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Last millennial environmental dynamics in the western Peruvian Andes inferred from the development of a cushion-plant peat hillock

Karsten Schittek[a,*], Markus Forbriger[a], Dominik Berg[b], Jonathan Hense[c], Frank Schäbitz[b], Bernhard Eitel[a]

[a] Institute of Geography, Universität Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany
[b] Institute for Geography Education, Universität zu Köln, Gronewaldstr. 2, 50931 Köln, Germany
[c] Nees Institute, Department of Biology, Universität Bonn, Meckenheimer Allee 170, 53115 Bonn, Germany

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A B S T R A C T

For the first time, an isolated cushion-plant peat hillock was investigated, a so far neglected feature of high-Andean spring ecosystems. These small hillocks typically cluster around springs within the upper catchment areas of larger cushion-plant peatlands at altitudes ranging from 4000 m to 5000 m a.s.l.

The size of the investigated peat hillock, located within the Río Viscas catchment area (Lucanas province, District of Ayacucho) at 4250 m a.s.l., is relatively small (about 10 m in diameter). Due to its dome-shaped and densely green habitus, it overlooks the surrounding vegetation by about 1–2 m and stands out by its color. Terrestrial laser scanning (TLS) techniques are used in order to provide insights into the spatial extension of the *Distichia muscoides*-dominated vegetation stand.

For the reconstruction of environmental dynamics during the past millennium, plant micro-/macrofossil analyses and total carbon/total nitrogen measurements were applied. Based on radiocarbon dating, the peat archive provides a chronology for the past 1050 years. We interpret phases of relatively high abundances of Poaceae pollen in our record as an expansion of Andean grasslands during humid phases. Drier conditions are indicated by a decrease of Poaceae pollen and higher abundances of Asteraceae pollen. The results reflect significant climate oscillations and provide evidence for a sustained dry phase between AD 900 and AD 1100. A more humid and cooler phase prevailed from around AD 1300 to AD 1825, during the Little Ice Age.

Our data provide evidence that such a spatially defined peat-accumulating ecosystem, as represented by the studied peat hillock, is capable to survive pronounced climatic oscillations as long as it does not lose its protective cushion-plant surface. As peat hillocks are heavily affected by grazing, multitemporal studies should be carried out to document changes and to provide new insights into adaption strategies of vegetation to changing environmental conditions.

1. Introduction

The central Andes are characterized by a great variety of landscapes, which is expressed in a diverse flora and fauna. The high-mountain landscape between the Eastern and Western Cordilleras, which commonly is referred to as the “Altiplano” or “Puna”, includes broad continuous, 3500–4100 m a.s.l. high plains. In these high-mountainous areas, the Andean flora is exposed to exceptionally harsh environmental conditions, including high solar radiation, pronounced diurnal temperature variation with frequent frosts, a prolonged dry season and low oxygen concentration (Schittek et al., 2012). Some plants show specific morphological adaptions, which facilitate the survival under these conditions. Impressive representatives of the typical, highly adapted plant growth-forms in high-altitude ecosystems of South America are the cushion plants. Their closely packed shoots with very short internodes grow so densely that they can form extensive, stable mats, ranging in shape from almost flat to hemispherical. The compact architecture protects them from strong winds and reduces the risk of water shortage (Sklenář, 2009).

Nevertheless, the occurrence of cushion plants is not necessarily restricted to desert-like ecosystems. The high-altitude cushion-plant peatlands of the Central Andes are a typical element of the high-Andean

Abbreviations: TLS, terrestrial laser scanning; SASM, South American Summer Monsoon; TC, total carbon; TN, total nitrogen; MCA, medieval climate anomaly; LIA, little ice age; LIP, late intermediate period

* Corresponding author.
E-mail address: schittek@uni-heidelberg.de (K. Schittek).

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vegetational belt at altitudes of 4000–5000 m a.s.l. The main peat-accumulating species of these soligenous peatlands are the Juncaceae *Distichia muscoides* and *Oxychloe andina* (Ruthsatz, 2012, 2000; Squeo et al., 2006). The shoots of *Distichia*- and *Oxychloe*-cushion plants continue to grow at their tops, but die off from the bottom (Rauh, 1988). On the cushion surface, they form dense mats with a strong apical dominance (Balslev, 1996). The cushions probably started to grow as a single individual producing numerous shoots and rhizomes, which over time transformed into smaller groups as the underground parts died off. The rhizomes continuously produce short aerial branches with small terminal rosettes. Due to anaerobic conditions and cold temperatures, the dead remains do not decay immediately. The older tissue is overgrown and deposited in the form of peat (Schittek, 2014; Benavides et al., 2013). High-Andean cushion peatlands can accumulate several meters of peat sediment (Schittek et al., 2012; Squeo et al., 2006; Earle et al., 2003). The palaeoenvironments, which facilitated peat deposition in the past, can be reconstructed using the peat structure retrieved from the peat column. The few studies available on high-altitude cushion peatlands in the Central Andes have shown that they can indeed be very suitable archives to retrieve palaeoecological and palaeoclimatic time series (Schittek et al., 2016, 2015; Schittek, 2014; Engel et al., 2014; Kuentz et al., 2011; Earle et al., 2003). Up to now, little is known about the establishment and growth habits of the characteristic, cushion-forming and peat-accumulating Juncaceae.

In this study, we investigate a single cushion-plant peat hillock, which is situated on a spring at an altitude of 4250 m a.s.l. So far, cushion-plant peat hillocks have only been reported by Schittek (2014), who observed similar structures in the spring areas within an extensive high-altitude peatland in the Eastern Cordillera of NW Argentina. In contrast, the here-described peat hillock is a markedly isolated feature, being surrounded by a sparse vegetation of low stature woody shrubs and tussock grasses.The approach of this study combines a plant inventory and a terrestrial laser scan of the hillock to investigate the current vegetation. We further aimed to conduct an analysis of palaeobotanical and geochemical patterns of peat sections retrieved from the peat hillock to check if the peat accumulation represents a continuous archive for palaeoenvironmental research. This was of special interest to possibly supplement the current knowledge about climatic and environmental changes in the western Andes of southern Peru, especially concerning the past centuries. A previously investigated peat record from the nearby Cerro Llamoca peatland (Schittek et al., 2015) lacked palaeoecological information about the past 500 years. Therefore, a special objective of our research was to gather more palaeoecological details about those missing centuries.The current state of knowledge on the climate history of the youngest period of the Holocene is still very limited, although indispensable for archaeological research. Especially in the Palpa/Nasca area and the valleys of the Río Grande drainage in southern Peru, further information on past climate variabilities concentrating on the time span from AD 1000-1550 is necessary for a better understanding of what happened during that cultural period (Sossna, 2016; Unkel et al., 2012; Reindel, 2009). Only few information is available about the environmental changes in the central Andes during the Little Ice Age (ca. AD 1500–1880) (Liu et al., 2005).

2. Study area

2.1. Geographical setting

The studied peat hillock is situated in the western cordillera of the Andes of southern Peru (14° 10′ S, 74° 44′ W) at an altitude of 4250 m a.s.l., within the water catchment area of Cerro Llamoca peatland (Schittek et al., 2015; Schittek et al., 2012) (Fig. 1). It is located west of the continental watershed in the Río Viscas drainage. Cerro Llamoca (4450 m a.s.l.), the overlooking and name-giving peak, is the highest point of the whole Río Grande drainage system.

The study site is characterized by a tropical climate (Lauer, 1993), shaped by distinct temperature and precipitation fluctuations on daily and yearly patterns. The ERA-Interim model (ECMWF, 2014) renders a mean annual precipitation of 349 mm per year for the location of Cerro Llamoca peatland, with about 90% of the annual precipitation falling during the austral summer (December to March). Rain tends to cluster in “rainy episodes” lasting about a week, interrupted by dry episodes of the same length (Garreaud, 2000). The duration and intensity of wetter and drier episodes in the summertime is highly sensitive to large-scale circulation anomalies (Garreaud and Aceituno, 2001). This concentration of precipitation during distinct periods of the year could be termed as a “monsoon-like” precipitation pattern (Zhou and Lau, 1998).

In total, 17 vascular plants were identified from the studied peat hillock (Table 1). Because our collections took place within the dry season, it is possible that some herbaceous species were not registered. The floristic composition is dominated by species, which, according to Ruthsatz (2012, 2000), typically occur in the high-altitude cushion-plant peatlands (bofedales) of the more humid, tropical central Andes, within the range of the humid Puna (*sensu* Troll, 1968), like *Distichia muscoides* and *Plantago tubulosa*. In contrast, the occurring *Phylloscirpus deserticola* is a typical representative of the drier western central Andean peatlands (Ruthsatz, 2012). *Distichia muscoides* is the most characteristic cushion-forming and peat-accumulating species of the hillock. Nowadays, superficial drying and the impact by the trampling of the hoofed animals (mainly cows) limit the growth of its cushions significantly. Dense mats of *Phylloscirpus deserticola* dominate degraded sections and drier cushion tops. *Plantago tubulosa* prevails where the surface is characterized by well-saturated conditions, but repeatedly trampled. Sections that are less frequented by the grazing animals are still grown with sporadic tussocks of *Deyeuxia rigida*, bordering well-saturated swards of *Werneria pygmaea*.

Especially the steep sides of the peat hillock originating to the west are highly degraded. This degradation is caused by cattle climbing on top of the hillock in order to reach fresh plants to feed on. Through this severe damage, the cushion-forming vegetation dies off. The loss of the protective vegetation accelerates water loss (Schittek et al., 2012). If the vegetation cover once is lost, the brown peat surface warms and dries quickly during daytime. Once if the peat dries out, the peat substrate is easily eroded by wind.

2.2. Geomorphometric mapping

Terrestrial laser scanning (TLS) techniques were applied for the first time on a single cushion-plant peat hillock in order to provide new insights into its spatial characteristics. Data acquisition was performed by using a time-of-flight scanner (Riegl VZ-400) with online waveform processing technology according to the methods described in Höfle et al. (2013). Four scan positions were necessary for capturing the whole peat hillock.

TLS allows to determine and to quantify exactly the extent of the investigated peat hillock. Fig. 2 shows the captured point cloud of the peat hillock. Different grey scales represent reflectance properties of the peat surface. The black color (i.e. no data values) results from either shading effects or open water areas. Assuming an underlying inclined plane, the total calculated volume of the hillock is ~24.5 m^3 (Forbriger et al., 2011).

The use of the laser reflection values was tested for derivation of plant segmentation, but due to distorting effects of partly dried plant material, backscatter values resulting from different species and reflection properties give only sparse information on vegetation units. Water content, with its high reflection variation, overlays the radiometric information of single plants (Fig. 3).