taxa, particularly in the northern part of the coastal desert. At night, dew forms frequently on the ground and may also represent an important source of water, however its role for Loma ecosystems

Fig. 2: The orographical fog-belt along the coastal mountains of Pan de Azucar (26°02'S; left) and scattered cacti of mostly dead *Eulychnia iquiquensis* near Cobija (22°33'S; right). Note the sedimentary fans below the steep escarpment, a typical landform for most of the study area

is not studied yet. On the other hand, even the rare rain episodes play a significant role for the long-term subsistence of the vegetation. They facilitate the reproduction, dispersal and establishment of annuals and perennials being of crucial importance for the replenishment of their seed banks (Dillon and Rundel 1990). The importance of rains as main water resource increases towards higher latitudes.

4 Results of a comparative floristic survey on the Chilean coastal desert

4.1 Characteristics of the Chilean *Loma* vegetation

Systematic investigation of the northern Chilean coastal vegetation started in the mid 19th century with the first and one of the most extensive works on the flora of the Chilean Loma by Rudolph Philippi (1860). It was continued during the 20th century by several researchers such as Reiche (1907), Johnston (1929), Werdermann (1931), Ricardi (1957), Rundel et al. (1991), Muñoz-Schick et al. (2001), and Dillon (2005), among others. The results of these botanical efforts reveal that more than 700 species of vascular plants are native to the coastal area between 18°S and 29°30'S, which according to Rundel et al. (1991 and 2007) corresponds to the distribution area of the Chilean Loma vegetation. About two-thirds of them consist of perennials, which in contrast to the Peruvian Loma vegetation are usually the predominant life-forms of the Chilean Lomas. Furthermore, the flora is characterized by a high number of endemics with a total of around 40% of the vascular plants being restricted to the coastal desert of Chile.

From its southern part at around 30°S, the Loma vegetation stretches as a relatively closed formation

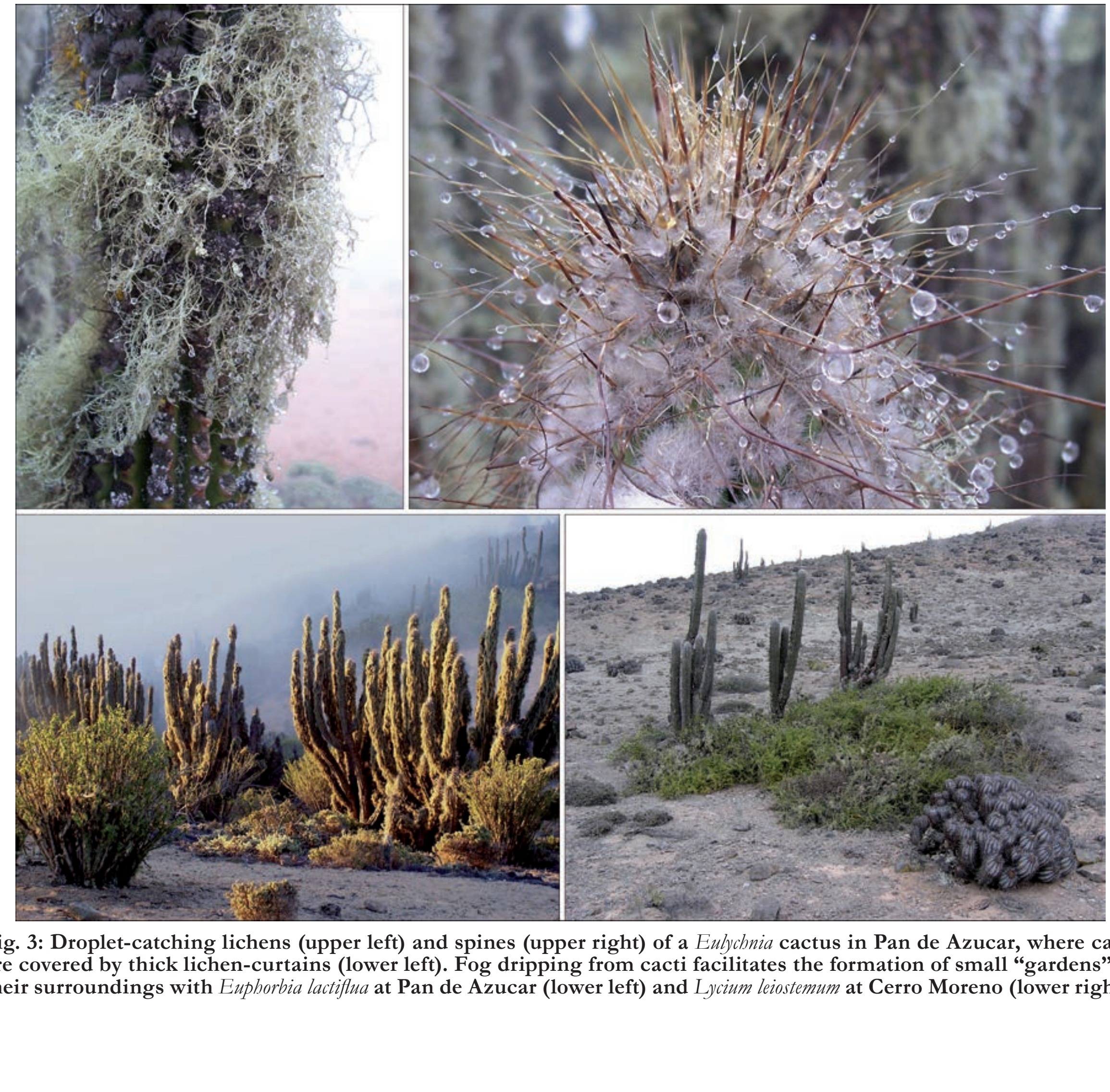

Fig. 3: Droplet-catching lichens (upper left) and spines (upper right) of a *Eulychnia* cactus in Pan de Azucar, where cacti are covered by thick lichen-curtains (lower left). Fog dripping from cacti facilitates the formation of small "gardens" in their surroundings with *Euphorbia lactiflua* at Pan de Azucar (lower left) and *Lycium leiostemum* at Cerro Moreno (lower right)

alongside the windward escarpment of the coastal mountain range towards the equator (RUNDEL et al. 2007). North of 26°S it shows a rather scattered pattern, and north of 21°30'S it concentrates on small vegetation patches on few sites with most abundant fog, usually on southern to western slopes. At northern and eastern hillsides with marginal fog impact and more intense insolation plant cover is normally sparse or absent. The same is true for areas situated above the stratus layer from 1000 - 1200 m a.s.l. upwards. However, on the floor of dry valleys or smaller creeks contracted but dense vegetation is usually present, profiting from the confluence of the slope runoff and hence, better hydrological conditions.

In most cases, the Lomas show a vertical differentiation of various plant communities. This results primarily from varying fog frequencies (intensities) along the altitudinal gradient (RUNDEL and MAHU 1976; RICHTER 1995), though further climatic forces may play an additional role (e.g., temperature, intensity of drizzle from stratocumulus clouds). The middle zone of the fog-influenced belt usually sustains a relatively dense plant cover formed by columnar cacti and diverse, mostly high-growing shrubs. Frequently they are densely covered by epiphytes (mainly by beard lichens, rarely by *Tillandsia geissei*). The dominance of nano- and micro-phanerophytes in this altitudinal belt reflects higher water inputs and consequently higher phytomass production. Greater moisture supply results primarily from higher fog frequency and intensity in the middle and upper fog zone (see CERECEDA et al. 2008; CORREA 1990). Particularly high-growing plants are capable of effective stripping of fog water due to their size and larger total surface (ELLENBERG 1959) and thus create their own favourable microclimate with tiny "gardens" of a benefiting "micro-ecosystem" (Fig 3). The lower and upper boundary fog zone, marked by sharply decreasing fog frequency, as well as areas below the fog layer, are usually populated, if at all, by open xerophytic communities composed mostly of dwarf shrubs and low-growing spherical cacti. However, such a simple relationship between hydrological characteristics of fog as, e.g., water content and vegetation properties does not exist when seen at a larger horizontal scale. Closer and species-richer vegetation can be found in zones with relative little measurable horizontal fog precipitation (e.g., Paposo, Cerro Perales, Fig. 1) while sparser, species-poorer vegetation inhabit sites where the highest values of horizontal precipitation were measured (e.g., Cerro Moreno, Iquique). These patterns suggest that other factors besides fog play a significant role for the large-scale vegetation differentiation. Here, the latitudinal precipitation (and temperature) gradient is probably of decisive importance.

4.2 Loma formations

Based on floristic features derived from an analysis of all perennial species from 29 selected Loma localities (Fig. 4) and on physiognomic differences in plant cover, a classification of the Chilean Loma vegetation is suggested. At least five different plant formations can be distinguished along the Chilean Loma region (Fig. 5), each of them with its respective spectrum of plant communities. This differentiation reflects in part classifications mentioned in the literature (e.g., RUNDEL et al. 1991; GAJARDO 1994). General characteristics of these formations are briefly described in the following subchapters (details in SCHULZ 2009).

a) The formation of isolated fog oases (18°30'S-21°30'S, group I)

The vegetation in this part of the desert is restricted to few relatively small areas mostly on southern to western slopes of larger headlands, recognized as zones of intense coldwater upwelling and frequent formation of dense orographic fog (BAHARONA and GALLEGOS 2000; CERECEDA et al. 2002). In total, nine isolated fog oases have been identified until now (PINTO and LUEBERT 2009, additionally Pabellon de Pica, 20°53'S). Towards the lower latitudes, they become species-poorer and decrease in size while bare sections between the oases increase (SIELFELD et al. 1995). Nevertheless, up to 70 species have been recorded in some of these areas up to now (PINTO and LUEBERT 2009).

Plant-covered areas (at least those formed by perennials) range from the 350-600 m a.s.l. level up to the cliff edge with their lower limit rising generally towards north. Vegetation is mostly dominated by shrubs and dwarf shrubs, smaller cacti and at some places by the columnar cactus *Eulychnia iquiquensis*. The latter forms extensive stands with up to several hundred individuals as for example at Cerro Camaraca (18°38'S), Pabellon de Pica (20°53'S) and Alto Chipana (21°16'S) (see also PINTO 2007). In the few years that have abundant rain, a multiplicity of annual plants and geophytes also appear, totally altering the aspect of vegetation for several months (MUÑOZ-SCHICK et al. 2001). Generally, the plant cover is characterized by a differentiation in species-poor communities at lower elevations and denser as well as species-richer communities within the zone of intense fog (example

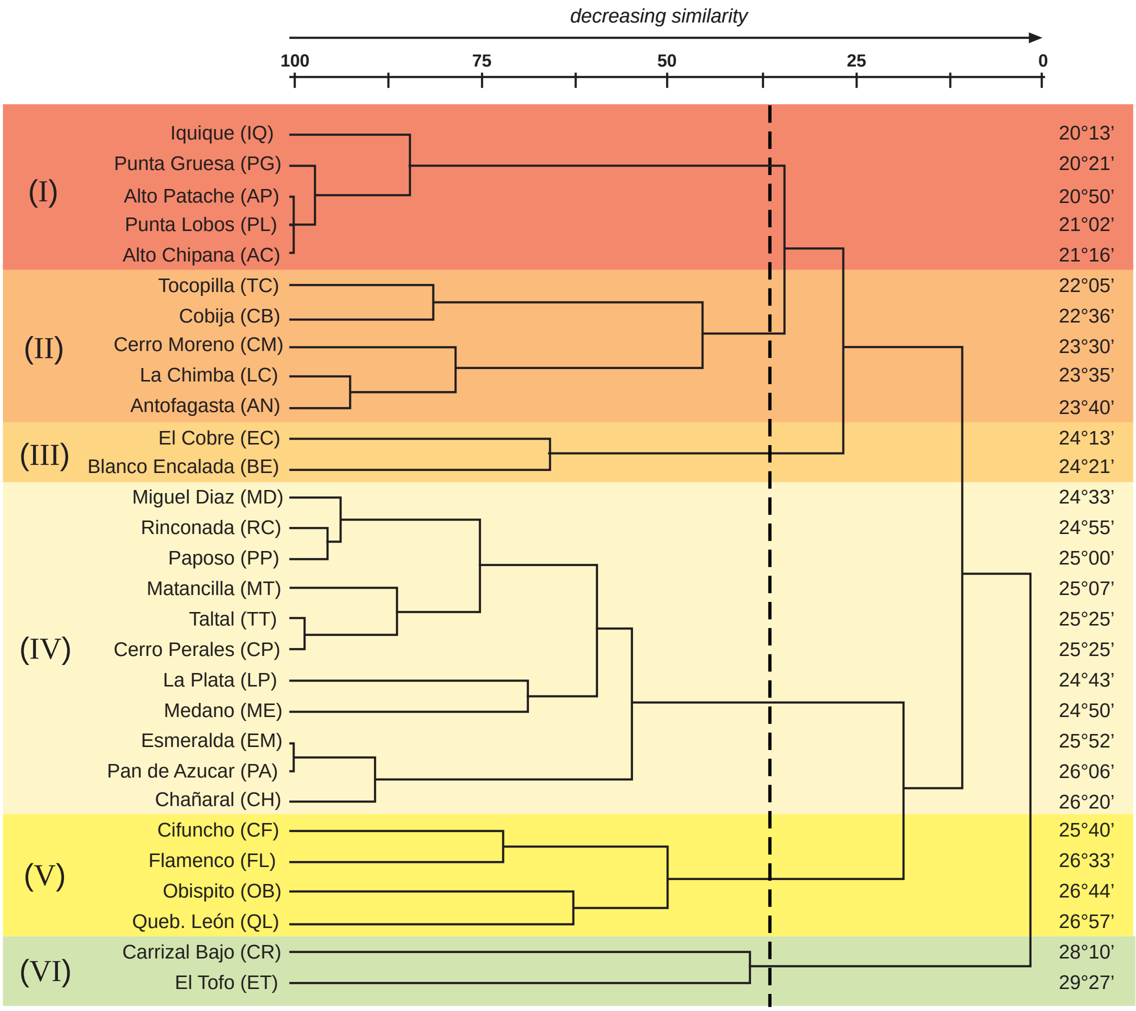

Fig. 4: Dendrogram of floristic similarity for selected Loma-localities (distance: Sørensen's coefficient, cluster algorithm: unweighted group average; only native perennial species were considered). The decoupling of group III and the displacement of Cifuncho to group V are probably explained by a relative small number of species at these sites and thus a smaller percentage of common species with other localities of the same plant formation

in Fig. 6a). Within the marginal upper fog zone, also monospecific stands of *Tillandsia* (mainly *T. landbecki*) were found further away from the coast, forming extended fields at elevations between 900 and 1200 m a.s.l. (Rundel et al. 1997; Pinto et al. 2006).

b) *Eulychnia iquiquensis* – succulent formation (21°30'S-24°30'S, groups II and III)

The southward adjacent *Eulychnia iquiquensis*–formation is represented by a relatively continuous, but widely scattered plant cover stretching alongside the seaward slopes at elevations between approx. 300 m a.s.l. and around 1100 m a.s.l. Characteristic for this region are relatively species-rich communities on upper hillsides, formed by *Eulychnia iquiquensis* and a variety of (dwarf) shrubs (Fig. 6b). At the end of relatively wet years, many annual and perennial herbs enrich these habitats. During dry periods the herb vegetation is rather sparse, mostly restricted to valley bottoms and gullies or forming micro-sites around columnar cacti (Fig. 3) and larger rocks, benefiting from favourable microclimatic conditions.

The density of plant cover and species richness declines gradually towards the drier foot area, where xerophytic shrubs prevail. In the southern part of this section, the lower as well as the upper boundary area of the fog zone is frequently dominated by relatively dense populations of spherical *Copiapoa* cacti, sometimes forming monospecific stands.

A quite conspicuous exception in this formation is constituted by the vegetation of Cerro Moreno, northwest of Antofagasta (23°30'S). Apart from being species-richer and considerably more vigorous due to specific climatic conditions (Richter 1995;

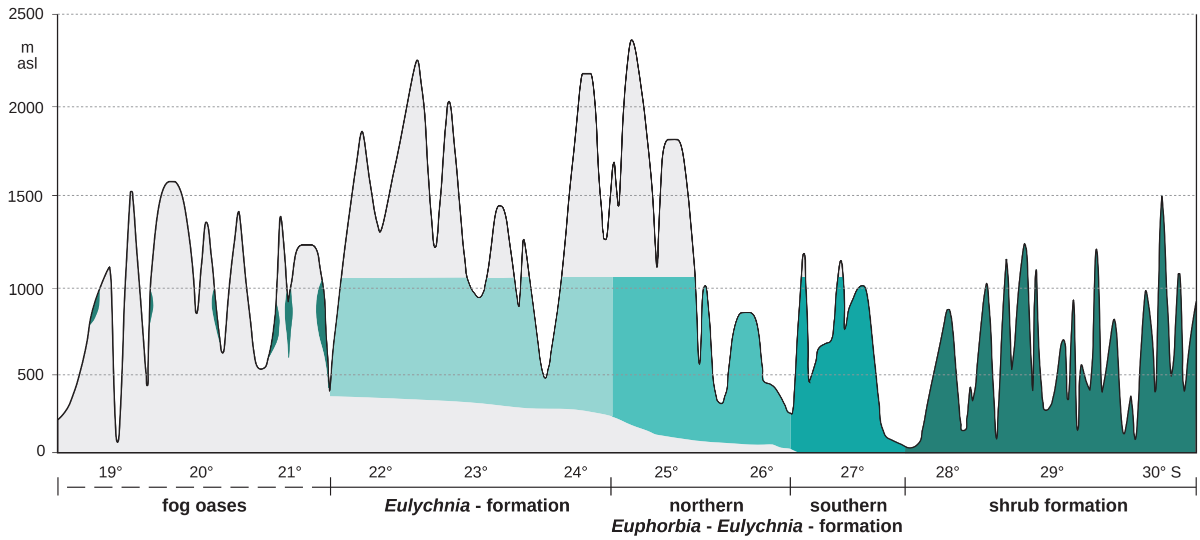

Fig. 5: Latitudinal position of the Loma formations with respective approximate altitude of the vegetation belt.

Espejo et al. 2001), it includes patches of relict vegetation preserved at very steep and foggy precipices on western and south-western sites of the massif. Surprisingly, taxa such as *Colliguaja odorifera* and even the ferns *Polystichum* sp. and *Elaphoglossum gayanum* occur here as disjunct populations, far away from their principal distribution areas in central and southern Chile.

c) Northern *Euphorbia lactiflua-Eulychnia* spp. – succulent shrub formation (24°30'S-26°20'S, group IV)

This formation occupies the central part of the coastal desert. Without any doubt the vegetation of this section, especially its northern part (vicinity of Paposo, 25°00'S), is considered an archetype of the Chilean Lomas. Distinguished by remarkable species richness for such an arid region, it harbours a high percentage of the Chilean Loma endemics. This said, it seems reasonable to regard its formations as a core area of the Chilean Lomas. Concerning the vegetation, this part of the coast is dominated by two characteristic elements, the high-growing shrub *Euphorbia lactiflua* and the columnar cactus *Eulychnia* (*E. iquiquensis* north of approx. 25°30'S and *E. breviflora* south of it). The most vegetated areas of the fog zone are comprised of numerous shrubs, herbs and various species of cacti. In areas of most intense fog moistening, which becomes obvious by dense covers of lichens on twigs and stones, also the epiphyte *Tillandsia geissei* grows on branches of *Eulychnia*, taller shrubs, and sometimes even on the ground and on rocky faces of foggy steeps.

Above and below the fog belt, the plant cover passes through series of communities compounded by more xerophytic shrubs and dwarf shrubs, frequently accompanied by the bromeliad *Deuterocohnia chrysantha* and smaller cacti (*Eriosyce* and *Copiapoa,* the latter showing its diversification centre here; Fig. 6c). However, higher inflow of slope runoff during rain events allows the development of surprisingly vigorous and species-rich azonal vegetation with abundant *Euphorbia* and *Eulychnia* on alluvial fans and older mudflow cones at the foot of the mountain escarpment.

d) Southern *Euphorbia lactiflua-Eulychnia* spp. – succulent shrub formation (26°20'S~27°30'S, group V)

This formation occupies only a relatively small section of the coast. Although *Euphorbia* and *Eulychnia* are still the dominant elements, species richness declines considerably in comparison with the northerly adjacent region. Due to more regular and abundant rainfalls, the vegetation cover is more homogenous. The community of *Euphorbia* and *Eulychnia* is widely spread through all elevation levels (except at the foot of the mountain) and exposures. Here, it is less dependent of a spatially variable fog moisture distribution, and thus no fog induced floristic differentiation of plant cover can be distinguished in this section (Fig. 6d). Nevertheless, the high abundance of epiphytic beard lichens indicates a continued important influence of fog. Most of the shoreline and the flat area below about 150 m a.s.l. are populated by dune and gravel communities (detailed information in Kohler 1970) with abundant annuals forming the famous "desierto florido" (flowering desert) during extraordinarily moist periods.

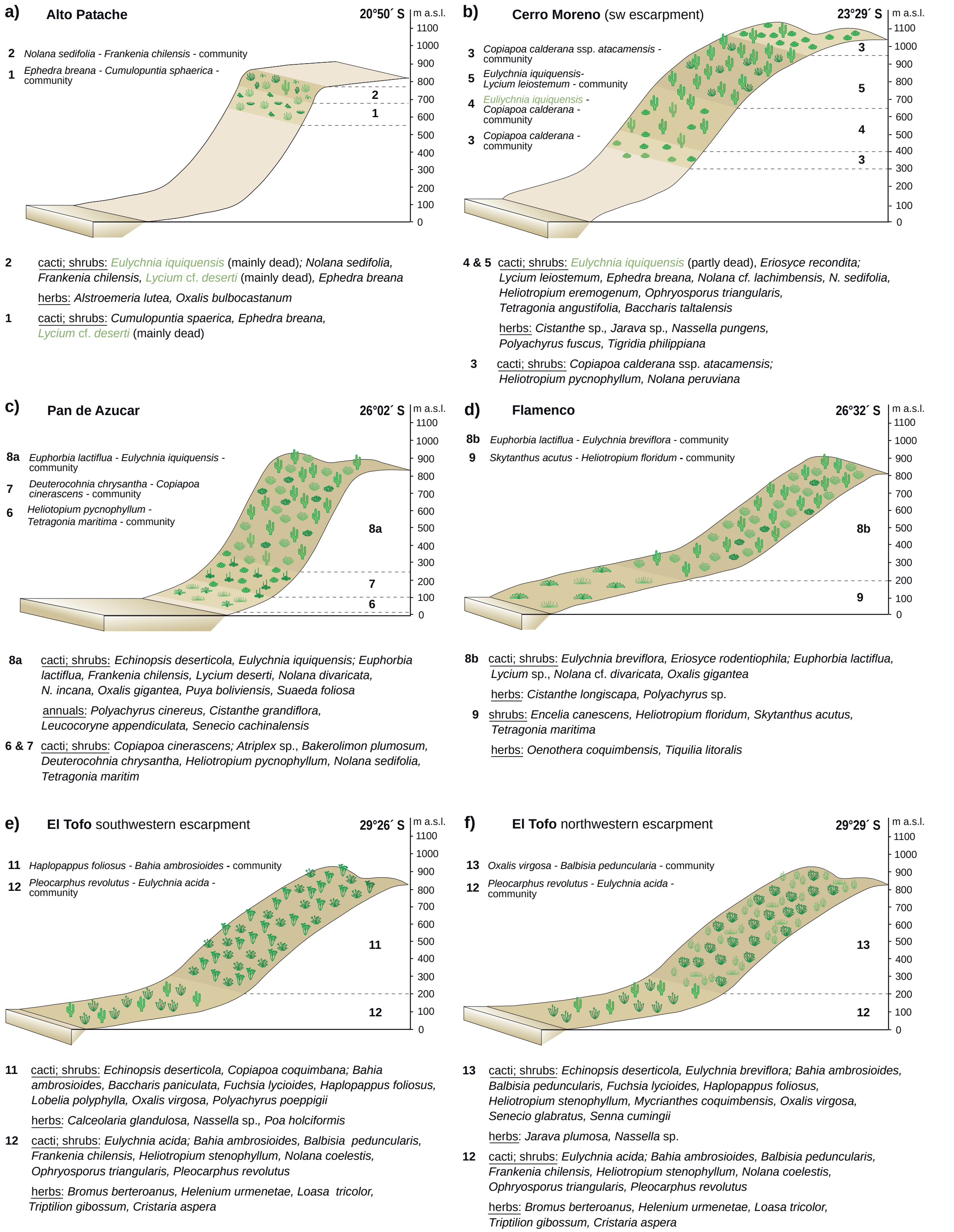

Fig. 6: Vertical distribution of plant communities within the Loma-belt at selected localities. a) Alto Patache; b) Cerro Moreno (only SW- and W-slopes); c) Pan de Azucar; d) Flamenco; e) and f) El Tofo (different slope orientation). Most abundant species are indicated below the respective sketches. Letters in grey indicate that most of the characteristic community members are dead

e) Various shrub formations of the southern Loma region (27°30'S-29°30'S, group VI)

Towards the south, the coastal desert harbours an increasing number of plant communities, described in detail among others by LAILHACAR (1986). A common feature of this section is an increased abundance of tall shrubs, mostly still accompanied by succulents. The higher percentage of species from central Chile suggests a stronger floristic affinity to the vegetation of the semiarid and semihumid coast. The community of *Haplopappus angustifolium* distributed in the strongly fog-influenced summit area of Cerro Negro (28°10'S) is a good example for this fact since it includes several floristic elements of the vegetation south of 30°S (e.g., *Gochnatia foliolosa, Baccharis vernalis, Senecio coquimbensis*). Similar to the flora of the famous National Park Fray Jorge (30°30'), the southern floral elements subsist here at climatically favoured sites as relicts of a supposed former vegetation community that extended further northward from moister parts of the country. Despite the considerably increased importance of relatively regular winter rains, the role of fog for microclimate regulation and as an additional water resource (ARAVENA et al. 1989) is still significant.

In this southernmost section, differentiation in the horizontal vegetation structure between N- and S-slopes is more pronounced than a vertical differentiation. Widely spread is the *Oxalis* spp.- *Balbisia peduncularis* community with a high abundance of various shrubby and herbaceous species. This plant ensemble is found on more sun-exposed hillsides. Instead, the succulent-poor *Haplopappus foliosus* community prefers S- and SW-slopes in the southern part of the region (El Tofo, 29°27'S; Fig. 6e and 6f). Once again, the foot zone of the escarpment is populated by communities of dunes and marine terraces containing numerous annual plants.

5 Vegetation change

Concerning the apparent vegetation decline in the northern part of the area, the dieback of *Eulychnia iquiquensis* is most frequently mentioned (KRAUS 1994; FOLLMANN 1995; RICHTER 1995; RUNDEL et al. 1997; PINTO et al. 2001; MUÑOZ-SCHICK et al. 2001; PINTO 2007; PINTO and KIRBERG 2009). An overwhelming part of these high-growing columnar cacti, which reach impressive sizes of up to seven meters, are in extremely poor condition along their northern distribution zone between Blanco Encalada (24°21'S) and Arica (18°S). Most of them are desiccated and collapsed, and retain only the skeleton of the inner tissue of stems and larger branches (Fig. 7). The occurrence of still vital individuals is mostly constrained to higher elevations that are strongly influenced by fogs. The reproduction rate in affected populations is low or none, at least in the northern part of this region, and the vegetative activity is restricted to the few years with abundant rainfall (PINTO 2007).

Fig. 7: Collapsing individuals of *Eulychnia iquiquensis* in the lower belt of columnar cacti at around 500 m a.s.l. on the southern escarpment of Cerro Moreno (left) and extensive dieback of the same species on the escarpment above Cobija (right).

A considerable number of further cacti apparently suffer in a similar way, such as various species of the genera *Copiapoa (C. humilis* ssp. *tocopillana, C. solaris)* and *Eriosyce, (E. iquiquensis, E. islayensis, E. paucostata* ssp. *echinus)* as well as *Cylindropuntia tunicata, Haageocereus australis* and *Cumulopuntia sphaerica* (Belmonte et al. 1998; Pinto and Kirberg 2005; personal observations). The loss of vitality of these taxa seems to be a recent process, since at least some of them showed noticeably better conditions around the middle of the last century. This is true for example, for populations of *Eriosyce islayensis* at Poconchile (hinterland of Arica), which were still composed of vigorous, prospering individuals in the 1950s, but meanwhile all of them are desiccated or dead (compare Ritter 1980 versus Pinto and Kirberg 2005). Ritter (1980) noted with meticulous precision in his detailed book on cacti of northern Chile (field work in the 1950s and 60s) each remarkable peculiarity of the studied species (e.g., endangerment by diseases, drought damages) without, however, mentioning the conspicuous poor condition of the same species affected nowadays. Recent dieback processes are also confirmed by various older inhabitants of the coastal zone.

Many shrubs and perennial herbs show corresponding signs of decline along the region between Iquique and Antofagasta. Plants with active vegetative organs within affected populations occur only sporadically and are mostly restricted to higher elevations, dry valleys and gullies. This situation stands in a striking contrast to vegetation descriptions by researchers and travellers up to the mid-20th century. For example, Reiche (1907), Werdermann (1931) and Johnston (1929) mention rather rich plant formations consisting of annual and perennial herbs and cacti above Iquique during the first decades of the previous century, while it is nearly bare of vegetation today (Pinto and Luebert 2009).

Furthermore, Jaffuel (1936), Reiche (1907), Johnston (1929) and Barros (1941) registered a relatively species-rich shrub and herb vegetation in the vicinity of Tocopilla (22°05'S) apparently appearing in an almost annual rhythm. According to various historical travel reports from the 18th and 19th century, an abundant herb and shrub vegetation also prospered in Cobija (22°36'S) during the winter and spring periods and provided sufficient fodder for limited animal husbandry (Frezier 1713; Feuille 1714; Cañete 1787; O'Connor 1825 all cited in Bittmann 1977). Today, an overwhelming part of shrubs and cacti around Tocopilla and Cobija is desiccated or dead. Despite intensive botanical field research, many shrub and herb species collected at Tocopilla and Cobija until the mid-20th century were not registered during the past few decades (see also Luebert et al. 2007). Among them *Adiantum chilense, Alstroemeria violacea, Bahia ambrosioides, Calceolaria paposana, Centaurea cachinalensis, Cheilanthes mollis, Chuquiraga ulicina, Cylindropuntia tunicata, Nolana* cf. *deflexa,* and *Ophryosporus anomalus* are to be mentioned for Tocopilla. Further south at Cobija, *Conanthera campanulata, Copiapoa humilis* ssp. *tocopillana, Ephedra chilensis, Frankenia chilensis, Nolana diffusa, N.* cf. *deflexa, N. sedifolia, Senna brongniartii, Alstroemeria violacea, Ophryosporus anomalus, Polyachyrus fuscus,* and *Puya boliviensis* seem to have been lost, although the occurrence of many of these species was registered as "frequent" in collections of W. Biese in 1949 (herbarium SGO). Even if the recent absence of the aforementioned and further species does not automatically prove their definite disappearance from the area, differences in the former and recent floristic composition are obvious.

The local lack of formerly abundant taxa goes along with a recent reduction of the distribution area of some species. Philippi (1860), Johnston (1929) and Follmann (1967) registered for example the occurrence of *Oxalis gigantea* for the northern areas from Miguel Diaz (24°33'S) up to Cerro Moreno (23°29'S). According to Heibl (2005) its present distribution limit is located far further south around Quebrada El Medano (24°50'S). Philippi (1860) and Ritter (1980) mentioned the cactus *Cylindropuntia tunicata* for the zone between El Cobre (24°13'S) and Arica (18°20'S). Interestingly, the second author noted that many of its individuals around Tocopilla and Arica did not survive the period of a severe drought around the mid-20th century (Ritter 1980). Currently, the northern distribution limit of this coastal species seems to be reduced to Miguel Diaz (24°32'), about 700 km further south.

According to some researchers, lichen vegetation has also impoverished along the coastal region. Between 1965 and the early 1990s, repeated floristic samplings by Follmann (1995) document a drastic reduction of species richness of up to 39-46% at selected study sites. However, this phenomenon is not only restricted to the north, but was also noted in the central coastal region of Chile (32°30'S). Likewise, a decline of epiphytic lichens as well as of the vascular epiphyte *Tillandsia geissei* has been reported for the past few decades (Rundel et al. 1991; Rundel and Dillon 1998).

Changes in vegetation are apparently associated with losses in the regional fauna. Various authors mentioned the occurrence of Guanaco populations (*Lama guanicoe*) for the coastal mountains between Iquique and Antofagasta up to the recent past (Bauver 1707 and Feuillee 1714 in Bittmann 1977; Mann et al. 1953; Nuñez and Varela 1967). Well preserved traces of their past presence can still be detected along the entire northern coastal zone (Richter 1995; Larrain et al. 2001). In the southwards adjacent area, at places where a denser and more vigorous vegetation provides sufficient feed and the decimation by man is minimal, Guanacos sustain their existence until today (e.g., north of Paposo, Pan de Azucar etc.). While this suggests that at least until the middle of the past century sufficient resources in form of lichens, cactus fruits and more abundant herbs and shrubs ensured the long-term survival of former populations around and north of Antofagasta, these preconditions are not given any longer.

6 Recent climate trends

Regarding the spatial dimension of the vegetation decline and the number of affected taxa, large-scale changes of environmental conditions are supposed to be a likely cause of the deterioration process. In particular, changes in precipitation, fog and cloudiness as principal factors influencing the Loma ecosystems have to be considered as potential triggers for dieback effects and thus are studied in detail. Owing to difficulties cited in chapter 2, no trend analyses were performed for fog. Nevertheless, it is to be expected that tendencies in low-level cloudiness reflect to some degree possible general tendencies in fogs, since the predominant advection fog is formed by coastward moving stratocumulus clouds.

6.2 Precipitation

In spite of very low amounts, long-term rainfall records reveal pronounced low-frequency changes on the interdecadal time scale over the past century (see Fig. 8), closely linked to the Interdecadal Pacific Oscillation (IPO, i.e., large-scale multidecadal climate variability in the Pacific region, e.g., Folland et al. 1999). Two relatively "humid" and two drier periods are distinguishable; a "humid" phase from the 1920s to the mid-1940s and from the mid-1970s until the end of the century, associated with positive (warm) IPO-phases, as well as a "dry" phase from the mid-1940s to the early 1970s and a short one around 1910, related to negative (cold) IPO-phases. A quite distinctive feature of the latter dry phase is the occurrence of a prolonged extremely dry period

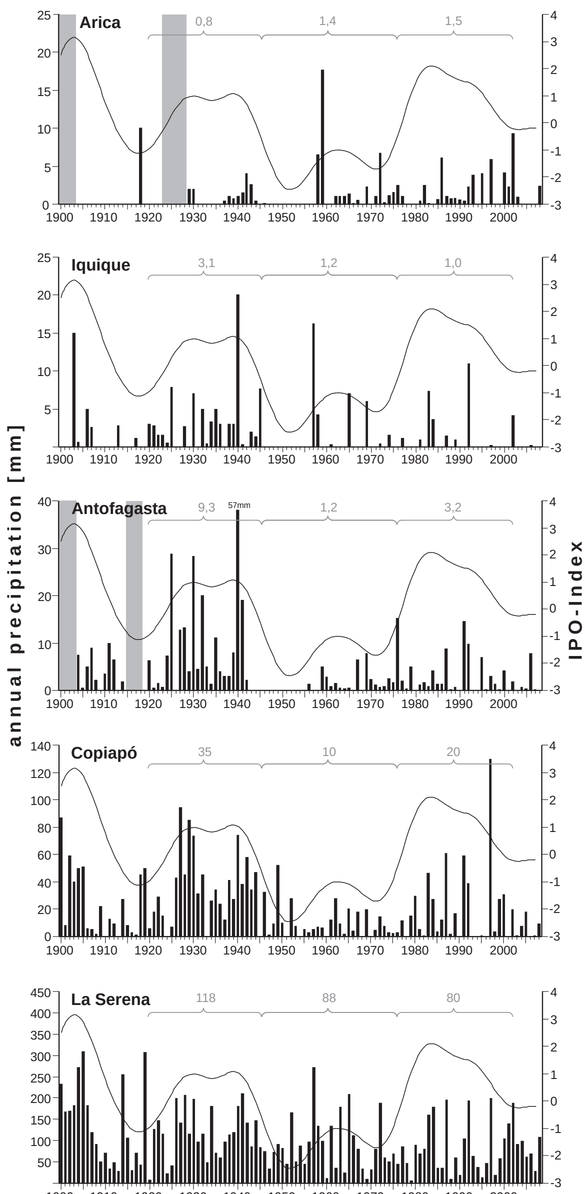

Fig. 8: Annual rainfall at five northern climate stations for 1900–2008 (bars) and IPO-index (line) for the same period, smoothed by an 11-yr low pass HadSST2 Chebyshev filter (http://www.iges.org/c20c/IPO_v2.doc). Rainfall averages derived from annual precipitation for three periods corresponding to distinct IPO-phases (1920–45, 1946–75, 1976–2001) are indicated at the top of each graph. Grey bands indicate periods of missing data. Note the different scaling for precipitation on the y-axis

around 1950, when absolutely no rain was registered along the coastal desert north of Antofagasta for more than a decade (Fig. 8).

During the previous century, the interdecadal precipitation variability, however, was superimposed by further changes of longer time scale, manifested in differences of mean annual rainfall amounts between the two more "humid" phases (Fig. 8), the latter being notably drier than the previous one (exception: Arica). This variation in multiannual rainfall means reveals a downward precipitation trend over the whole period 1900-2008 prevailing in most parts of the study area. Analyses of daily rainfall events (≥1 mm) indicate that the difference resulted from a reduction of the mean rainfall intensity and less frequent rainy days during the latter "humid" period (Tab.1). The reduction of rain frequency is particularly pronounced at Iquique, where the mean annual number of days with rainfall ≥ 1 mm decreased from 1.2 during the period 1920–1945, to just 0.3 during 1976–2001. At least for the drier northern part of the desert, this fact implies that there has been a sustained decrease in the frequency of rainfall events since the mid-century, probably as a result of a declining cyclonic activity at lower latitudes (see SCHULZ et al. 2011).

Due to the lack of long rainfall records, it is difficult to assess when this negative trend set in. However, longer rainfall series of Copiapó and La Serena in the central-southern portion of the desert reveal a rather extended desiccation trend since at least the late 19th century, though strongly modulated by significant variability at the interdecadal time scale (Fig. 9). The prevalence of more humid conditions prior to 1900 seems to be also supported by palaeoclimatological studies indicating wetter conditions in central(-northern) Chile during the past three to four centuries, especially in the 19th century (VALERO-GARCES et al. 2003; LE QUESNE et al. 2008).

6.3 Cloudiness

Analyses of the total cloud cover reveal a rather strong and significant decline of cloudiness since the mid-1970s, particularly at Arica (Fig. 10). The intensity of this trend decreases towards the higher latitudes alongside the coastal desert. In Antofagasta, after a phase of increasing total cloud cover from the mid-1960s to the mid-1970s and an abrupt decrease towards the end of the 1970s, a rather stable regime seemed to establish itself. Notwithstanding, studies on the stratocumulus deck show a slight but persistent decrease in stratocumulus cloud cover since the mid-1970s in Antofagasta and to a lesser degree in La Serena since at least 1980 (QUINTANA and BERRIOS 2007; BERRIOS 2008). In Arica and Iquique, in contrast, no coherent tendencies were found in stratocumulus cover during the period of 1980-2005. Furthermore, for the period 1960-2005, a notable, statistically significant decline in the frequency of low clouds occurrence was detected in Arica and a statistically significant increase in Antofagasta (data not shown here). The frequency tendency in low clouds likely implies a downward trend in advection fog frequency in Arica, while the opposite tendencies in stratocumulus cover and frequency in Antofagasta do not permit any coherent conclusions about changes in high fog in this part of the desert. As fog characteristics are determined by a complex coaction of different factors, further studies are required for the analysis of fog evolution during the recent past decades.

The remarkable decrease of the total cloud cover at Arica is consistent with changes in the mean seasonal and annual frequency of cloudy and cloudless days (all types of clouds), which experienced a notable reduction of 45 days and a strong increase of 41 days, respectively, between the periods 1957–1976 and 1977–2008 (Tab. 2). Changes of the same direction, although of lower magnitude, were registered also in Antofagasta.

Tab.1: Frequency of wet events (mean number of days with rainfall amounts ≥ 1.0 mm) and median of daily rainfall at selected stations calculated for various periods.

	Period	Iquique	Antofagasta	Copiapó	La Serena
Mean number of days of rainfall ≥ 1.0mm	1920–1945	1.2	1.3	3.2	10.7
	1946–1975	0.3	0.5	1.6	8.6
	1976–2001	0.3	0.9	2.0	7.0
Median of daily rainfall ≥ 1.0mm (in mm)	1920–1945	1.8	3.9	7.5	5.5
	1976–2001	1.6	1.7	4.4	4.1

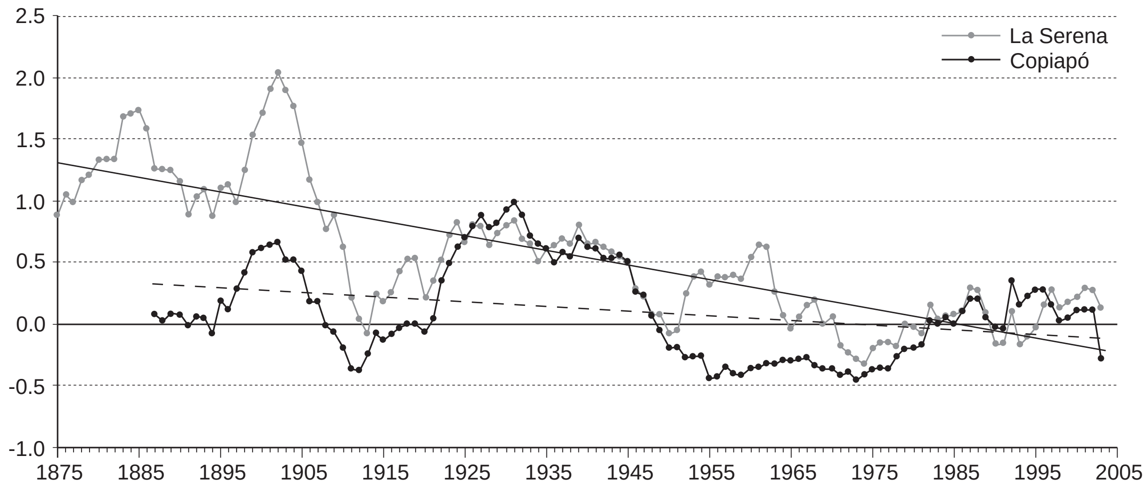

Fig. 9: Annual rainfall in La Serena (grey line) and Copiapó (black line), normalized and smoothed by an 11-yr moving average.

7 Vegetation change driven by climate change?

Taking the desiccation symptoms of the plant cover and the rainfall as well as cloudiness decline into account, changes in climate during the past decades must be considered as the decisive force for the creeping dieback processes affecting the water balance and reducing the regeneration capacity of plants. Although an extreme scarcity of rainfalls and the scantiness of their amounts are a specific feature of the coastal desert in northern Chile, extraordinary prolongations of dry periods such as around the 1950s may complicate the establishment of seedlings and a periodic revitalisation of the perennial vegetation. Taking Tocopilla as example, table 3 manifests the connection between the recent vegetation decline and decreasing rainfall events. Although significant rain episodes occurred nearly annually in the first half of the past century, rainfall was registered only once (2002: 16 mm) over the course of the recent period 1994-2005. Likewise, rainfall (> 1mm) occurred in Iquique in only one of the 16 years during the period 1993-2008 (Fig. 8). In the surroundings of both sites, rare rainfall events provoke an exuberant sprout and bloom of annual herbs as well as an increased vitality of the perennial vegetation (Muñoz-Schick et al. 2001; Hoxey 2004; H. Larrain, Universidad Bolivariana, Iquique, pers. com.), still noticeable during the following years (Pinto et al. 2001). Whereas in the surroundings of Tocopilla, researchers found excellent conditions to compile extensive plant collections within few hours during the wetter period at the beginning of the past century, nowadays an analogous procedure requires several days to get a relatively decent plant compilation, pointing to a relation between the recent rainfall decline and the poor preservation status of the present vegetation. In addition to the drought-pro-

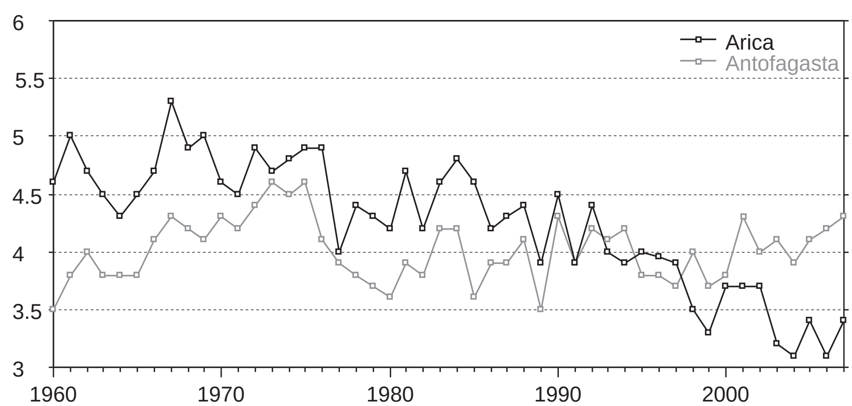

Fig. 10: Annual total cloud cover in Arica (black line) and Antofagasta (grey line).

Tab.2: Long-term mean of the number of cloudy days (total cloud cover ≥6/8 oktas) and cloudless days (total cloud cover ≤2/8 oktas) for the periods 1957–1976 and 1977–2008 in Arica and Antofagasta; (**) statistically significant at 1%-level; (*) statistically significant at 5%-level.

		Number of days with total cloud cover >6/8					Number of days with total cloud cover <2/8				
		DJF	**MAM**	**JJA**	**SON**	**Year**	**DJF**	**MAM**	**JJA**	**SON**	**Year**
Arica	1957–1976	19.6	20.9	49.8	39.5	129.8	15.1	17.8	2.7	3.6	38.9
	1977–2008	10.0	10.8	40.2	24.2	85.0	32.1	35.5	3.9	8.3	79.8
	diff.	- 9.6**	- 10.1**	- 9.6**	- 15.3**	- 44.8**	+ 17.0**	+ 17.7**	+ 1.2	+ 4.7**	+40.9**
Antofagasta	1957–1976	11.5	14.1	27.5	29.1	82.5	28.3	24.1	9.4	5.3	66.4
	1977–2008	8.2	10.6	24.8	21.9	65.0	30.3	28.6	8.6	6.9	75.7
	diff.	-3.3*	- 3.5*	- 2.7	- 7.2**	- 17.5**	+ 2.0	+ 4.6*	- 0.8	+ 1.7*	+ 9.3*

voked effects, the reduced number of cloudy days in the northern part of the coastal desert implies a longer and more frequent exposure of the Loma vegetation to intense solar radiation, which may enhance and prolong hydric stress by elevated transpiration rates. Trends in stratocumulus clouds also suggest a decrease in fog frequency in the northern area (Arica) that is expected to have similar effects on the water balance of plants. Despite little being known about the southern area, possible changes in fog characteristics not necessarily directly linked to stratocumulus cover and frequency are not excluded, and could be a further factor contributing to changes in vegetation in the study area.

Apart from climate change, in few coastal sections the decline of plant cover and species richness may suffer from enhanced vulnerability to further stressors such as air pollution. Investigations of the environmental conditions around copper deposits at Paposo confirm negative effects of mining on plants in this area since especially the emission of dust particles occludes leaf stomata (Ruelle 1995). Heavy metals also might affect plant growth, even though some species indicate extraordinary tolerance against elevated concentrations (e.g., *Nolana divaricata*, Ruelle 1995). One more negative effect on vegetation must be expected from coal dust emissions of a thermoelectric plant in Tocopilla, which strongly contaminates air in the surroundings (DICTUC 2006). The effects of pollution are, notwithstanding, limited to the proximity of pollution sources and do not explain the poor conservation status of plants in areas with little or no mining activity such as e.g., the entire coastal area north of Iquique.

8 Conclusions and outlook

The results of the study indicate a strong decline of the Loma vegetation in the area north of 24°30'S in particular during the past five decades. It is manifested by decreasing plant vitality, the disappearance of various taxa from their northern distribution area and a complete or partial dieback of individual plant populations. Particularly cacti and epiphytes are affected, and probably some perennial shrub and herb species. These vegetation changes are further likely responsible for the loss of Guanaco populations from the arid coastal area between 20°S and 23°30'S.

Since different plant species are affected, large-scale pathogenic effects as well as natural population oscillations (e.g., cohort dieback) can be widely excluded as crucial agents. Based on the current state of knowledge, plant cover and species richness are most likely affected by the recent changes in climate, i.e., by reduced precipitation inputs and frequencies as well as by prolonged insolation phases due to diminished cloudiness in the northernmost area. These climatic effects are expected to have a negative impact on the water balance, reproduction and preservation of plants. At the local scale, other factors such as environmental pollution might have additionally contributed to a degradation of the vegetation.

Tab.3: Annual rainfall in Tocopilla.

Year	Rainfall (mm)	Year	Rainfall (mm)
1925	9.1	*1952–63*	*no data*
1926	0.5	1964	0.0
1927	5.8	1965	14.0
1928	6.0	1966	1.2
1929	0.0	1967	6.0
1930	15.0	1968	0.0
1931	0.0	1969	4.0
1932–39	*no data*	1970	0.0
1940	11.0	*1971–93*	*no data*
1941	5.0	1994	0.0
1942	9.0	1995	0.0
1943	0.0	1996	0.0
1944	0.0	1997	0.0
1945	0.0	1998	0.0
1946	0.0	1999	0.0
1947	0.0	2000	0.0
1948	0.0	2001	0.0
1949	0.0	2002	16.0
1950	0.0	2003	0.0
1951	0.0	2004	0.0
1952	1.0	2005	0.0

In the context of prospective projections, the question about the resilience capacity of the affected vegetation arises. According to current regional climate projections, the rainfall decline is expected to continue at the arid coast of Chile towards the end of the century (Fuenzalida et al. 2006). Apart from that, the IPO has shown predominantly negative values since the end of the 20th century, suggesting that a shift towards a negative phase is underway and drier conditions will predominate at the arid coast of northern Chile during the next decades. Consequently, chances for an improvement of growing conditions of the vegetation are limited in the near future and a tendency towards further impoverishment of the northern Loma formations is to be expected, which would endanger the subsistence of this floristically diverse and highly sensitive ecosystem.

In the light of these projections, there is an increasing need finding a way to preserve these endangered endemic species. Irrigation at selected sites using fog collectors is a potential in-situ technique and has shown effective results (Pinto and Kirberg 2009), but requires considerable manpower and financial input for a continuous maintenance of the installations. Another possibility is offered by ex-situ cultivation or the establishment of seedbanks. The latter one is already practiced by the Royal Botanic Gardens in collaboration with INIA (Chile) in parts of the desert. Aside from focusing on northern Lomas, also the southernmost parts of the desert ecosystem need a more systematic incorporation into these conservation strategies, since these areas still host a variety of further endemic species that are increasingly endangered by emerging land use activities.

However, these strategies must be considered only a drop in the bucket since climate change is (and always has been) a worldwide phenomenon that can hardly be countervailed by local actions.

Acknowledgements

The authors gratefully thank Gina Arancio, Melica Muñoz-Schick, and Clodomiro Marticorena from the herbaria CONC, HULS, and the National Museum of Natural History SGO for providing extensive data on plant collections from the northern Chilean coast. Gina Arancio and Helmut Walter are thanked for identification of the collected material. The Dirección Meteorológica de Chile and Juan Quintana were generous supporters of the data on precipitation. Special thanks go to the German National Merit Foundation (Studienstiftung des Deutschen Volkes) for a full-time grant for N. Schulz and to the Department of Geophysics of the Universidad de Chile for the support of this work.

References

Alexandersson, H. (1986): A homogeneity test applied to precipitation data. In: Journal of Climatology 6, 661–675. DOI: 10.1002/joc.3370060607

Almeyda, E. (1948): Pluvometría de las zonas del desierto y las estepas cálidas de Chile. Editoral Universitaria. Santiago.

Aravena, R.; Suzuki, O. and Pollastri, A. (1989): Coastal fog and its relation to groundwater in the IV region of northern Chile. In: Chemical Geology (Isotope Geoscience Section) 79, 83–91. DOI: 10.1016/0168-9622(89)90008-0

Baharona, M. and Gallegos, R. (2000): Surgencias en la costa norte de Chile durante las temporadas Niña 1996–1997 y Niño 1997–1998. In: Revista de Geografía Norte Grande 27, 53–60.

Barros, E. (1941): Excursion botanica a la provincia de Antofagasta. In: Revista Universitaria 26 (2), 83–88.

Belmonte, E.; Faundez, L.; Flores, J.; Hoffmann, A.; Munoz, M. and Teillier, S. (1998): Categorias de conservacion de cactaceas nativas de Chile. In: Boletin Museo Nacional Historia Natural 47, 69–89.

Berrios, P. (2008): Estratocúmulos en la costa norte de Chile: variabilidad y tendencia. Tesis Universidad de Valparaiso. Valparaiso.

Bittmann, B. (1977): Notas sobre la poblacion de la costa del Norte Grande chileno. Universidad del Norte. Antofagasta.

Cereceda, P.; Osses, P.; Larrain, H.; Farias, M.; Pinto, R. and Schemenauer, R. S. (2002): Advective, orographic and radiation fog in the Tarapacá region, Chile. In: Atmospheric Research 64, 261–271. DOI: 10.1016/S0169-8095(02)00097-2

Cereceda, P.; Larrain, H.; Osses, P.; Farias, M. and Egaña, I. (2008): The spatial and temporal variability of fog and its relation to fog oases in the Atacama Desert, Chile. In: Atmospheric Research 87, 312–323. DOI: 10.1016/j.atmosres.2007.11.012

Correa, H. F. (1990): Caracterización y evaluación del fenomeno de la camanchaca en la III Región de Atacama. Memoria, Universidad de Chile, Facultad de Ciencias agrarias y forestales. Santiago.

DICTUC (2006): Análisis de la calidad del aire para MP-10 en Tocopilla. Informe Final. Pontificia Universidad Católica. Santiago.

Dillon, M. O. (2005): LOMAFLOR, Searchable Database. Andean Botanical Information System. http://www.sacha.org

Dillon, M. O. and Hoffmann, A. E. (1997): Lomas formations of the Atacama Desert, Northern Chile. In: Davis, S. D.; Heywood, V. H.; Herrera-MacBryde, O.; Villa-Lobos, J. and Hamilton, A. (eds.): Centres of plant diversity: a guide and strategy for their conservation. Vol. 3: The Americas. Cambridge, 528–535.

Dillon, M. O. and Rundel, P. W. (1990): The botanical response of the Atacama and Peruvian Desert flora to the 1982–83 El Niño Event. In: Glynn, P. W. (ed.): Global ecological consequences of the 1982–83 El Niño-Southern Oscillation. Elsevier Oceanography Series. Amsterdam, 487–504.

Ellenberg, H. (1959): Über den Wasserhaushalt tropischer Nebeloasen an der Küstenwüste Perus. In: Berichte Geobotanische Forschung des Institut Rübel für 1958. Zürich, 47–74.

Espejo, R.; Demergasso, C.; Galleguillos, P.; Piantelli, E. and Escudero, L. (2001): Climatolgcal and microbiological characteristics of the camanchaca phenomenon at Cerro Moreno, Antofagasta, Chile. In: Proceedings of the Conference on Fog and Fog Collection, St. John's, Canada, 463–466.

Folland, C. K.; Parker, D. E.; Colman, A. and Washington, R. (1999): Large scale modes of ocean surface temperature since the late nineteenth century. In: Navarra, A. (ed.): Beyond El Niño: Decadal and Interdecadal Climate Variability. Berlin, 73–102.

Follmann, G. (1967): Die Flechenflora der nordchilenischen Nebeloase Cerro Moreno. In: Nowa Hedwigia 14, 215–281.

– (1995): On the impoverishment of the lichen flora and the retrogression of the lichen vegetation in coastal central and northern Chile during the last decades. In: Cryptogamic Botany 5, 224–231.

Fuenzalida, H.; Sanchez, R. and Garreaud, R. (2005): A climatology of cut off lows in the Southern Hemisphere. In: Journal of Geophyical Research 110, D1801, DOI: 10.1029/2005JD005934

Fuenzalida, H.; Falvey, M.; Rojas, M.; Aceituno, P. and Garreaud, R. (2006): Estudio de la variabilidad climática en Chile para el siglo XXI. Informe final. DGF Universidad de Chile.

Gajardo, R. (1994): La vegetación natural de Chile. Clasificación y distribución geográfica. Editoral Universitaria. Santiago.

Garreaud, R. (2009): The Andes climate and weather. In: Advances in Geoscience 22, 3–11. DOI: 10.5194/adgeo-22-3-2009

Garreaud, R. and Rutllant, J. (1996): Análisis meteorológico del los aluviones de Antofagasta y Santiago de Chile en el periodo 1991–1993. In: Atmósfera 9, 251–271.

Garreaud, R.; Barichivich, J.; Christie, D. A. and Maldonado, A. (2008): Interannual variability of the coastal fog at Fray Jorge relict forests in semiarid Chile. In: Journal of Geophysical Research 113, G04011. DOI: 10.1029/2008JG000709

Grau, J. (2000): El Niño – Leben für die untergehende Pflanzenwelt der Atacama. In: Biologie in unserer Zeit 30, 4–13.

Heibl, C. (2005): Studies on the systematics, evolution, and biogeography of *Oxalis* sections *Caesiae, Carnosae,* and *Giganteae*, endemic to the Atacama Desert of northern Chile. Diploma thesis. Ludwig-Maximilian-Universität München.

Hoffmann, A. and Walter, H. (2004): Cactaceas en la flora silvestre de Chile. Fundación Claudio Gay. Santiago.

Hoxey, P. (2004): Some notes on *Copiapoa humilis* and the description of a new subspecies. In: British Cactus and Succulent Journal 22, 29–42.

Jaffuel, P. F. (1936): Excursiones botánicas a los alrededores de Tocopilla. In: Revista Chilena de Historia Natural 40, 265–274.

Johnston, I. M. (1929): Papers on the flora of northern Chile. 1. The coastal flora of the departments of Chañaral and Taltal; 2. The flora of the nitrate coast. In: Contributions Gray Herbarium 85.

Kohler, A. (1970): Geobotanische Untersuchungen in Küstendünen Chiles zwischen 27 und 42 Grad südl. Breite. In: Botanische Jahrbücher 90, 55–200.

KRAUS, R. (1994): Die Bedeutung der Küstennebel in Chile für die Kakteenpopulation. In: Kakteen und andere Sukkulenten 45 (11), 242–247.

LAILHACAR, S. (1986): Las grandes formaciones vegetales de la zona desértica y mediterránea preárida y árida de Chile: con énfasis en sus aptitudes forrajeras. In: Boletin Sociedad Chilena de la Ciencia del Suelo 5, 145–231.

LARRAIN, H.; CERECEDA, P.; PINTO, R.; LAZARO, P.; OSSES, P. and SCHEMENAUER, R. S. (2001): Archaeological observations at a coastal fog-site in Alto Patache, South of Iquique, Northern Chile. In: Proceedings of the Conference on Fog and Fog Collection, St. John's, Canada, 289–292.

LARRAIN, H.; VELÁSQUEZ, P.; CERECEDA, R.; ESPEJO, R.; PINTO, R.; OSSES, P. and SCHEMNAUER, R. S. (2002): Fog measurements at the site "Falda Verde" north of Chañaral compared with other fog stations of Chile. DS. In: Atmospheric Research 64, 273–284. DOI: 10.1016/S0169-8095(02)00098-4

LE QUESNE, C.; ACUÑA, C.; BONINSEGNA, J. A.; RIVERA, A. and BARICHIVICH, J. (2008): Long-term glacier variations in the Central Andes of Argentina and Chile, inferred from historical records and tree-ring reconstructed precipitation. In: Palaeogeography, Palaeoclimatology, Palaeoecology 281, 334–344. DOI: 10.1016/j.palaeo.2008.01.039

LUEBERT, F.; GARCIA, N. and SCHULZ, N. (2007): Observaciones sobre la flora y vegetación de los alrededores de Tocopilla (22°S, Chile). In: Boletin Museo Nacional Historia Natural 56, 27–52.

MANN, G.; ZAPFE, H.; MARTINEZ, R . and MELCHER, G. (1953): Colonias de guanacos (*Lama guanicoe*) en el desierto septentrional de Chile. In: Investigaciones Zoologicas de Chile 10, 11–13.

MARTICORENA, C.; MATTHEI, O.; RODRÍGUEZ, R.; ARROYO, M. K.; MUÑOZ, M.; SQUEO, F. and ARANCIO, G. (1998): Catálogo de la flora vascular de la Segunda Región (Región de Antofagasta), Chile. In: Gayana Botánica (Chile) 55, 23–83.

MARTICORENA, M.; SQUEO, F.; ARANCIO, G. and MUÑOZ, M. (2001): Catálogo de la flora vascular de la IV Región de Coquimbo. In: SQUEO, F.; ARANCIO, G. and GUTIERREZ, J. R. (eds.): Libro rojo de la flora nativa y de los sitios prioritarios para su conservación: Región de Coquimbo. La Serena.

MUÑOZ-SCHICK, M.; PINTO, R.; MESA, A. and MOREIRA-MUÑOZ, A. (2001): Oasis de neblina en los cerros costeros del sur de Iquique, región de Tarapacá, Chile, durante el evento El Niño 1997–1998. In: Revista Chilena de Historia Natural 74, 323–339.

NUÑEZ, L. and VARELA, J. (1967): Sobre los recursos de agua y el poblamento prehispánico de la costa del Norte Grande de Chile. In: Estudios Arqueologicos 3-4, 7–47.

PHILIPPI, R. A. (1860): Reise durch die Wüste Atacama auf Befehl der chilenischen Regierung im Sommer 1853–54. Halle.

PINTO, R. (2007): Estado de conservación de *Eulychnia iquiquensis* (Schumann) Britton et Rose (Cactaceae) en el extremo norte de Chile. In: Gayana Botanica 64 (1), 98–109.

PINTO, R. and KIRBERG, A. (2005): Conservation status of *Erosyce* (Cactaceae) in northernmost Chile. In: Bradleya 23, 7–16.

– (2009): Cactus del extremo norte de Chile. Santiago.

PINTO, R. and LUEBERT, F. (2009): Datos sobre la flora vascular del desierto costero de Arica y Tarapaca, Chile, y sus relaciones fitogeograficas con el sur de Perú. In: Gayana Botanica 66 (1), 28–49.

PINTO, R.; BARRÍA, I. and MARQUET, P. A. (2006): Geographical distribution of *Tillandsia* lomas in the Atacama Desert, northern Chile. In: Journal of Arid Environments 65, 543–552. DOI: 10.1016/j.jaridenv.2005.08.015

PINTO, R.; LARRAIN, H.; CERECEDA, P.; LAZARO, P.; OSSES, P. and SCHEMENAUER, R. S. (2001): Monitoring fog-vegetation communities at a fog-site in Alto Patache, south of Iquique, Northern Chile, during "El Niño" and "La Niña" events (1997–2000). In: Proceedings of the Conference on Fog and Fog Collection. St John's, Canada, 297–300.

QUINTANA, J. and BERRIOS, P. (2007): Study of the coastal low cloud in the northern coast of Chile: variability and tendency. 4th Int. Con. on Fog, Fog Collection and Dew. La Serena, 189–192.

REICHE, K. (1907): Grundzüge der Pflanzenverbreitung in Chile. In: ENGLER, A. and DRUDE, O. (eds.): Die Vegetation der Erde. Leipzig.

RICARDI, M. (1957): Fitogeografia de la costa del departamiento de Taltal. In: Boletin Sociedad Biologica de Concepcion 32, 3–9.

RICHTER, M. (1981): Klimagegensätze in Südperu und ihre Auswirkungen auf die Vegetation. In: Erdkunde 35, 12–30. DOI: 10.3112/erdkunde.1981.01.02

– (1995): Klimaökologische Merkmale der Küstenkordillere in der Region Antofagasta (Nordchile). In: Geoökodynamik 16 (3), 283–332.

RICHTER, M.; SCHMIDT, D. and WILKE, H. G. (1993): Das Unwetter von Antofagasta. In: Praxis Geographie 23, 44–47

RITTER, F. (1980): Kakteen in Südamerika. Band 3. Chile.

RUELLE, S. (1995): Etude d´impact de la pollution métallique sur le site de Paposo (II Région, Chili). Travail de fin d´études. Faculté Universitaire des Sciences Agronomiques de Cembloux.

RUNDEL, P. W. and DILLON, M. O. (1998): Ecological patterns in the Bromeliaceae of the lomas formation of Coastal Chile and Peru. In: Plant Systematics and Evolution 212, 261–278. DOI: 10.1007/BF01089742

Rundel, P. W. and Mahu, M. (1976): Community structure and diversity in coastal fog desert in northern Chile. In: Flora 165, 493–505.

Rundel, P. W.; Dillon, M. O.; Palma, B.; Mooney, H. A.; Gulmon, S. L. and Ehleringer, J. R. (1991): The phytogeography and ecology of the Coastal Atacama and Peruvian Deserts. In: Aliso 13 (1), 1–49.

Rundel, P. W.; Palma, B.; Dillon, M. O.; Sharifi, M. R. and Boonpragob, K. (1997): *Tillandsia landbeckii* in the coastal Atacama Desert of northern Chile. In: Revista Chilena de Historia Natural 70, 341–349.

Rundel, P. W.; Villagra, P. E.; Dillon, M. O.; Roig-Juñent, S. and Debandi, G. (2007): Arid and semi-arid ecosystems. In: Veblen, T. T.; Young, K. R. and Orme, A. R (eds): The physical geography of South America. Oxford, 158–183.

Schulz, N. (2009): Loma-Formationen der Küsten-Atacama/Nordchile unter besonderer Berücksichtigung rezenter Vegetations- und Klimaveränderungen. http://www.opus.ub.uni-erlangen.de/opus/volltexte/2009/1289/

Schulz, N.; Boisier J. P. and Aceituno, P. (2011): Climate change along the arid coast of northern Chile. International Journal of Climatology (accepted).

Sielfeld, W.; Miranda, E. and Torres, J. (1995): Información preliminar sobre los oasis de niebla de la costa de la Primera Región de Tarapacá. Programa de Recursos Hidricos y Naturales Renovables. Universidad de Tarapacá, Iquique, Chile.

Squeo, F.; Arroyo, M.; Marticorena, A; Arancio, G; Muñoz-Schick, M.; Negritto, M.; Rojas, G.; Rosas, M.; Rodriguez, R.; Humaña, A.; Barrera, E. and Marticorena, C. (2008): Catálogo de la flora vascular de la Región de Atacama. In: Squeo, F.; Arancio, G. and Gutierrez, J. R. (eds.): Libro rojo de la flora nativa y de los sitios prioritarios para su conservación: Región de Atacama. La Serena.

Valero-Garces, B. L.; Delgado-Huertas, A.; Navas, A.; Edwards, L.; Schwalb, A. and Ratto, N. (2003): Patterns of regional hydrological variability in central-southern Altiplano (18°-26°S) lakes during the last 500 years. In: Paleogeography, Paleoclimatology, Paleoecology 194, 319–338.

Werdermann, E. (1931): Die Pflanzenwelt Nord- und Mittelchiles. In: Vegetationsbilder 21 (6/7), 31–42.

Authors

Dr. Natalie Schulz
Pontificia Universidad Católica del Perú
Lima
Peru
nschulz@pucp.edu.pe

Prof. Dr. Patricio Aceituno
Department of Geophysics
FCFM
University of Chile
Santiago
Chile
aceituno@dgf.uchile.cl

Prof. Dr. Michael Richter
Department of Geography
University of Erlangen-Nürnberg
Kochstr. 4/4
91054 Erlangen
mrichter@geographie.uni-erlangen.de