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Environmental change and fire history of southern Patagonia (Argentina) during the last five centuries

Torsten Haberzettl[a,*], Michael Wille[b], Michael Fey[a], Stephanie Janssen[b], Andreas Lücke[c], Christoph Mayr[c], Christian Ohlendorf[a], Frank Schäbitz[b], Gerhard H. Schleser[c], Bernd Zolitschka[a]

[a]Geomorphology and Polar Research (GEOPOLAR), Institute of Geography, University of Bremen, Celsiusstr. FVG-M, 28359 Bremen, Germany
[b]Seminar for Geography and its Didactics, University of Cologne, Gronewaldstr. 2, 50931 Cologne, Germany
[c]Institute of Chemistry and Dynamics of the Geosphere V: Sedimentary Systems, Research Center Jülich, 52425 Jülich, Germany

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Abstract

Geochemical, geophysical, charcoal and pollen analyses from the very poorly investigated southern Patagonian steppe area show that in the vicinity of Laguna Potrok Aike (Santa Cruz Province, Argentina) and north of the Strait of Magellan the detectable impact of Europeans as explorers, settlers and farmers on fire intensity, vegetation and lake ecosystems started with first regional signs during the 1840s. A massive anthropogenic impact on a supra-regional scale followed as the result of the introduction of sheep farming at the end of the 19th century. Furthermore, since the first European explorations, fires in the steppe areas of southernmost Patagonia as recorded at Laguna Potrok Aike occurred contemporaneously in the steppe-forest ecotone further west and probably also in the Andean forest itself. Environmental changes which are not caused by anthropogenic influence are also revealed and were most likely the result of temperature variations and enhanced and reduced wind speeds, respectively. A fire event around AD 1600, before the arrival of European settlers, occurred during a dry period in the forest and steppe-forest ecotone and followed a wet phase in the steppe that caused favorable ignition conditions in all environments.

1. Introduction

For various reasons fire is an important ecological factor in the southern Patagonian steppe environment, as for example burned areas are more prone to deflation processes. It has clearly been a highly influential factor in the development of past vegetation by changing plant successions and altering the composition of plant communities (Innes et al., 2004). The importance of the two principal factors controlling fire frequency in Patagonia, human impact and climate has already been discussed vividly (Heusser, 1987; Huber and Markgraf, 2003). Analyses of fire periodicities from records between 36 and 55 °S in Patagonia show that fire frequency is driven by climate, primarily caused by recurrence of droughts (Markgraf and Anderson, 1994) resulting in at least favorable ignition conditions in the woodlands and steppe-forest ecotone. On the other hand, fire in the steppe is not dependent on dry fuel but on fuel in general which is produced during moisture conditions (Clark et al., 2002; Huber and Markgraf, 2003; Brown et al., 2005). Nevertheless, reasons for historical fire events, i.e. after the arrival of Ferdinand Magellan in Patagonia in AD 1520 (Mainwaring, 1983; Martinic, 1997), still remain vague and need to be investigated further. A sediment record from Río Rubens peat bog (52°08′15″ S, 71°52′53″W) situated at the steppe-forest ecotone (Fig. 1) shows a major charcoal peak around AD 1600. However, the level of decomposition of peat does not definitely yield evidence for drier conditions (Huber and Markgraf, 2003), which would allow to conclude that climate might have also been the cause for fire during this time.

Another topic of discussion is the environmental impact of Europeans as explorers, settlers and farmers in

*Corresponding author. Tel.: +49 421 218 655; fax: +49 421 218 9658.
E-mail address: habi@uni-bremen.de (T. Haberzettl).
URL: http://www.salsa.uni-bremen.de.

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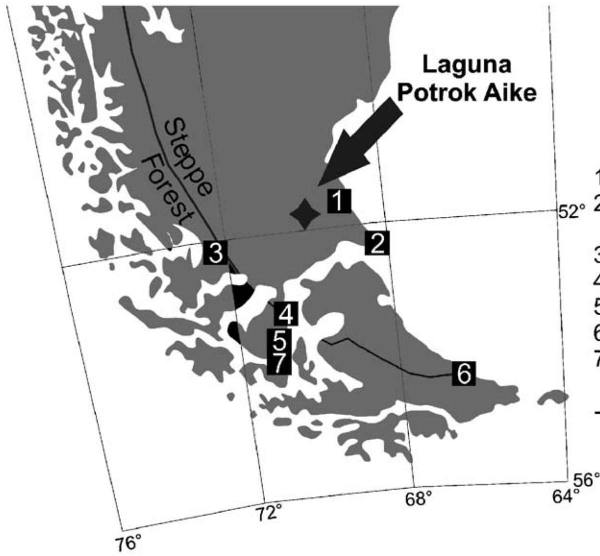

Fig. 1. Research area with Andean Forest Line and other locations discussed in the text.

Patagonia. For a long time, the first appearance of pollen from the European weed *Rumex acetosella* was used as an indicator for disturbance of the natural vegetation and therefore as time marker for late 19th century permanent European settlement (Mancini, 1998, 2002; Huber and Markgraf, 2003). However, in the Río Rubens peat bog record *Rumex* already appeared in the early 17th century (Huber and Markgraf, 2003).

This paper aims to reconstruct the European impact and also natural environmental changes that influenced south-eastern Patagonia. The reconstruction is based on geochemical, geophysical and pollen data as well as on a new charcoal record from Laguna Potrok Aike, Santa Cruz (51°58′S, 70°23′W, Fig. 1). This maar lake is situated in the steppe region of Patagonia, an area with hitherto no charcoal record at all (Huber et al., 2004). Furthermore, the focus will be directed to the identification of the sources and effects of fire as this is an essential part of any fire regime reconstruction (Whitlock and Anderson, 2003). Results from Laguna Potrok Aike will be compared to the record from Río Rubens peat bog in order to obtain information about synchronous fire events in the steppe and steppe-forest environments and to identify fire causes in historical time. Both archives are located at the same latitude at a distance of 100 km from each other in representative locations for steppe and steppe-forest environments. The dominating climatic element of Patagonia is the westerly wind constituting more than 50% of the wind directions and reaching mean monthly wind speeds of $9\,m\,s^{-1}$ during early summer (Endlicher, 1993). This element is also responsible for the present day permanent mixing of the water column of Laguna Potrok Aike. The rain shadow effect east of the Andes results in a precipitation decrease from west to east with less than 200 mm of annual precipitation at Laguna Potrok Aike during dry years, which is one of the causes for the steppe environment. However, Laguna Potrok Aike belongs to the few permanent lakes in the dry lands of southern Patagonia, which assures a continuous sediment record even during dry periods (Haberzettl et al., 2005). More detailed information about Laguna Potrok Aike (Schäbitz et al., 2003; Zolitschka et al., 2004; Haberzettl et al., 2005) and Río Rubens peat bog (Huber and Markgraf, 2003; Huber et al., 2004) is provided elsewhere.

2. Methods

Five gravity cores (PTA02/1–5) with lengths of up to 113.5 cm were recovered from Laguna Potrok Aike during the first SALSA (South Argentinean Lake Sediment Archives and Modeling) field campaign in 2002 using a modified ETH-gravity corer (Kelts et al., 1986) equipped with a messenger system. In the laboratory sediment cores were stored dark and cool at +4 °C. Cores were split, photographed, described lithologically and sampled continuously and volumetrically in 1 cm intervals. Detailed multiproxy investigations were carried out on core PTA02/4 with a length of 1 m from the center of the lake (Haberzettl et al., 2005).

Samples for pollen analyses were treated following standard procedures (Faegri and Iversen, 1989) with a subsequent heavy liquid separation by $ZnCl_2$. Pollen concentrations were calculated with the help of Lycopodium spore tablets (Stockmarr, 1971). The detailed pollen percentage diagram is shown elsewhere (Haberzettl et al., 2005). Charred particles $>20\,\mu m$ were quantified on pollen slides. A second set of sediment samples, each consisting of about $2\,cm^3$ of sediment, was sieved through a $100\,\mu m$ mesh after KOH treatment and macroscopic charcoal fragments were counted under a binocular microscope.

Sample position of this second set in most cases was 1 cm above or below the pollen samples. This method should extend the information about local fires as, in contrast to that, pollen slide charcoal typically is exported preferentially from the burn area (Clark et al., 2002) and hence local fires normally are not recorded. In order to enhance comparability to the Río Rubens record accumulation rates were calculated for sieved macroscopic charcoal.

All volumetric sediment samples for geochemical analyses were freeze-dried. Prior to measuring total nitrogen (TN) and total carbon (TC) using a CNS elemental analyzer (EuroEA, Eurovector), dried samples were ground in a mortar and homogenized. For determination of total organic carbon (TOC), subsamples were treated with 3% and 20% HCl at 80 °C to remove carbonates and then measured with the same device. Total inorganic carbon (TIC) was calculated as the difference between TC and TOC. Biogenic silica was determined using a continuous flow system with UV–VIS spectroscopy (Müller and Schneider, 1993). From the element distribution data (Ti, Fe, Mn) obtained with a CORTEX XRF-scanner (Zolitschka et al., 2001) Fe/Mn ratios were calculated. Frequency-dependent magnetic susceptibility was determined using a Bartington sensor (type MS2E).

The chronology of the 100 cm long and 1600-year-old record of Laguna Potrok Aike is based on a second-order polynomial function derived from four radiocarbon dates (Haberzettl et al., 2005) calibrated with the southern hemisphere calibration curve (McCormac et al., 2002). The Río Rubens time scale of the uppermost 43 cm of the record representing the last 1300 years is based on a third-order polynomial regression derived from nine ^{210}Pb- and three ^{14}C-datings (Huber and Markgraf, 2003). As the time of European impact is the main object of this paper only the last 500 years are plotted. However, both records go much further back in time.

3. Results

Except for charcoal, data in general show low variations in the older part of the record. First trends to more positive values in many parameters can be observed from the early 18th century onward, further increasing or decreasing in the early 19th century.

Rumex and *Pediastrum* are not present in the oldest part of the Laguna Potrok Aike record (Fig. 2). Only charcoal and TIC show a distinct peak shortly before AD 1600. Until the early 19th century, most proxies do not show marked variations except for TN, TOC, biogenic silica and Fe/Mn ratios which increase during the late 18th century (Fig. 2).

During the first half of the 19th century, *Rumex* and *Pediastrum* appear for the first time with increasing values to the top. Values for TN, TOC and biogenic silica still rise and stay on a high level showing decreases in the mid-20th century. Fe/Mn ratios show a continuous decrease from the early 19th century to present day with a minima in the 1880s.

TIC values are below detection limit before they increase during the mid-20th century. Poaceae show low values in the early 20th century followed by a continuous increase. Charcoal values decrease after a peak in the 1840s with a slight increase in recent times (Fig. 2).

Altogether, two prominent peaks around AD 1600 and in the 1840s are visible in the sieved charcoal record from Laguna Potrok Aike (Fig. 3). Another period with increased charcoal values is between ca. AD 1650 and ca. AD 1770 with a slight peak in the 1760s.

For better comparison, pollen slide charcoal concentrations are plotted on a depth scale. The profile shows slightly more peaks (Figs. 4–6) at 1 (mid-1990s), 15 (1840s), 20 cm (1780s) and 35 cm (around 1600) sediment depth (Figs. 4–6). A less prominent peak is at 8 cm (1920s). Extended minima are visible between 2 (late 1980s) and 13 cm (1860s) as well as between 23 (1740s) and 33 cm (1620s). Further minima are observed at 18 (around 1800) and 38 cm (1560s, Figs. 4–6).

Andean forest pollen, consisting of *Nothofagus dombeyi* (>15%), *Myzodendron* (<3%), *Podocarpus* (<2%), *Drimys*, *Gunera* and *Nothofagus obliqua* (all <1%), show an inverse pattern to pollen slide charcoal (Fig. 4). Peaks in pollen percentages are found at 0.5 (around 2000), 18 (around 1800), 33 (1620s), 38 (1560s) and 45 cm (around 1500) and broad maxima are between 2 (late 1980s) and 13 cm (1860s) as well as between 23 (1740s) and 28 cm (1680s). According to that distinct minima are at 15 (1840s), 20 (1780s), 30 cm (1660s) and lower values can be observed at 1 (mid-1990s), 35 (around 1600) and 40 cm (1530s, Fig. 4).

Frequency-dependent magnetic susceptibility given as percent (%) and Ti shown as counts per second (cps) show a rather variable pattern (Fig. 5). Maxima above 5 cm (1950s) in the record are followed by distinct minima around 5 cm (1950s). Both records increase in value to a depth of 16 cm (1830s) with various smaller peaks and minima in between. Below a minima between 17 (1850s) and 19 cm (1790s), both records increase again and Ti shows highest values of the record. Further down the record values are lower except for two peaks in frequency-dependent magnetic susceptibility at 26 (1710s) and 35 cm (around 1600). The latter is accompanied by a slight rise in Ti although there is an obvious minima in the counts of that element in that depth. Nevertheless, frequency-dependent magnetic susceptibility and Ti show very similar peaks compared to sieved macroscopic charcoal accumulation rates (Fig. 5).

Total pollen concentration shows a very similar pattern to pollen slide charcoal (Fig. 6). A peak at 1 cm (mid 1990s) depth is followed by a pronounced decreasing trend down to 13 cm (1860s). Further down three maxima are visible at 15 (1840s), 20 (1780s) and 25 cm (1720s). Lowest values of the record between 28 (1680s) and 33 cm (1620s) are followed by the highest at 35 cm (around 1600).

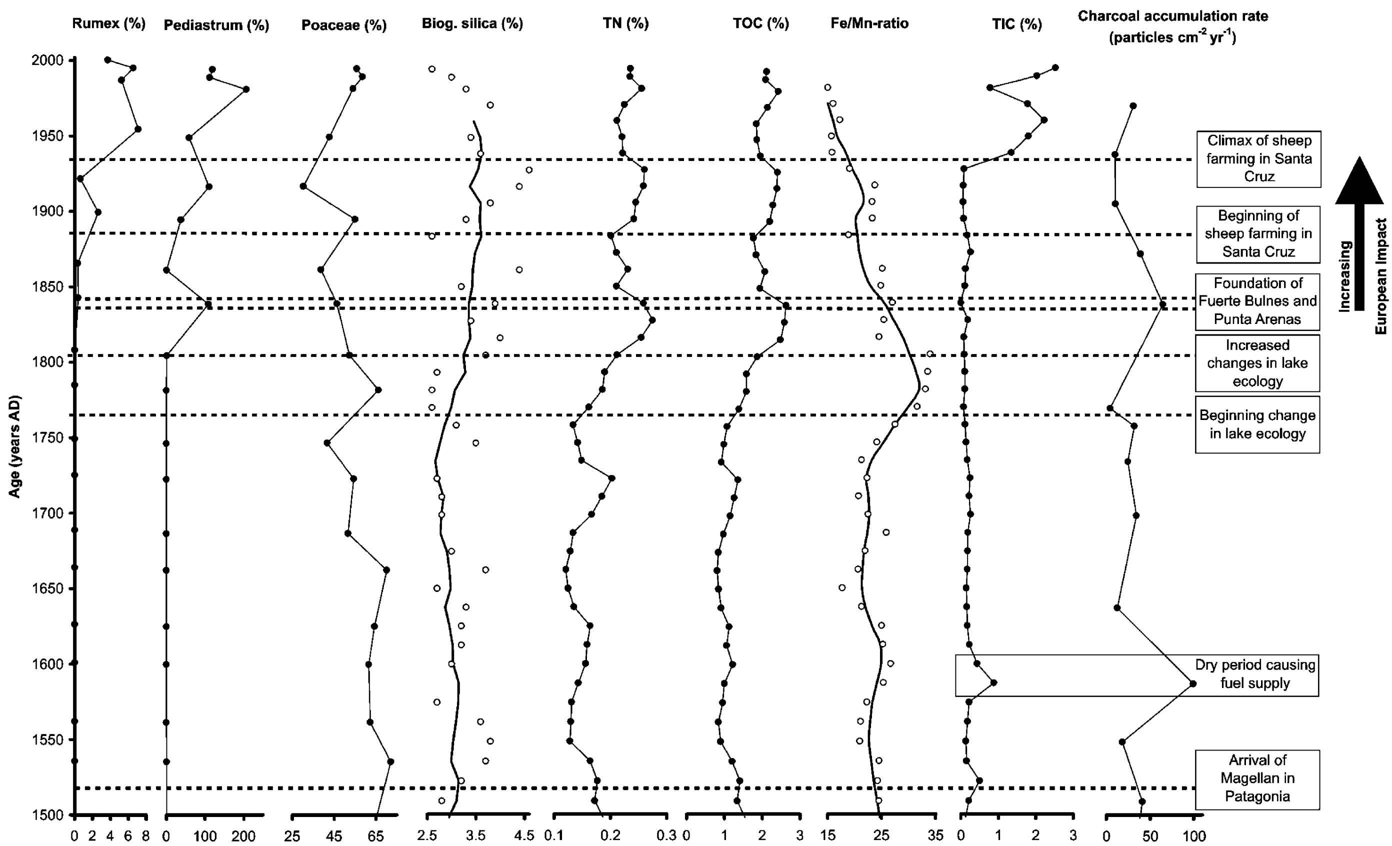

Fig. 2. Profiles of selected pollen, charcoal and geochemical data.

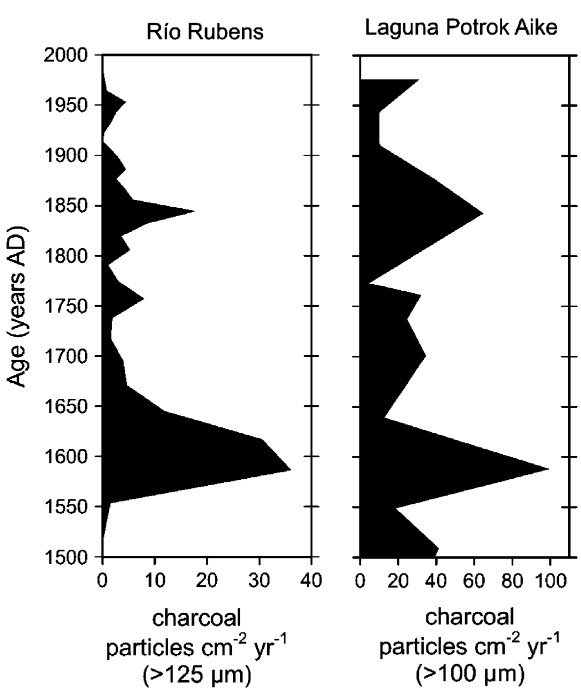

Fig. 3. Charcoal accumulation rates for Laguna Potrok Aike and Río Rubens peat bog with similar patterns.

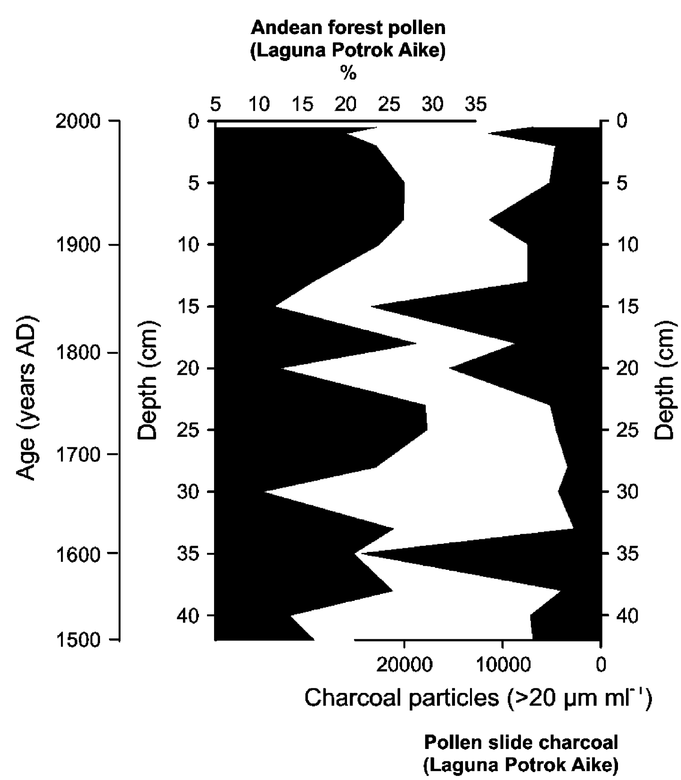

Fig. 4. Comparison of pollen slide charcoal with the amount of Andean forest pollen (95% *Nothofagus*) showing an inverse correlation pattern in the Laguna Potrok Aike record.

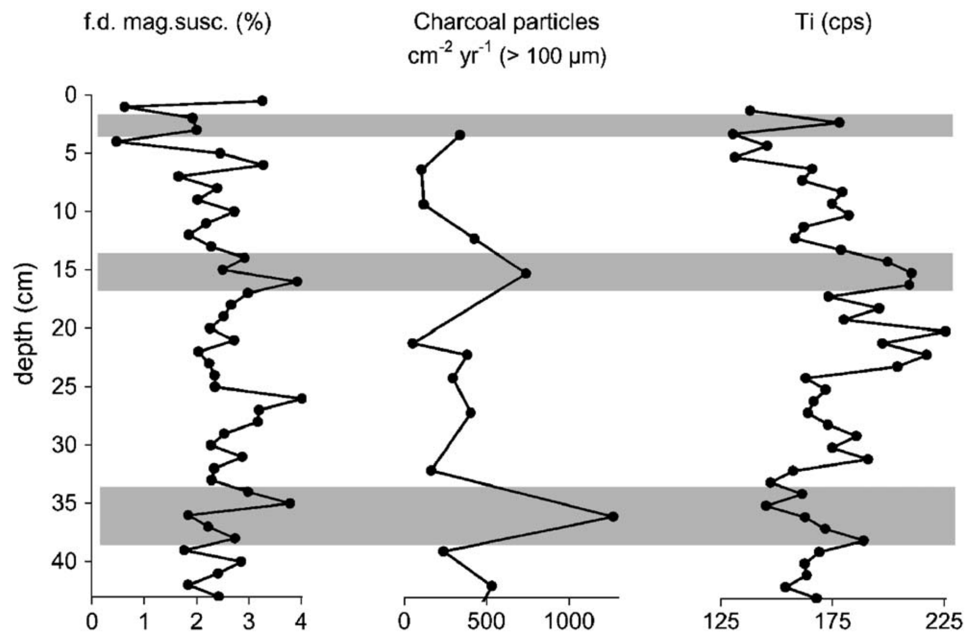

Fig. 5. Comparison of sieved macroscopic charcoal accumulation rates from Laguna Potrok Aike with respective frequency dependent magnetic susceptibility (F.d. MS) and titanium (Ti). Slightly different peak locations result from different measurements and sampling intervals.

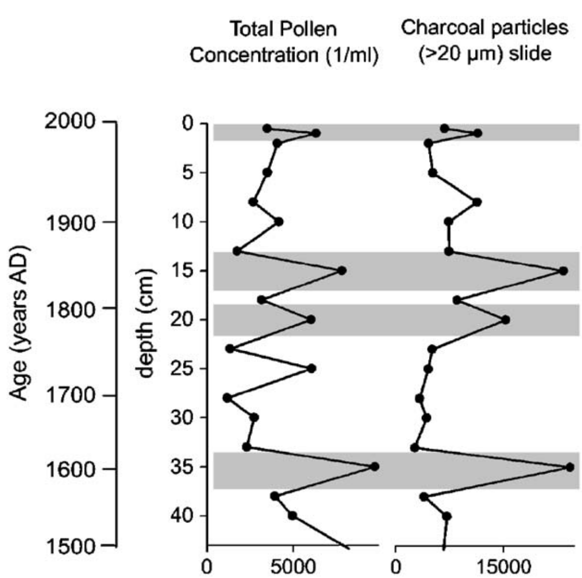

Fig. 6. Comparison of total pollen concentration and pollen slide charcoal of Laguna Potrok Aike

4. Interpretation and discussion

4.1. European impact versus climate change

The beginning and continuation of European impact should be visible in almost all described parameters. For example eutrophication indicating TOC, TN and biogenic silica are expected to increase with an increased supply of nutrients, new European pollen like *R. acetosella* are supposed to invade southern Patagonia (Huber and Markgraf, 2003) or fire frequencies should rise due to the slash and burn activities Europeans were used to (Caldararo, 2002).

However, there might be a difference in the magnitude of a signal depending on the distance to the origin and the transport mode. Aeolian transport (e.g., pollen) for example, should reflect a more supra-regional signal, whereas episodic fluvial input (e.g., Ti, Haberzettl et al., 2005) is expected to mirror a more local signal.

4.2. Charcoal peaks in southern Patagonia around AD 1600

The arrival of Magellan in Patagonia in AD 1520 (Goodall, 1979; Mainwaring, 1983; Martinic, 1997) had no detectable impact on Laguna Potrok Aike (Fig. 2). Neither had the first two European settlements that were established along the northern shore of the Strait of Magellan in AD 1584, Nombre de Jesús near Cabo Vírgenes (Fig. 1) and Puerto Hambre (Fig. 1) farther to the west (Goodall, 1979; Mainwaring, 1983; Huber and Markgraf, 2003). The first hint of a European impact might be a charcoal peak around AD 1600 (Fig. 2), which could be caused by settlement activities, changed hunting or cultivation strategies, etc. This peak distinctly exceeds the amount of charcoal found in older sections of Laguna Potrok Aike (Haberzettl et al., 2005). Within the dating uncertainties this peak matches with the establishment of the settlements, but contemporaneous charcoal peaks were found in the record of Río Rubens peat bog (Figs. 1 and 3). As Río Rubens is located northeast of the settlements this indicates that fire during this period seems to have been a widespread regional phenomenon.

In the Río Rubens profile, the charcoal peak is interpreted as a possible result of a decrease in effective moisture (Huber and Markgraf, 2003). This assumption is based on strongly decomposed peat below the charcoal horizon related to a desiccation of the bog. However, increased humification below a charcoal layer can also be related to 'ash fertilization' with a substantial increase in nutrients and microbial activity and thus intensified decomposition (Markgraf, 1993; Huber and Markgraf, 2003). A hydrology-reflecting pollen record from Cabo San Pablo Mire (Fig. 1) in Tierra del Fuego (Heusser and Rabassa, 1991; Huber and Markgraf, 2003) which shows similar paleoenvironmental conditions yielded no further evidence for a decrease in effective moisture due to the low temporal resolution of that record.

In the high-resolution record of Laguna Potrok Aike, TIC was demonstrated to be a lake-level indicator reflecting the hydrological regime (Haberzettl et al., 2005). High values are caused by calcite precipitation during lake-level low stands and therefore indicate dry conditions whereas low values due to dilution processes in the lake reflect lake-level high stands and therefore moister conditions (Haberzettl et al., 2005). The TIC record of Laguna Potrok Aike points to a drier period during the fire event around AD 1600 and a wet period preceding this period (Fig. 2). That implies if hydrological conditions at Laguna Potrok Aike could be transferred to the West during that time that several decades of wet and favorable conditions for plant growth, which also means an enhanced fuel production in the forest as well as in the steppe and steppe-forest ecotone, were followed by a short, dry phase. During this drought, plants might have suffered from water stress causing favorable ignition and expansion conditions for fire in all environments (for modern fire-climate relations in Patagonia see e.g., Dentoni, 2001). However, recent findings in a longer record from Laguna Potrok Aike (unpublished data) indicate that hydrological conditions between Laguna Potrok Aike and the Andean region might have been inverse. This would imply drier conditions in the Andes before and after the TIC peak (dry conditions) at Laguna Potrok Aike at AD 1600, which would also explain why after AD 1600 a relationship between fires and droughts is not visible at Laguna Potrok Aike. The TIC record shows only wet conditions except for around AD 1600 and since AD 1940 (Fig. 2). Hence, conditions at Laguna Potrok Aike have been wet and if conditions were inverse near the Andes it was dry which causes favorable ignition conditions in both environments as in the steppe environment grasses desiccate quickly and are commonly dry enough to support fires even during non-drought years (Clark et al. 2002; Huber et al., 2004; Brown et al., 2005). This might also be an explanation why Laguna Potrok Aike and Río Rubens peat bog show a similar charcoal pattern (Fig. 3).

4.3. Limnological changes and European impact during the late 18th and early 19th century

The increase of Fe/Mn ratio, TN and TOC during the late 18th and early 19th century as well as the increase of biogenic silica and the subsequent rapid decrease of the Fe/Mn ratio during the early 19th century indicate a change in lake ecology (Fig. 2). Though today Laguna Potrok Aike is a polymictic lake due to its exposure to the strong westerly winds, it is supposed that during the Little Ice Age wind speeds have been lower. This assumption is based on the fact that today during winter time wind speeds at the weather stations in Río Gallegos (Hoppe, 1997) and Punta Arenas (Endlicher, 1991) are significantly lower than during summer. Highest wind speeds are recorded during day time of the austral summer (Endlicher, 1991).

This results from less insolation during the austral winter and an intensified pressure gradient during the austral summer. This in turn is produced by a strong temperature gradient that develops during an extension of the subtropical high-pressure field that meets the cold air masses of the polar region (Endlicher, 1991). In analogy to this present day phenomenon, a prevalence of less windy conditions is assumed for the Little Ice Age. Furthermore, according to the TIC record in Laguna Potrok Aike and contemporaneous radiocarbon datings of bones incorporated in lake-level terraces well above the present shoreline, the lake level was higher (Haberzettl et al., 2005). Thus, a permanent mixing of the water column by wind was harder to achieve. Under such conditions, the establishment of thermal stratification of the water body of the lake might have occurred more often.

Under stratified conditions and due to the decomposition of increased amounts of organic matter, the oxycline would have moved out of the sediment into the water column. The increased amounts of organic matter result from enhanced epilimnic primary production at the transition from cold conditions during the Little Ice Age to warmer conditions indicated by enhanced production (TN, TOC, Fig. 2). A stable anoxic zone might have developed at the sediment/water interface and possibly in hypolimnic waters. In this case, the cycling of manganese would not have been restricted to the sediment itself anymore. Instead manganese would have remained in solution in the hypolimnion. As a result the Fe/Mn ratio would have risen. A similar model was developed for Zugersee and Baldegersee in Switzerland (Schaller and Wehrli, 1996).

Immediately after AD 1800 wind strength increased leading to a mixing of the lake. Due to this process, the manganese in the water column was oxidized and reprecipitated leading to the observed decrease in the Fe/Mn ratio. After a stabilizing phase similar processes seem to have happened during the 1870s.

This climatic explanation (warming/increasing wind) for the changes in lake ecology is strengthened by a comparison with the behavior of the Patagonian glaciers. The most recent (Little Ice Age) glacial advances in Patagonia are dated between AD 1600 and 1850 (Luckman and Villalba, 2001; Wenzens, 1999), between AD 1600 and 1900 on the eastern side of the North Patagonian Icefield (Glasser et al., 2002) and AD 1750 and 1850 in the Southern Patagonian Icefield (Mercer, 1970). A scheme of

Neoglacial advances developed from dendrochronological analyses identifies the Little Ice Age glaciation between AD 1600 and 1760 (Glasser et al., 2004). Considering the differences between the two archives (glaciers, sediments) and chronologies this supports the idea of rising temperatures after the advances (Little Ice Age), during the changes in lake ecology of Laguna Potrok Aike. As glaciers start to melt mixing due to increased wind speed starts at Laguna Potrok Aike. Therefore, changes in lake ecology during the late 18th and early 19th century might have been triggered by increasingly warmer conditions at the end of the Little Ice Age also leading to enhanced lacustrine production. This results in enhanced accumulation of organic matter in the sediment column, but also in an increase of the total amount of organic matter decomposition at the sediment/water interface.

Since the foundation of the permanent settlements Fuerte Bulnes and Punta Arenas in the 1840s (Martinic, 1997), the changes in lake ecology of Laguna Potrok Aike might be enhanced by European impact. Though each settlement was about 180 and 130 km away, an intensification of the lake internal changes at least to a smaller degree by e.g., aeolian transport might be conceivable. Moreover, maps reveal many expeditions passing the vicinity of Laguna Potrok Aike (Martinic, 1999). The name Potrok Aike is a composition of the Spanish word "potro" (foal) and the Tehuelche word "aike" (Baleta, 1999). As Laguna Potrok Aike is one of the few permanent water bodies in southern Patagonia and the native Tehuelche word "aike" implies a stopping place where meat, water and firewood were stored (Mainwaring, 1983), periodic/episodic camps (eventually with European participation) are very likely. However, there is no detailed information about that.

During the 1840s, TN, TOC and biogenic silica show highest or at least elevated values (Fig. 2) indicating persistent changes in lake limnology. This is supported by the first peak in *Pediastrum*. Further evidence for human activity is given by the first appearance of *Rumex*, presumably *R. acetosella*, with very low values. This European weed is often used as evidence for European influence (Huber and Markgraf, 2003). *R. acetosella* in the pollen record commonly is interpreted as sign for disturbances (Mancini, 1998, 2002), like fire and grazing as it is the case in northwestern Patagonia (Ghermandi et al., 2004).

However, *Rumex* should not be used as a time marker for permanent European settlement (Huber and Markgraf, 2003) in the direct vicinity of the respective climate archive. *Rumex* seeds are wind dispersed and pollen values in the Laguna Potrok Aike sediment record are very low until the end of the 19th century (Fig. 2). Considering the high wind speeds in southern Patagonia, *Rumex* pollen in the sediments of Laguna Potrok Aike can be considered as evidence for permanent European settlements at a large distance. Therefore, also if there is a human impact on Laguna Potrok Aike during the late 18th and early 19th century, it is assumed to originate from a distant source.

4.4. Impact of sheep farming

The most striking human impact on the southern Patagonian landscape, the beginning of sheep farming, is also recognizable in the Laguna Potrok Aike record. Sheep were introduced to southern Patagonia in 1877–78 (Martinic, 1997). By 1884 "all best 'camps' along the Straits" (Mainwaring, 1983) and consequently in the surrounding of Laguna Potrok Aike had been leased or reserved. The massive introduction of sheep has altered the steppe ecosystem distinctly (Hoppe, 1997). Today there are no areas where sheep grazing has not taken place (Soriano, 1983).

Apparently, the 'abrir campos' practice, the clearing of forest for sheep or cattle grazing by burning and logging (Huber and Markgraf, 2003) as it is typical for human interaction with forests in the Americas after European contact (Caldararo, 2002), was not necessary in the steppe environment around Laguna Potrok Aike. This might be an explanation why only little charcoal, probably from distant sources, was found from that time (Fig. 2). The landscape was described as "pastures full of soft grasses" (Mainwaring, 1983); ideal conditions for sheep farming. A marked rise of biogenic silica (Fig. 2) as well as elevated TN and TOC values and a small re-increase of *Pediastrum* indicate further changes in lake ecology (eutrophication tendencies) during the late 19th century.

This is interpreted as a consequence of the presence of sheep. Eutrophication in the lake might be intensified due to excrements and enhanced soil erosion after the destruction of the protecting natural vegetation cover. *Rumex* reaches significantly higher values for the first time during the late 19th century indicating intensified disturbances supporting this hypothesis (Fig. 2).

Around 1900 and during the early 20th century biogenic silica and *Pediastrum* increase, TN and TOC constantly stay on a high level and Poaceae decrease indicating constant or even increasing eutrophication and hence enhanced impact of sheep farming until the 1940s. During this time stocks of sheep were highest and decreased since then (Hoppe, 1997). This decline might be expressed by a slight decrease of TN, TOC and *Pediastrum*, though these parameters still stay on a high level. Furthermore, this seems to be visible in the sharp decrease of biogenic silica. The persistent anthropogenic impact on Laguna Potrok Aike is indicated by values above the average in TN, TOC and *Pediastrum* as well as values below average for Poaceae, especially compared to the oldest part of the record (Fig. 2). High *Rumex* values indicate still intensive human impact within the vicinity of Laguna Potrok Aike. In general, an increasing European impact is recorded in the Laguna Potrok Aike sediment record possibly starting as early as the foundation of Fuerte Bulnes and Punta Arenas continuing until the climax of sheep farming persisting until present day (Fig. 2, indicated by arrow).

4.5. Effects of fires on the sediment record of Laguna Potrok Aike

Lithologic analyses have demonstrated to be a useful indicator of fire-related erosion in some regions (Whitlock and Anderson, 2003). Through the destruction of the vegetation cover fires enlarge areas of bare soil (Clark et al., 2002) and hence support erosion. This becomes evident by comparing the sieved charcoal accumulation rates to erosion indicating proxies like titanium (Ti) or frequency-dependent magnetic susceptibility in the Laguna Potrok Aike sediment record (Fig. 5). Normally, peaks of those proxies are supposed to happen contemporaneously or Ti and frequency-dependent magnetic susceptibility should follow the fire events immediately. If this is not exactly the case, it can be ascribed to the different analytical methods used (e.g., Cortex scanner for XRF data versus discrete samples) and the coarser resolution (average sampling distance 3.3 cm) of the charcoal record. Clastic input during the past five centuries is mainly controlled by erosion and transport by water during episodically surface runoff as shown by an inverse pattern of Ti compared to TIC (Haberzettl et al., 2005). TIC, the former mentioned lake-level indicator of Laguna Potrok Aike, indicates wet conditions in most cases. Wildfires alter the infiltration response of burned watersheds by changing both the physical and chemical characteristics of the watersheds. Steady-state infiltration measurements in New Mexico and Colorado, USA revealed that infiltration rates were less at all burned sites (Martin and Moody, 2001). In steep-sided water sheds in Yellowstone National Park, USA peaks in magnetic susceptibility corresponded well with charcoal peaks suggesting a relationship to fire events (Millspaugh and Whitlock, 1995; Whitlock and Anderson, 2003).

4.6. Locations and regional extent of fires recorded in the sediment of Laguna Potrok Aike

A comparison of the steppe lake record of Laguna Potrok Aike with the record from Río Rubens peat bog situated at the steppe-forest ecotone (Fig. 3) reveals similarities in the distribution of charcoal peaks. This is particularly the case for the peaks shortly before AD 1600, in the 1760s and 1840s. Considering that at Río Rubens burned mosses were observed, it can be assumed that fires were locally present (Huber and Markgraf, 2003). This can be taken as evidence that fires recorded in the sediment record of Laguna Potrok Aike in many cases did not occur in the steppe exclusively.

It is likely that most pollen as well as most charcoal particles originate either from long-distance transport from the west or from the vicinity of the respective archive as prevailing winds affect charcoal transportation (Gardner and Whitlock, 2001). The validity of this assumption is also evident from large proportions of Andean forest pollen found in the pollen record of Laguna Potrok Aike (Fig. 4) though it is located approximately 80 km west of the present Andean forest line (Fig. 1). Due to the prevailing wind speeds in the "furious fifties" (Weischet, 1996) of southern Patagonia, where the southern westerlies reach their greatest strength (Heusser, 1995), a charcoal transport from the Andean forest might be conceivable.

Plume buoyancy is another factor influencing transport of particles and this is very much dependent on fire intensity (Clark and Patterson, 1997). As anemophilous *Nothofagus* pollen, which is the dominant representative of the Andean forest pollen taxa in the Laguna Potrok Aike record, is usually over-represented in pollen records (Markgraf et al., 1981), fires in dense *Nothofagus* forests have to be very large to be detected (Huber and Markgraf, 2003). An inverse correlation between charcoal and Andean forest pollen detected at Laguna Potrok Aike (Fig. 4) indicates that fires in the Andean forest were massive and plumes were very high enabling transport of larger charcoal particles to Laguna Potrok Aike, or fires in the surrounding of the lake happened at the same time as in the forest.

The mentioned fact that charcoal record and proportion of Andean forest pollen are inversely correlated in the Laguna Potrok Aike record is particularly visible in the charcoal fraction counted on pollen slides (Fig. 4). Due to the smaller size fraction on pollen slides, in contrast to the sieving method, the recorded charcoal is more likely to encompass large source areas and therefore allows the detection of regional trends more clearly (Carcaillet et al., 2001).

All this implies that locations of fires recorded in the Laguna Potrok Aike sediments were contemporaneously located in the Andean forest and thus Andean forest pollen decreased, as a grass-dominated assemblage in a period characterized by forest taxa might indicate a fire event. Nevertheless, the inverse correlation of pollen slide charcoal and Andean forest pollen could also be triggered exclusively by fires occurring in the steppe nearby. Those could trigger an enhanced steppe pollen production, following the fire event that led to a dilution of Andean pollen. One hint for that assumption may be an enhanced total pollen concentration coinciding with most charcoal peaks (Fig. 6). Hence, Andean forest pollen might show lower pollen values while actually contributing a constant absolute influx.

The most probable scenario seems to be a mixture of both processes, with different fire locations in the Andes as well as in the steppe, both recorded simultaneously in the sediments of Laguna Potrok Aike. A large number of separate fires in all different environments might have occurred simultaneously or within short time spans. In the 1995–96 wildfire season, for e.g., Patagonia was affected by approximately 500 fires (Cwielong, 1996). Eighty-two percent of the affected surface area corresponded to grassland (steppe). Second position was taken by fires in native forests, where also the most extensive wildfires happened (Cwielong, 1996). Only a few areas with shrubs and reforested areas were affected by fires (Cwielong, 1996). This recent pattern supports the assumption of a reduction of Andean forest pollen production by fires in the woodlands coinciding with an increased production and dispersal of steppe pollen after steppe fires.

4.7. Implications of the methods and interpretation for different charcoal accumulation rates in Laguna Potrok Aike and Río Rubens peat bog

The different charcoal accumulation rates in the records of Laguna Potrok Aike and Río Rubens (Fig. 3) are based on various reasons. First of all, samples were sieved with different mesh sizes (100 μm in Laguna Potrok Aike, 125 μm in Río Rubens peat bog). Due to the narrower mesh size used for Laguna Potrok Aike sample preparation, particles between 100 and 125 μm are supplementary in this record. Furthermore, there might be an accumulation effect in lakes by surface inflows or secondary deposition (Clark et al., 1998) that does not occur on peat bogs (Clark and Patterson, 1997) but episodically at Laguna Potrok Aike. Thus, the absence of this process at the Río Rubens peat bog could lead to a poor representation of local non-peat fires (Huber and Markgraf, 2003). Additionally, charcoal deposited on peat bog surfaces is not protected from redistribution by wind, which seems to be likely in Patagonia. In contrast, charcoal deposited in a lake is trapped by the water cover. Taking those considerations into account, charcoal of one fire event could have accumulated in lakes during more than 1 year (Whitlock and Anderson, 2003).

It is suspected that sediments from centers of lakes (where the presented cores were obtained from) overestimate particle production (Clark and Patterson, 1997). Peat is therefore expected to yield lower charcoal accumulation rates than lake sediments (Clark and Patterson, 1997). This would be a further explanation for higher charcoal values in the steppe lake Laguna Potrok Aike in contrast to Río Rubens bog. Due to prevailing westerly winds the steppe lake received charcoal from fires in the Andes as well as from steppe fires, while the Río Rubens site (Fig. 1) only recorded fires located in the woodlands or the steppe-forest ecotone. Hence, charcoal peaks present in Laguna Potrok Aike but not in Río Rubens peat bog probably represent fire events exclusively occurring in the steppe, but absent in the Andes.

5. Conclusions

Laguna Potrok Aike was influenced by European activities much earlier than the arrival of the first sheep farmers in southern Patagonia in the late 19th century. Though the charcoal peaks recorded from ca. AD 1840 onwards are possibly human induced, the presented data point to European impact at larger distances from the lake. In this context, the first appearance of *Rumex* is not believed to represent a local signal. At the beginning of the sheep farming in the late 19th century, disturbance gets obvious also in the vicinity of Laguna Potrok Aike lasting until today.

Limnological changes during the late 18th and early 19th century are believed to be the result of rising temperatures and accompanying changes in wind strength, probably marking the end of the Little Ice Age. Nevertheless European impact might have supported the changes.

The charcoal record of Laguna Potrok Aike seems to reflect fires in the steppe that coincided with fires in the Andean forest. As values for charcoal from the steppe lake Laguna Potrok Aike are generally higher and show more fire events than the Río Rubens peat bog record, it is assumed that steppe fires were more frequent and enlarged the contribution of charcoal to the lake. In general, fire events recorded in Laguna Potrok Aike are accompanied by fluvial erosion. The fire event around AD 1600 seems to be triggered by dry conditions in the Andes causing favorable fire conditions in the forest and the steppe-forest ecotone and after a wet period in the steppe.

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