

# Mires and mire types of Peninsula Mitre, Tierra del Fuego, Argentina

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## SUMMARY

In 2007, a field visit by members of the International Mire Conservation Group (IMCG) to the Atlantic coast of Peninsula Mitre (the easternmost part of Isla Grande de Tierra del Fuego, Argentina) gathered information on mire diversity in this remote wild area with largely pristine mires. Our expedition showed that Peninsula Mitre hosts a wide variety of habitats across two exciting ecological gradients: (i) a regional west–east gradient from *Sphagnum magellanicum* dominated mires in the west to *Astelia pumila* dominated mires in the east; and (ii) a gradient from extremely acid to extremely carbonate rich mire types induced by local bedrock. The large variety of hydromorphological mire types comprises raised bogs, blanket bogs, sloping fens, string fens, flat fens and calcareous spring fens. In the Atlantic coastal area, the abundance of *Sphagnum magellanicum* in the ombrogenic systems decreases conspicuously from west to east with the species being almost absent in the east. However, the fossil record shows thick layers of *Sphagnum* peat close beneath mire surfaces everywhere, indicating that substantial hydrological and ecological changes have taken place in the recent past. We observed large scale erosion in the mires along the Atlantic coast. Locally, well-developed fen systems are present, including calcareous spring fens with active travertine (tufa) deposition.

The regional vegetation can be regarded as a parallel to that of boreal oceanic regions in the northern hemisphere. The mires and peatlands of the peninsula are of global significance. They are impressive, peculiar, extensive and largely pristine mires in a globally very rare climatic and biogeographical context embedded in a landscape with significant natural dynamics. The damaging impact of free-roaming cattle on the mires and upland vegetation is, however, conspicuous and needs urgent attention. Peninsula Mitre deserves the highest possible protection, e.g. as a provincial protected area and a World Heritage Site.

**KEY WORDS:** *Astelia pumila*; hydrology; land uplift; Patagonia; peatland; *Sphagnum magellanicum*; travertine

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## INTRODUCTION

The mires of Tierra del Fuego represent 95 % of the peatlands of Argentina (Rabassa *et al.* 1996) and are increasingly threatened by peat extraction (Iturraspe & Urciuolo 2004). The landscape of the eastern part of Isla Grande de Tierra del Fuego is dominated by mires. Peninsula Mitre roughly consists of the area east of the Río López, with the Irigoyen River as its north-western limit (Figure 1). According to Iturraspe *et al.* (2013), mires cover 2,394 km<sup>2</sup> or 45.3 % of this area and more than 80 % of several of its eastern catchments. Peat mining has not been carried out in Peninsula Mitre due to lack of roads, and new provincial land use policies exclude this territory from the area available for new peat mining permissions. However, these mires are threatened by other factors which are explained below.

Climatic conditions in Peninsula Mitre are not well known, but an impression can be gained by comparing meteorological data from Río Grande (to the north) and Ushuaia (to the west). Mean annual temperature is 5.5 °C in both of these locations. In Río Grande, mean January temperature is 10.8 °C and mean July temperature is -0.4 °C. The corresponding figures for Ushuaia are 9.1 °C and 1.2 °C. Annual precipitation may range from less than 600 mm to more than 1000 mm, depending on proximity to mountain ranges (Auer 1965, Tuhkanen *et al.* 1990, Iturraspe *et al.* 2013), and there is evidently a precipitation gradient along the Atlantic coast from west (less than 600 mm) to the wetter east, due to the increasing penetration of wet, oceanic air masses from the south and south-west (Rabassa *et al.* 2006). There is no corresponding temperature gradient along the coast.

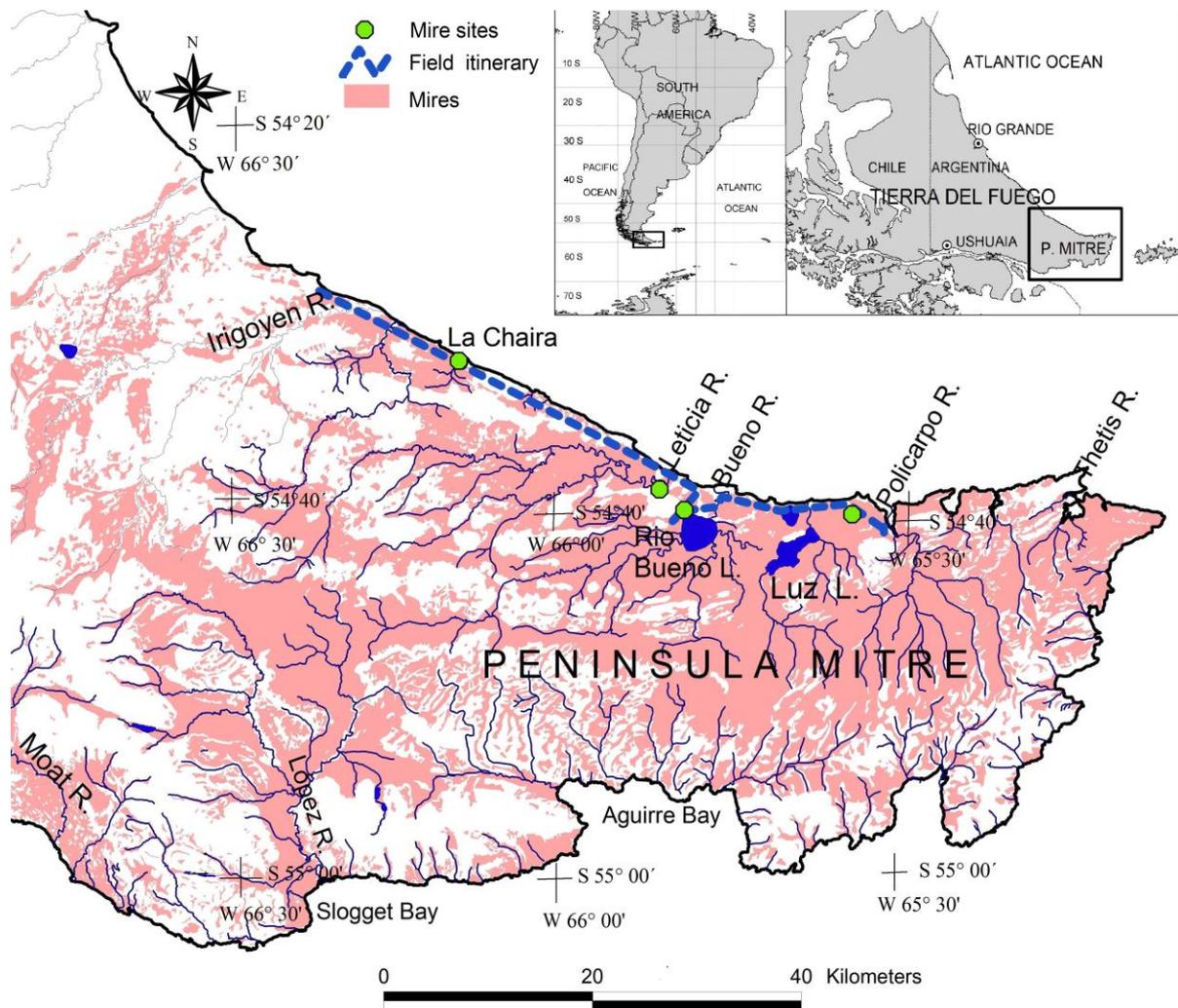


Figure 1. The mires (pink) of Peninsula Mitre in the eastern part of Isla Grande de Tierra del Fuego. Peatland areas mentioned in this paper are indicated by green dots (from west to east: La Chaira mires, Leticia mires, Lago Rio Bueno mires and Policarpo mires).

The vascular flora of Tierra del Fuego is rather poor compared to other temperate and boreal regions (Moore 1983). Forests (35 % of the Argentinean part of Tierra del Fuego; Collado 2001) are basically formed by three *Nothofagus* species. Most forests in Peninsula Mitre (total cover 41 %) are mixed and consist of deciduous *Nothofagus pumilio*, evergreen *N. betuloides* and also *N. antarctica*. *N. pumilio* dominates the northern coast, and *N. betuloides* the southern coast (Romanyà *et al.* 2005). In the wetter southern parts of Peninsula Mitre, *Drimys winteri* may also be abundant. The poorness of the flora is also illustrated by the number of *Sphagnum* species, of which only three occur in Tierra del Fuego (compared to about 50 species in analogous parts of boreal Europe, Flatberg 2002). *Sphagnum magellanicum* is by far the most abundant and

widespread *Sphagnum* species, giving many Fuegian mires their characteristic red appearance. *Sphagnum fimbriatum* is rather common and occurs in minerogenous fens. *Sphagnum falcatulum* (*S. cuspidatum* coll.) can be found in wet carpets and pools in ombrogenous and poor fen vegetation (Kleinebecker *et al.* 2007, 2010).

Various scientists and expeditions working in Tierra del Fuego have produced a voluminous literature, with 900 titles being listed by Tuhkanen *et al.* (1990). However, few studies have been performed in Peninsula Mitre. For example, the large monograph on mires in Tierra del Fuego by Roivainen (1954) does not include any localities in Peninsula Mitre. As a result, little is known about the mires and mire types of this area (cf. Figure 2), although we might expect that they remain largely undisturbed.

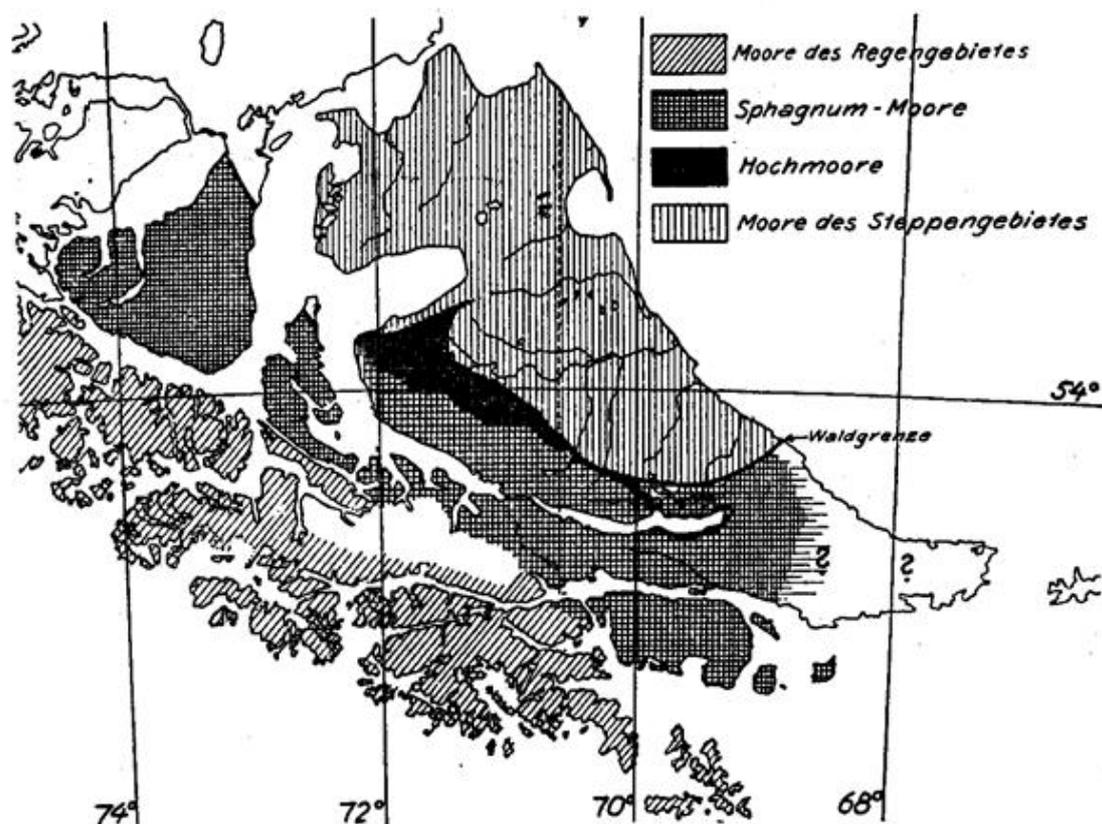


Figure 2. Map of the mire types of Tierra del Fuego after Auer (1941), which shows conspicuous question marks in Peninsula Mitre.

To the west of Peninsula Mitre, large and well-developed raised bogs dominated by *Sphagnum magellanicum* are present in the valleys between the mountains (Grootjans *et al.* 2010). To the southwest, around Moat, blanket bogs dominated by cushion plants like *Astelia pumila* and *Donatia fascicularis* illustrate the proximity of the 'Magellanic Moorland' (Moore 1983) in the extreme west and south of the region, which is more exposed to the harsh ocean winds. The *Astelia* cushion bogs in this area seem to be relatively recent: Heusser (1995) showed that *Astelia pumila* invaded the Moat area *ca.* 2600 years ago, probably as a result of climate change, and that the mire was previously dominated by *Sphagnum magellanicum*.

Because Peninsula Mitre is remote and roadless, we might expect to find that its mires are rather pristine. However, it is likely that human activities have changed the landscape to some degree. Fifty years ago, several farms were engaged in sheep breeding and logging, but nowadays logging of forest is prohibited and human activities have shifted to the west where better infrastructure is available. In the north-west, south of Río Ingoyen and 30 km west of La Chaira, active forest logging

is still in progress. Cattle raising and other farming activities occurred in Bahía Aguirre (southern Peninsula Mitre) until 2004. Along the Atlantic coast, real farms are no longer operational but more than 15,000 cows and a few hundred horses still roam freely, monitored by 3–4 gauchos who are semi-permanent residents. Every year several hundred cows and some dozens of horses are rounded up, driven to Estancia Maria Luisa (near the west bank of the Irigoyen River) and sold. Also, 25 pairs of Canadian beaver (*Castor canadensis*) were introduced to Tierra del Fuego in 1946 and the population has now expanded to more than 100,000 animals (Lizarralde *et al.* 2004), which have a large impact on the landscape. Beavers arrived in Peninsula Mitre *ca.* 1970 (Anderson *et al.* 2009).

In March 2007, members of the International Mire Conservation Group (IMCG) made a ten-day expedition on horseback along the Atlantic coast of Peninsula Mitre to gather information on the diversity of mires, in order to inform provincial plans to improve the protection of the area (Loekemeyer 2002). In this article we describe some characteristics of the range of mire types that were encountered.

## METHODS

We studied four mire areas in the Atlantic coastal zone, namely: La Chaira, Leticia River, Río Bueno Lake and the western margin of Policarpo River. Different mire types were distinguished on the basis of vegetation composition and landscape hydrology. Nomenclature follows Moore (1983) for vascular plant species and Matteri (2003) for bryophytes.

Peat cores were collected with an Eijkelkamp chamber auger, inspected and described in the field, then wrapped for transport.

Electrical conductivity (EC25 in  $\text{mS m}^{-1}$ ), indicating total dissolved minerals, was measured in surface water with a WTW-Retch conductivity meter. Water samples from open water bodies were acidified and stored in PVC bottles at 4 °C in the dark until analysis in the laboratory. Ca, Mg, Si, and total S were measured using Inductive Coupled Plasma - Optic Emission Spectrometry (ICP-OES; Techno Electron Cooperation). Na and K were measured with a flame photometer (Technicon Flame Photometer IV Control). Chloride was measured colorimetrically using a Bran+Luebbe AutoAnalyser 3.

## RESULTS

### Analysis of surface water

The pool waters of mires interpreted as (ombrogenous) bogs indeed showed very low concentrations of dissolved minerals compared to surface water from (minerogenous) fens and spring systems. Most of the bog water samples had higher concentrations of magnesium than of calcium. Sodium and chloride concentrations in bog water collected from exposed areas close to the sea were higher than in bog water sampled in more sheltered areas that were probably less impacted by salt spray (Table 1).

Spring water had high concentrations of calcium, sulphur and silicon. Silicon appears to be a good tracer for water that has been in contact with the mineral substrate. The water sample from Lago Río Bueno bog 2, which is situated close to a river floodplain, had high concentrations of magnesium, sodium and chloride, indicating that the river sometimes floods the bog vegetation with brackish water. Most rivers in the coastal area are under tidal influence, and brackish water may regularly enter their floodplains.

Table 1. Composition of surface water samples ( $\mu\text{mol L}^{-1}$ ) in various fens and bogs in Peninsula Mitre.

Site	<i>Lat. S</i>	<i>Long. W</i>	Ca	Mg	Si	K	Cl	Na	S
Lago Río Bueno bog 1	54° 40' 04"	65° 35' 36"	28.37	24.32	0.00	2.29	227.23	190.95	14.19
Lago Río Bueno bog 2	54° 40' 28"	65° 49' 44"	51.18	63.28	0.00	4.09	665.91	566.34	37.86
Lago Río Bueno bog 3	54° 40' 28"	65° 49' 44"	16.48	9.84	0.00	0.73	110.33	86.82	2.30
Lago Río Bueno bog 4	54° 39' 69"	65° 47' 92"	19.29	26.57	0.00	1.15	308.97	167.81	12.66
Lago Río Bueno bog 5	54° 39' 69"	65° 47' 92"	26.40	31.79	0.00	4.12	337.54	272.25	12.91
Lago Río Bueno bog 6	54° 39' 24"	65° 47' 27"	35.23	58.34	0.41	5.88	679.61	512.84	13.27
Lago Río Bueno bog 7	54° 39' 70"	65° 47' 87"	31.09	39.00	0.63	2.38	434.59	346.85	7.99
Lago Río Bueno lake	54° 40' 40"	65° 49' 47"	36.53	29.53	0.19	6.75	318.85	295.04	19.17
Lago Río Bueno spring	54° 40' 22"	65° 49' 54"	725.59	120.02	76.77	15.21	1135.68	904.75	50.43
Lago Río Bueno spring	54° 39' 77"	65° 48' 22"	704.63	184.20	133.38	13.22	751.28	910.40	103.79
Lago Río Bueno fen	54° 40' 23"	65° 49' 51"	276.71	38.89	14.09	5.90	317.04	288.87	8.31
Río Bueno flood plain	54° 40' 51"	65° 46' 94"	187.81	371.94	14.85	47.78	2021.43	1915.20	28.13
Leticia bog	54° 39' 08"	65° 51' 22"	45.99	63.98	0.00	4.23	686.69	531.54	16.85
La Chaira fen	54° 33' 87"	66° 10' 17"	44.96	82.58	2.12	5.37	769.70	569.82	16.41
La Chaira bog	54° 33' 87"	66° 10' 17"	32.59	50.11	0.15	5.51	459.69	354.81	13.14

### La Chaira mires

Puesto La Chaira is the easternmost permanently inhabited settlement along the coast. The mires in this vicinity form an extensive mire landscape dominated by flat and gently sloping poor fen ecosystems (Figure 3). Locally, these mires have numerous pools separated by narrow dry strips (Figure 4). Sloping fens (slope 3–8 degrees) occur at the bases of the hills and in other locations that are connected to springs.

At a small bog massif south of the Puesto (54° 33' 46" S, 66° 09' 16" W), coring revealed 2.5 m of slightly decomposed *Sphagnum* peat overlying a 5 cm thick orange-yellow tephra layer which, in turn, covers an additional 5–10 cm of peat over clay. The clay contains coarse sand and gravel at larger depths. The 15 cm of peat immediately above the tephra layer is very strongly humified.

Poor fen vegetation dominates the large mire landscape. Common species in lawns and carpets are *Azorella filamentosa*, *Caltha appendiculata*, *C. dionaeifolia*, *Carex magellanica*, *Chilotrichum*

*diffusum*, *Empetrum rubrum*, *Marsipospermum grandiflorum*, *Rostkovia magellanica* and *Tetroncium magellanicum*. Vigorously growing *Sphagnum magellanicum* hummocks are common, but only in sheltered places. In most of the mire complex peat growth seems to be stagnating. *Sphagnum fimbriatum* is extensive in areas influenced by surface water.

Spring fens occur at the mire margin, towards the surrounding hills. The water here has pH 6.8 and EC 32 mS m<sup>-1</sup>. The most typical components of the rich fen and spring vegetation are the dominant brown mosses which include species of *Bryum*, *Calliergon*, *Campylium*, *Cratoneuron* and *Drepanocladus*. Characteristic vascular plant species are *Caltha sagittata*, *Gentianella magellanica*, *Koenigia islandica*, *Primula magellanica* and *Scirpus* cf. *cernuus*.

Rich fen vegetation is also present in the centre of the mire complex. At first sight, the presence of fens fed by calcareous groundwater in the middle of the poor fen is surprising. Apparently, water

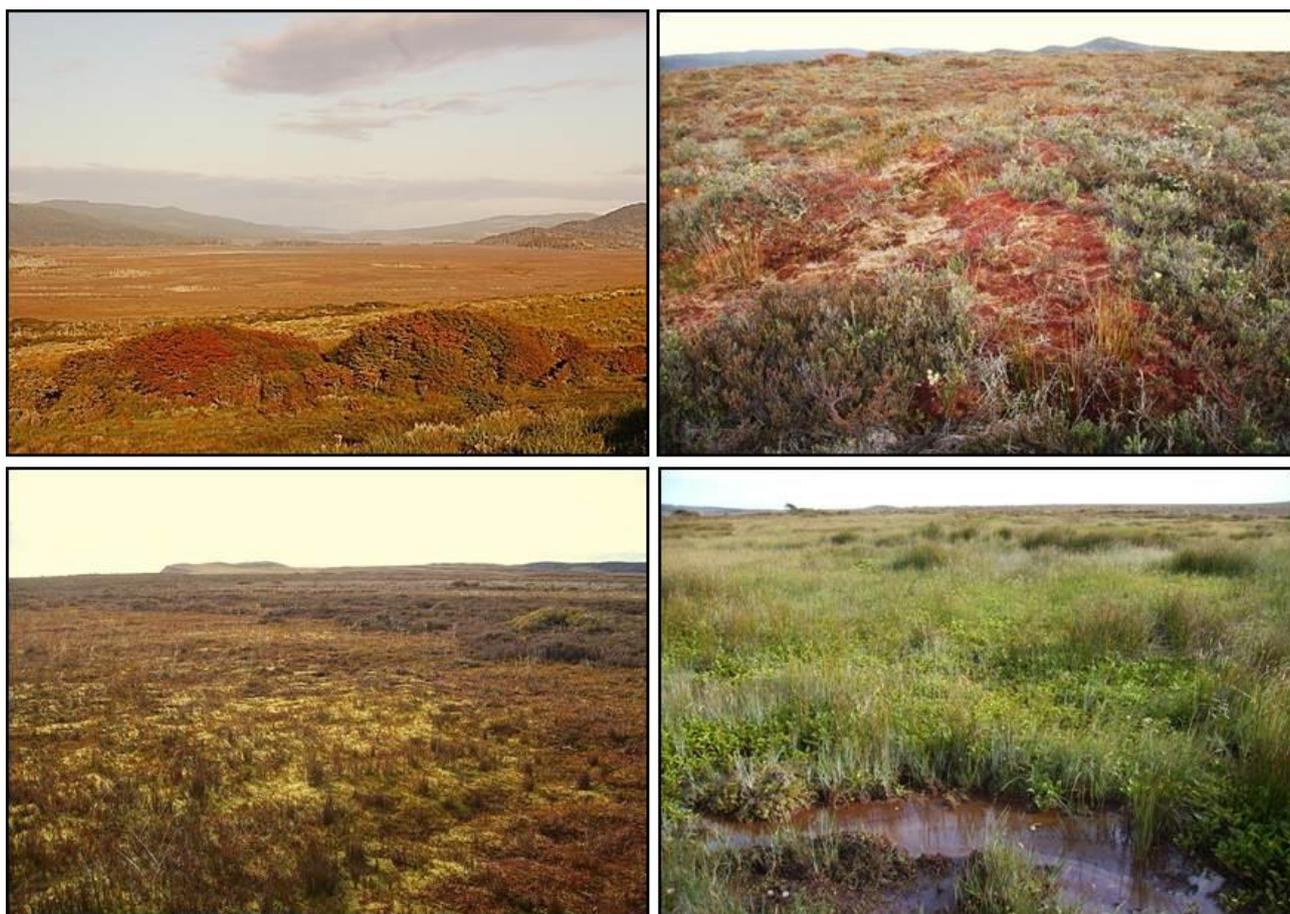


Figure 3. General view of the La Chaira mires (top left). *Sphagnum magellanicum* is the dominant species of low hummocks (top right). Growing carpets of *Sphagnum fimbriatum* indicate shallow flowing water within the large mire (bottom left), and *Caltha sagittata* is dominant where iron-rich groundwater discharges in the centre of a large mire complex (bottom right).

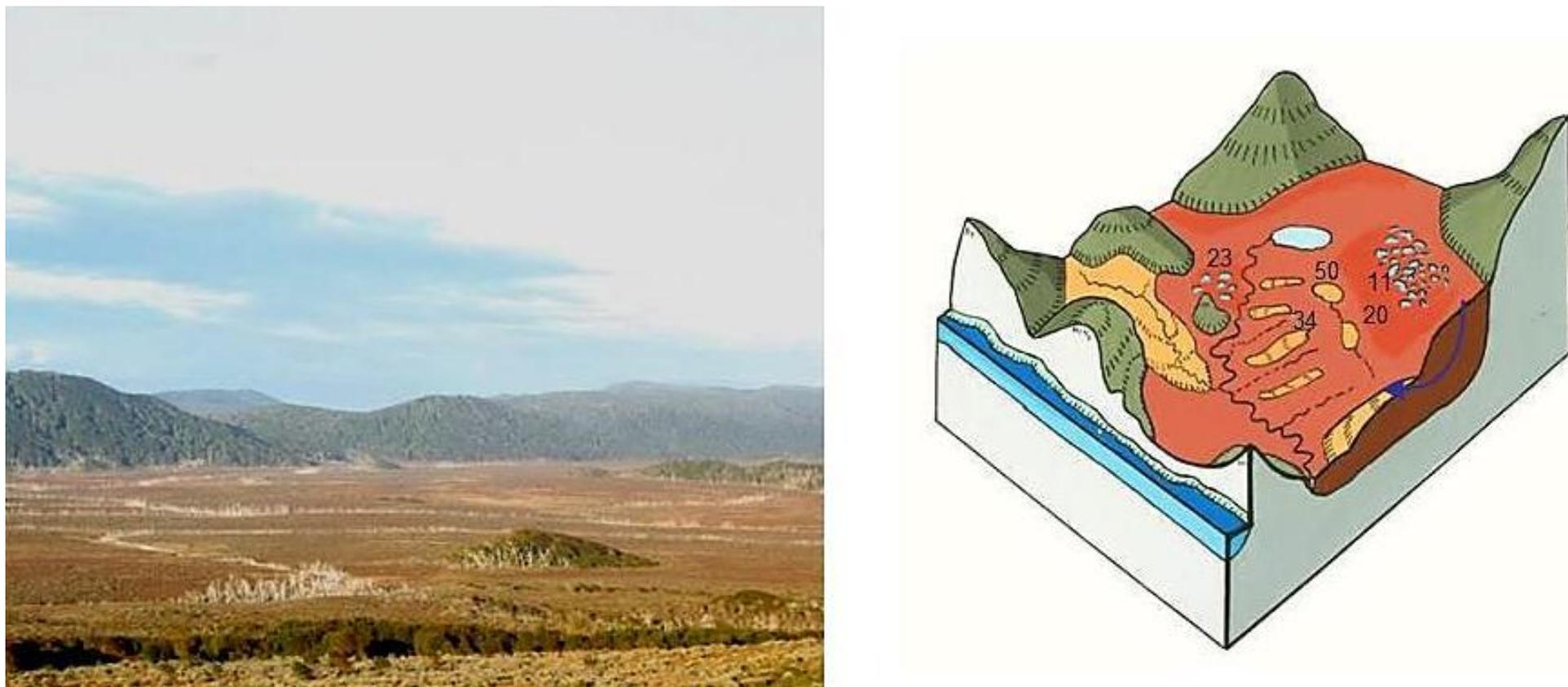


Figure 4. Overview (left) and schematic drawing (right) of the La Chaira mires. Digits show EC values ( $\text{mS m}^{-1}$ ) measured in surface water on 20 March 2007. Red: *Sphagnum magellanicum* dominated mire; orange: percolating fen, mainly rich fen vegetation; light blue: open water; dark blue: sea; grey/green: forest.

infiltrating from the surroundings of the mire complex has found a way to exfiltrate in the middle of the mire. This water is very rich in iron and calcium and has an electrical conductivity of more than  $50 \text{ mS m}^{-1}$ . *Caltha sagittata* is the dominant plant species in such seepage windows.

### Leticia mires

The mires in Leticia are very diverse and consist of raised bogs, flat and gently sloping fens and calcareous spring mires (Figure 5). A large eccentric bog has irregular interconnected pools many tens of metres long (with *Sphagnum falciculatum* and hepatics) that separate ‘strings’ dominated by *Azorella filamentosa*, *Empetrum rubrum* and *Caltha dionaeifolia*. The bog is intersected by the large Leticia River, which cuts deeply into the sediments.

The difference in water level between the pools and the river is more than four metres. This difference has generated deep erosion gullies near the river. Farther away, the small streams that transport calcareous groundwater from the

surrounding hills have dropped below the peat surface, a phenomenon called ‘soil piping’. In the centre of the bog the uppermost 5 cm of peat is strongly humified, and below this we found 3 m of slightly humified *Sphagnum* peat, 60 cm of radicle (sedge) peat and, at the bottom, very humus-rich fine clayey sand (total depth cored: 367 cm).

Especially near the margins of the mire, we found many rather fresh cadavers of cows that had drowned on the peatland.

Fen systems occur between and at the bases of the hills, which supply them with groundwater. Two calcareous spring complexes with active travertine deposition (Figure 5) have developed in seepage areas fed by calcareous groundwater which has passed through carbonate rocks such as limestone, marl, grain stone and calcareous sandstone (Río Bueno Formation, Eocene; Olivero *et al.* 2002). The groundwater emerging from the springs rapidly releases dissolved  $\text{CO}_2$  when it loses pressure in contact with the atmosphere and, as a result,  $\text{CaCO}_3$  is deposited on the mire surface (Pentecost 2005).

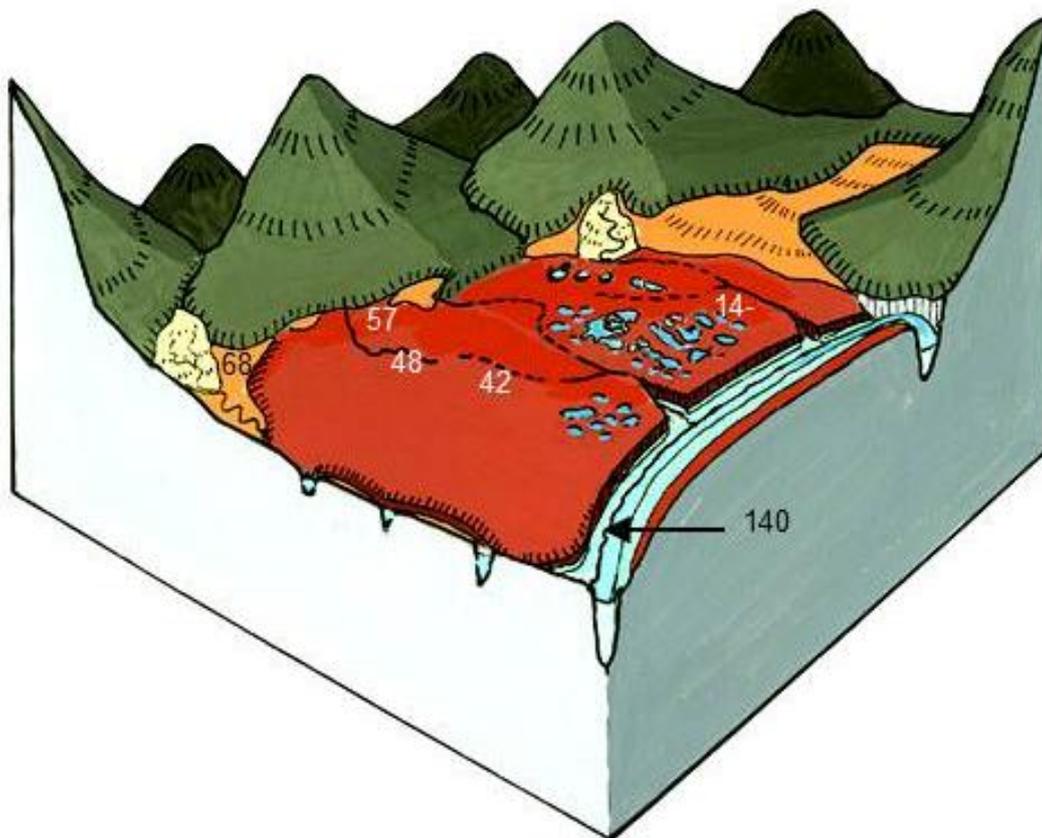


Figure 5. Schematic drawing of the Leticia mires with eccentric raised bogs dominated by *Sphagnum magellanicum* and well developed fen systems. There are two calcareous mires with active precipitation of travertine at the side of the valley. The bogs have many local pools, separated by areas of short cushion plant and *Sphagnum* vegetation. Several deep drainage channels stimulate below-ground pipe flow (‘soil piping’). Digits show EC values ( $\text{mS m}^{-1}$ ) measured in surface water on 18 March 2007. Red: bogs; orange: groundwater fed fens; yellow: calcareous (travertine) mires; grey/green: forest; light blue: Leticia River.



Figure 6. General view of the Leticia mires with numerous irregular elongated pools forming an eccentric pattern in the foreground and the Leticia River approaching from the east (top left). Most pools in flatter parts of the mire are interconnected (top right). At the bases of the surrounding hills, several calcareous mires actively precipitate travertine ( $\text{CaCO}_3$ ) (bottom left). The numbers superposed on this picture indicate the electrical conductivity of the surface water in  $\text{mS m}^{-1}$ . In the wettest parts of such calcareous mires, travertine deposits on the leaves of *Chara* plants give them a green-grey appearance (bottom right).

The EC measurements in the small rivulets reflect this process: going downstream, EC values drop quickly from 60–75  $\text{mS m}^{-1}$  near the bases of the hills (Figure 6, bottom left) to 40–50  $\text{mS m}^{-1}$  near the large river. The EC of the water in the large river is high ( $>140 \text{ mS m}^{-1}$ ), indicating that salt water from the sea enters the river at high tides.

#### Lago Río Bueno mires

The lake (Lago Río Bueno) is named after the river Río Bueno, which flows through the lake and empties into the Atlantic Ocean. Puesto Río Bueno, a cabin where our guide Ruben lived, is situated near the mouth of the river on a dry plain of raised beach pebble ridges with *Bolax gummifera*, much *Gunnera magellanica*, *Blechnum penna-marina*, *Azorella filamentosa* and *Abrotanella emarginata*.

The lowlands surrounding Río Bueno Lake are

dominated by a mosaic of mires and small lakes (Figure 7). Water bodies cover 22 % of the area (Iturraspe *et al.* 2013). The landscape consists of many mire complexes separated by rivulets, forested slopes and open hills. Raised bogs with marked features, along with flat and gently sloping fens (up to 10 degrees of slope), cover large areas. A few spring fens occur.

*Sphagnum magellanicum* is present in narrow fringes around the numerous pools and in small depressions, where it is often pale and submerged. *Astelia pumila* occurs as scattered patchy dense cushions together with *Caltha dionaeifolia*, *Drosera uniflora*, *Empetrum magellanicum* and *Tetroncium magellanicum*. *Astelia* is most common close to pools and in some highly exposed (to wind) patches close to the sea. A local patch (2 × 3 m) with *Astelia* (54° 39' 42" S, 65° 47' 56" W) appeared to have

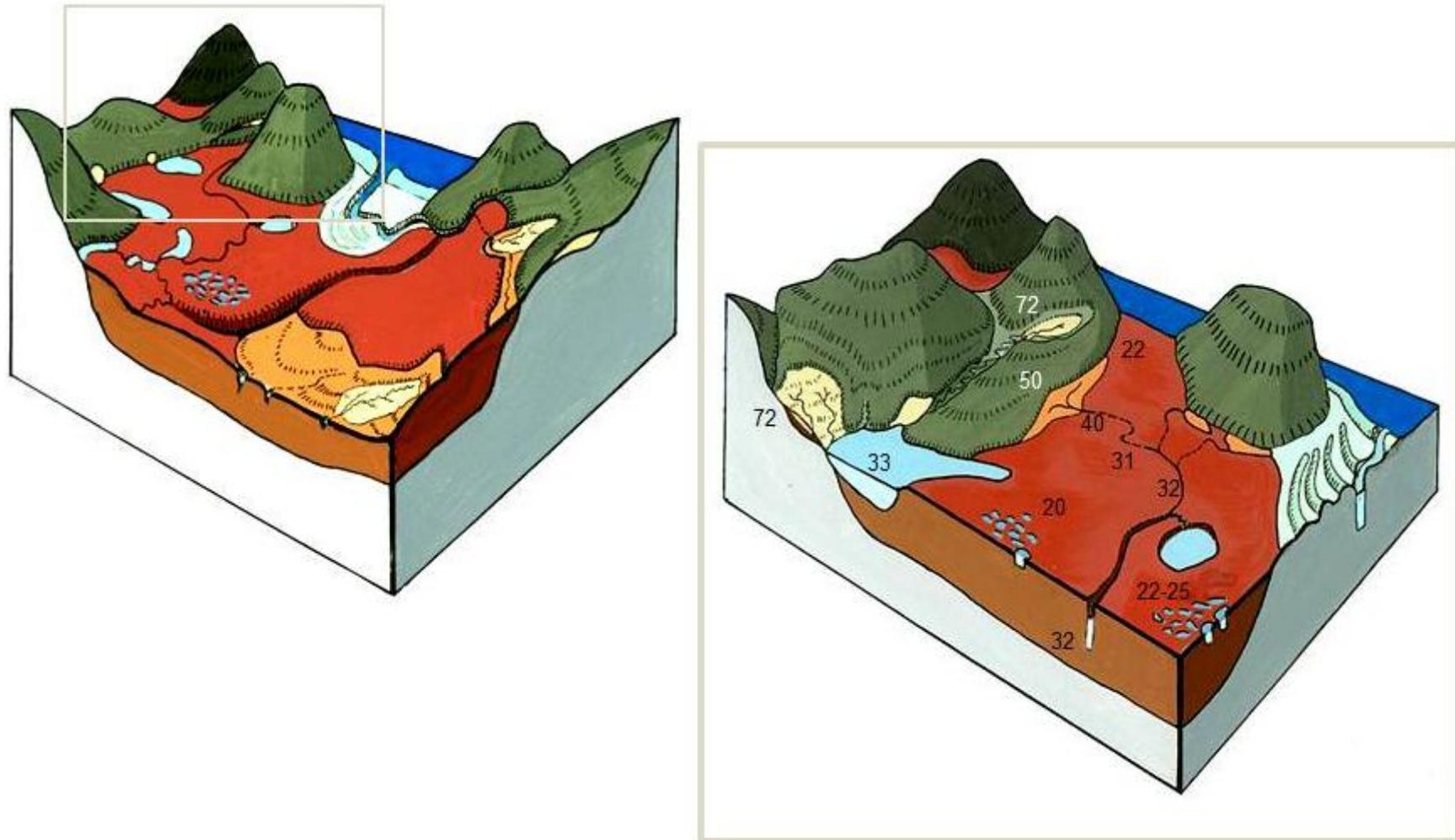


Figure 7. Schematic drawings of the mires west of Lago Río Bueno. The drawing on the right represents the part of the left-hand diagram that is enclosed within the grey square. Digits show EC values ( $\text{mS m}^{-1}$ ) measured in surface water on 14 March 2007. The *Sphagnum magellanicum* bogs have local pool complexes, but are rather dry due to drainage by deep erosion channels and soil piping. A notable feature is the occurrence of well-preserved calcareous fens with active travertine deposition on the slopes of the mountains. Red: *Sphagnum magellanicum* bogs; orange: groundwater fed fens; white: calcareous fens with active travertine deposition; light blue: open water; dark blue: sea; grey/green: forest; light areas along the river: flooded grasslands with ancient beach shores consisting of overgrown pebble shorelines.

only superficial *Astelina* peat (< 35 cm) underlain by almost five metres of typically ‘zebra’ striped *Sphagnum* peat (cf. Figure 10), 70 cm of sedge radicle peat, and clay from 5.70 to 6.00 m (end of coring). Thus, the peat stratigraphy shows that *Sphagnum magellanicum* dominated the mire for thousands of years. The uppermost 50 cm of *Sphagnum* peat contains a dense network of *Astelina* roots which may be instrumental in introducing oxygen to the waterlogged soil.

Extremely rich (calcareous) fens were noted west of Puesto Río Bueno. Their vegetation is dominated by small tussock-forming sedge species, and brown mosses are present in the bottom peat layer (Figure 8). Tufa (travertine) is deposited on the leaves of *Chara* species in the pools.

We found three calcareous mires that were well preserved, two that were severely damaged by cows and one that was completely destroyed by cows, exposing the travertine. Coring in one of the damaged mires, we found peat below a superficial travertine layer 80 cm thick, indicating that

travertine deposition is a rather recent phenomenon at that location.

Around Lago Río Bueno we found a broad zone that has apparently been affected by a conspicuous lowering of the lake level. The vegetation here consists of *Empetrum rubrum*, *Marsippospermum grandiflorum*, *Rostkovia magellanica* and *Caltha dionaeifolia*. Parts of the lake seem to have dried out completely and new mire vegetation has developed over the former lake floor. Other signs of lake drainage include long cracks parallel to the lake shore (that have been refilled with peat-forming vegetation), older and newer ‘bog bursts’ at the shore of Lago Bueno (Figure 10) and the phenomenon that small pools close to the lake have merged to form larger ones, lowering water levels and exposing bare peat in the pools upstream. Some low-lying areas adjacent to Lago Bueno (with *Sphagnum fimbriatum*, *Marsippospermum* and *Calamagrostis stricta*) appear to be former large pools and river courses that have been truncated and drained during westward expansion of the lake.



Figure 8. Tertiary limestone outcrops (with local *Drimys winteri* and *Berberis darwinii* forests) are present high in the landscape in the Lago Río Bueno area (top left). Downslope, a calcareous fen actively deposits travertine in the pools (top right). Many calcareous fens have been degraded by cattle that trample the vegetated top layer (bottom left). We often found peat beneath the travertine layers (bottom right).

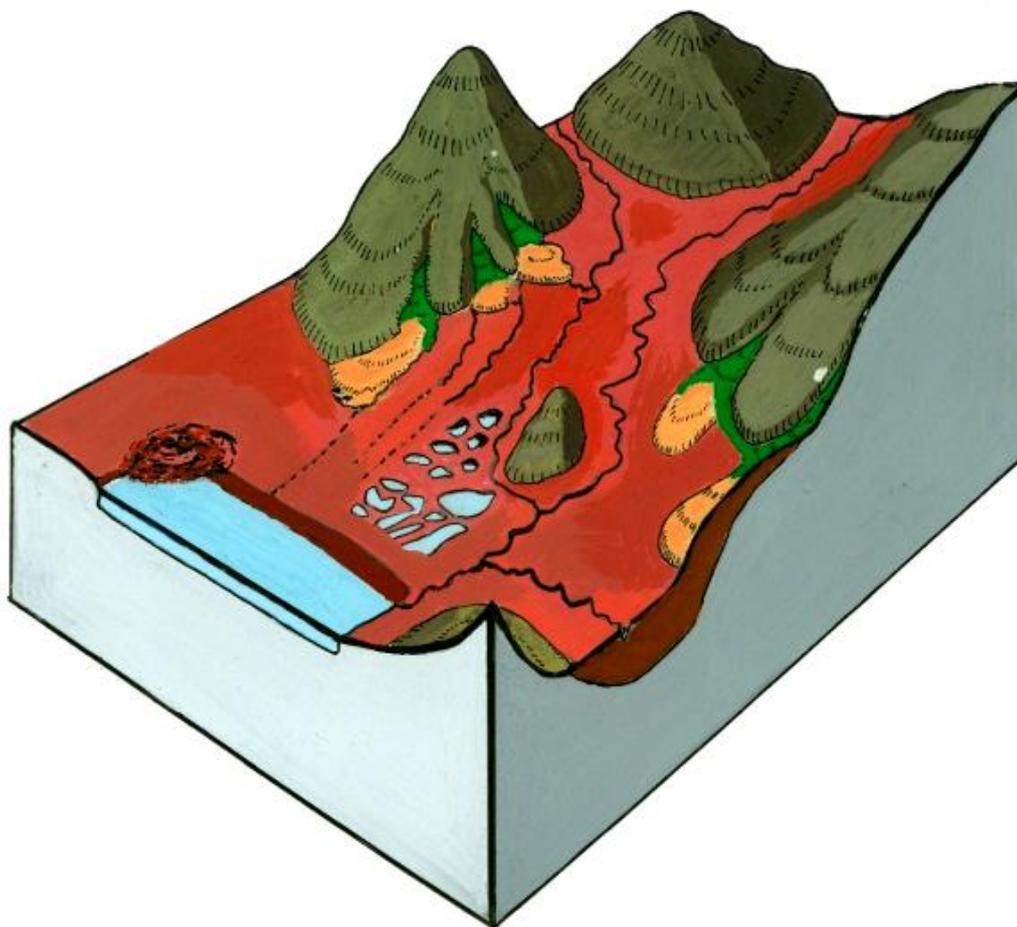


Figure 9. Schematic drawing of the southern part of Lago Río Bueno mires, with extensive *Sphagnum magellanicum* bogs interspersed with many rivulets flanked by elongated fens. Pools are present only close to, and increasing in size towards, the lake. Most bogs are rather dry due to drainage by erosion channels and soil piping (indicated by dotted lines). Digits show EC values ( $\text{mS m}^{-1}$ ) measured in surface water on 13 March 2007. Red: *Sphagnum magellanicum* bogs; orange: groundwater fed fens; green: forested mires at the bases of the hills; light blue: open water; grey/green: forest.

Furthermore, we observed ‘soil piping’, with small streams disappearing suddenly into the peat and continuing over a less permeable (‘stagnating’) layer, usually of clay, at the base of the peat. Soil piping is triggered when the hydrological gradient is too steep and the water starts eroding the peat (Holden *et al.* 2009). A coring 30 m west of the lake shore ( $54^{\circ} 39' 053''$  S,  $65^{\circ} 51' 159''$  W) revealed 15 cm of strongly humified peat with ericaceous roots at the surface, underlain by 150 cm of banded *Sphagnum* ‘zebra’ peat, 100 cm of gyttja-rich *Tetroncium* peat, 5 cm of radicle peat and 150 cm of white clay.

East of Lago Río Bueno, much erosion and large pools interconnected by broad, winding gullies up to 4 m deep make access to the *Empetrum*-rich

peatlands virtually impossible (see Figure 11). Other components of the vegetation are *Caltha dionaeifolia*, *Tetroncium magellanicum*, *Rostkovia magellanica*, *Caltha appendiculata*, *Uncinia lechleriana*, *Oreobolus obtusangulus*, abundant lichens including *Icmadophila* cf. *ericetorum*, and local cover of *Rhacomitrium lanuginosum* on some high hummocks. Here, beneath a humified root zone (8 cm thick) at the surface, a 330 cm thick layer of slightly humified *Sphagnum* ‘zebra’ peat is underlain by 65 cm of root/radicle peat. From 395 cm to 430 cm depth (end of coring) we found clay grading into silty clay with a decreasing content of rootlets. Living *Caltha* roots are conspicuous in the *Sphagnum* peat up to a depth of 100 cm ( $54^{\circ} 39' 738''$  S,  $65^{\circ} 46' 057''$  W).



Figure 10. General view of the mires bordering Lago Río Bueno to the south and east (top left). Close to the wooded hills, a small stream that rises in the fens at the base of the hill creates a very diverse gradient perpendicular to the stream, with rather calcareous groundwater in the stream and acid bog water within one metre (top right). The stream disappears into peat near the lake, due to soil piping (Figure 9). The water level in the lake is now much lower than in the surrounding bog, and this has created local ‘bog bursts’ (breakdown of sections of the peat; bottom left). Steep peat cliffs more than three metres high expose the ‘zebra’ pattern of lighter and darker layers, typical for Fuegian *Sphagnum magellanicum* peat, that reflects wetter and drier conditions for bog growth (Mauquoy *et al.* 2004) and is possibly caused by autogenic movement of ridges and hollows (Couwenberg & Joosten 2005) (bottom right).



Figure 11. General views of large ponds in the Lago Río Bueno area. Some of these result from damming of spring rivulets by beavers. The water floods the mire and the neighbouring forested slope, killing *Nothofagus* trees nearby.

**Policarpo mires**

Between Luz Lake and Policarpo River, *Astelia pumila* becomes much more prominent and *Sphagnum magellanicum* is practically absent at the present time. The landscape is dominated by extensive *Astelia pumila* mires with *Bolax gummifera*, *Caltha dionaeifolia*, *Azorella filamentosa*, *Tetroncium magellanicum* and locally dominant *Carpa alpina*. The most striking feature of the Policarpo mires is the abundance of lakes and extensive pools, which are separated by clear green blankets of *Astelia*. The smallest pools are situated relatively high in the mire landscape (Figure 12). Small pools at lower altitudes merge to form larger ones with lower water levels, leading to rapid discharge of surface water, partly by pipe flow. The largest lakes are situated close to the sea, although very large lakes also occur inland. Soil piping is pronounced in this landscape, with half-open tunnels sometimes running four metres below the mire surface.

The peat stratigraphy (65° 35' 777" W, 54° 40' 018" S) consists of 20 cm of *Tetroncium* peat with living *Caltha* roots, 70 cm of moderately humified fibrous radicle peat with some wood, 75 cm of slightly humified *Sphagnum* peat with radicle-rich mud bands and Ericaceae rootlets, 35 cm of muddy radicle peat with some wood and *Tetroncium* seeds, 265 cm of very muddy strongly decomposed peat with radicels and some wood, below which the strongly decomposed peat becomes gradually more sandy and, from 480 cm depth, also contains gravel. From 500 cm, the deposit is a sandy/silty clay with some gravel (cored to 507 cm depth).

The lack of dense root systems makes the strongly decomposed (and poorly structured) peat susceptible to erosion. When the peat dries out, lichens often form dense carpets. This vegetation type offers little resistance to water flow and easily gives way when the water pressure in the lakes becomes too high. Such breaches trigger peat erosion and expose extensive mud flats (Figure 13).

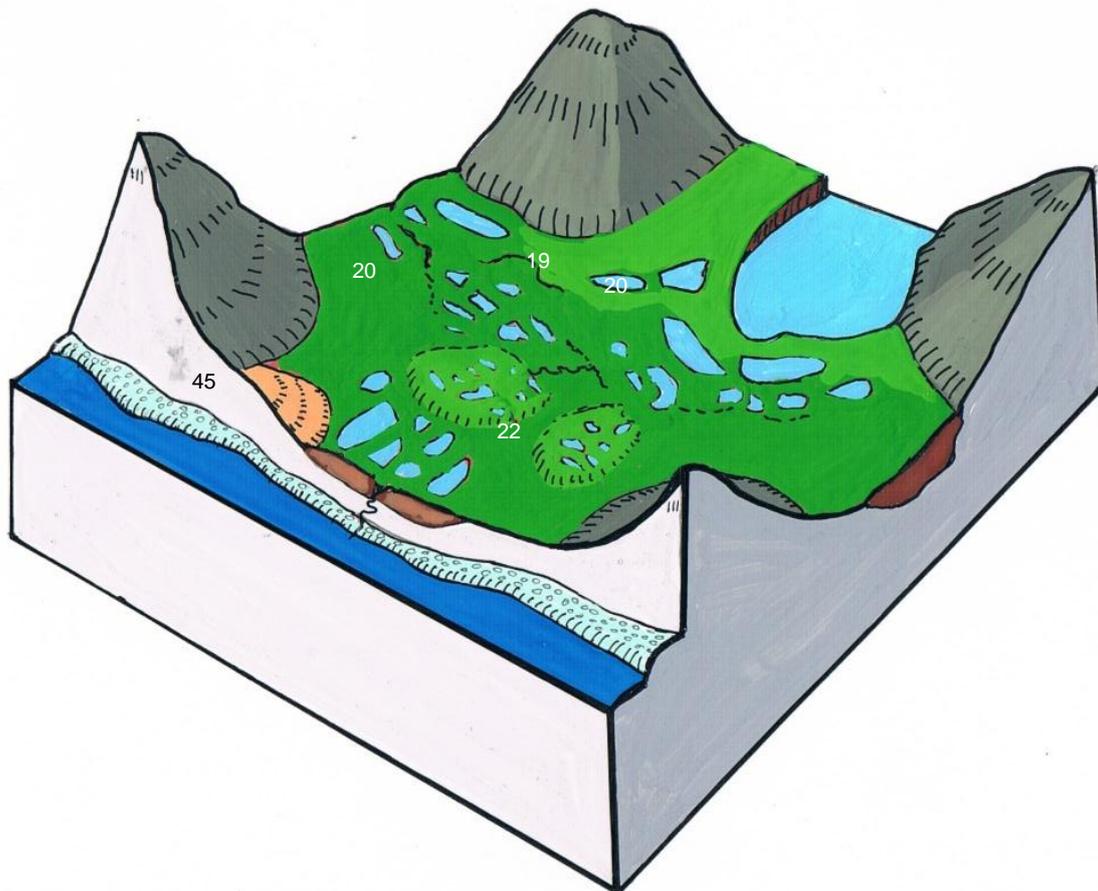


Figure 12. Sketch of the Policarpo mires in the eastern part of Peninsula Mitre. The landscape is dominated by *Astelia pumila* cushion bogs and *Sphagnum magellanicum* is rare. The highest parts of the rather flat peatlands have the smallest ponds. Between the ponds, small erosion gullies and underground streams (tunnelling) indicate much water erosion. Digits show EC values ( $\text{mS m}^{-1}$ ) measured in surface water on 16 March 2007. Green: *Astelia* cushion bogs; orange: groundwater fed fens; light blue: open water; dark blue: sea; grey/green: forest.

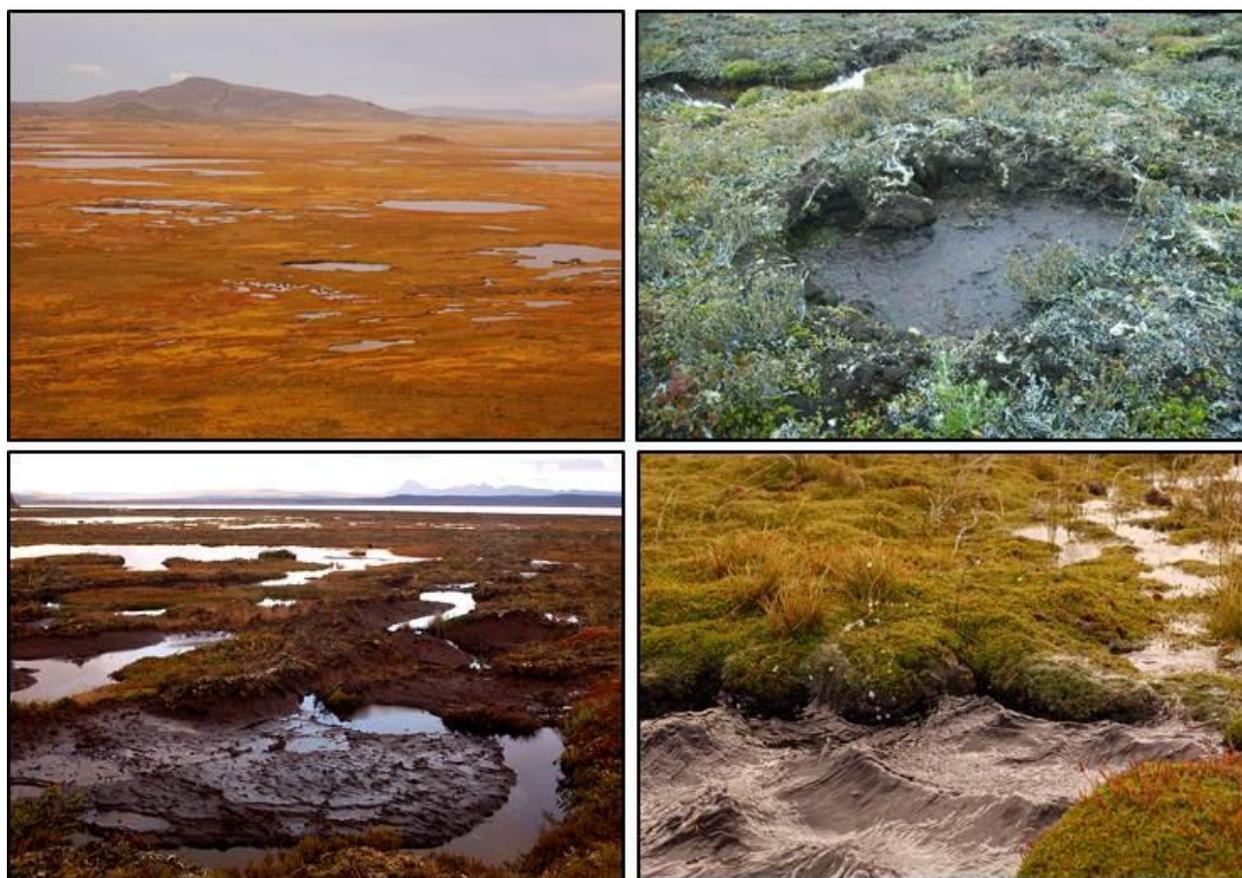


Figure 13. General view of Policarpo mires showing extensive *Astelia pumila* cushion bogs interspersed with numerous small to large pools (top left). *Sphagnum magellanicum* is almost absent in this landscape. Dried-out peat without *Astelia pumila* shows many erosion features, including frost heaving (top right) and bare peat flats resulting from the collapse of peat ‘dams’ between pools (bottom left). The *Astelia* carpets are very firm, appearing to stabilise the peat surface and to prevent or even repair erosion (bottom right).

We suspect that frost damage also accelerates peat erosion. When *Astelia* is present it can form extensive firm cushions that stabilise the peat between the pools (Figure 13).

Small areas of bog occur, but we did not see well developed raised bogs. The large mire areas are ombrotrophic or extremely poor minerotrophic, with 3–4 m of peat covering slopes up to 10 degrees, and can be classified as blanket bogs. Large fens are rare in the Policarpo area, but fens do occur at the bases of the sandy hills that intervene between the coastal strip and the blanket bogs. These hills discharge calcareous groundwater into small rich fens.

## DISCUSSION

### Mire types and zonation in Peninsula Mitre

Moving from the Equator to the poles and from lowland to upland, different vegetation zones can be distinguished. The zonation is linked to the different

demands of plants for warmth during the growing season. For Tierra del Fuego, Tuhkanen *et al.* (1990) differentiate between southern, middle and northern antiboreal zones (as analogues for the circumboreal zones of the northern hemisphere), and between lowland and upland. Within the system of ecoclimatic regions of Tuhkanen (1992), the lowlands of Peninsula Mitre can mainly be included in the northern antiboreal vegetation zone (parallel to the southern boreal of the northern hemisphere) and the upland areas would be classified as middle antiboreal (parallel to middle boreal). Typical raised bogs in Tierra del Fuego reach their lower-latitude limit within the northern antiboreal zone, reflecting the situation in the southern boreal of Fennoscandia.

Boreal areas with oceanic climate, such as the eastern part of Peninsula Mitre, are climatically very special and geographically very rare. The boreal zones cover much larger areas in the northern hemisphere than in the southern hemisphere, where land at similar latitudes is scarce. Even so, in the

northern hemisphere, boreal-oceanic climates are found only on the south-western coast of Alaska and in parts of north-western Europe (Tuhkanen 1992). Typical mire types for this climate are blanket bogs and sloping fens.

On the basis of extensive studies of mire stratigraphy (e.g. Auer 1965, 1970) and vegetation (e.g. Roivainen 1954, Moore 1983, Pisano 1983, Tuhkanen *et al.* 1990), three primary mire types have hitherto been distinguished in Tierra del Fuego, namely: 1) 'Steppenmoore', i.e. flat fens without *Sphagnum* in depressions with seasonally high groundwater (e.g. Maria Bethy Fen, Grootjans *et al.* 2010), in the dry (continental) areas; 2) '*Sphagnum* bogs' including (but not limited to) typical raised bogs; and 3) 'Polstermoore', i.e. cushion-plant blanket bogs, in the most oceanic areas. These types partly overlap in distribution and, according to Auer (1965, 1970), have changed their positions during the postglacial period as a result of climate change. In the transitional zones both peat stratigraphy and present vegetation are very diverse.

Common to all of the Peninsula Mires mires we saw are the vast expanses of open vegetation, where any trees exhibit dwarfism except in the *Nothofagus* dominated carrs (swamps) associated with nutrient-rich groundwater springs. The mires in the westernmost part of the study area (La Chaira mires, with the most continental climate) have some continental traits; although partly dominated by *Sphagnum*, they are poor fens and there are no true 'raised bogs'. The Policarpo mires (farthest east), with large areas of *Astelia* cushions and scattered occurrences of *Sphagnum magellanicum*, exhibit important features of 'Polstermoore' (Table 2). Of the peatlands described by Grootjans *et al.* (2010), Moat is the clearest example of 'Polstermoore' with large areas of cushion mires, blanket bogs and steep sloping fens. We do not have any records from Peninsula Mitre of *Donatia fascicularis*, which is a second conspicuous cushion plant at Moat and typical for later succession stages (Heusser 1995).

An unexpected finding in Peninsula Mitre was the occurrence of many calcareous spring fens with active travertine (tufa) deposition. As far as we know, this mire type has not previously been reported from Tierra del Fuego. The abundant limestone rocks outcropping between Río Leticia and Río Policarpo (Río Bueno Formation; Olivero *et al.* 2002) are the likely source of the responsible calcium and bicarbonate rich groundwater. High concentrations of these ions do not necessarily result in travertine deposition, as several fen systems in Peninsula Mitre illustrate. Travertine is formed by a process called 'degassing' when very calcareous groundwater discharges at the soil surface, losing

pressure so that dissolved CO<sub>2</sub> escapes to the atmosphere (Pentecost 2005). Aquatic plants such as *Chara* species and algae, which can use waterborne CO<sub>2</sub> directly for photosynthesis, can stimulate travertine deposition on their leaves. Such spring systems are rare but widely distributed worldwide. They have been described in Europe (e.g. England, Slovakia, Poland, Latvia, Switzerland) and North America, as well as in South Africa (Hájková *et al.* 2012, Grootjans *et al.* 2012).

### Mire degradation and vegetation change

Indications of lowered water levels are evident at all of the sites we visited along the Atlantic coast of Peninsula Mitre. Peat growth seems to be stagnating in most of the La Chaira mires, and the occurrence of *Sphagnum* declines substantially east of Puesto La Chaira (Table 2). Leticia mire, the large peatland east of La Chaira, suffers directly from low water levels in the Leticia River, and drainage of the mire is further promoted by soil piping of groundwater discharging from the surrounding hills. Moving east from Leticia River, the mires show decreasing *Sphagnum* cover and an increasing abundance of dwarf shrubs such as *Empetrum rubrum*, *Chilotrimum diffusum* and dwarf *Nothofagus antarctica*.

Farther to the east, in the vicinity of the large Río Bueno Lake, the density of lakes and pools increases. A drop in lake water level is conspicuous from the bog bursts and peat cliffs. Lakes are larger and more frequent in the most easterly of the peatlands we visited (Policarpo mires). Here peat erosion is evident, *Astelia pumila* is dominant and *Sphagnum* survives only in sheltered areas (Table 2).

This leads us to the question: what has caused the apparent desiccation of the La Chaira and Leticia mires, the expansion of *Caltha dionaeifolia* in the Leticia and Río Bueno mires, the large-scale erosion processes in the Río Bueno and Policarpo mires and the dominance of *Astelia* in the Policarpo area? And how can the evidence that the shift from *Sphagnum* to *Astelia* dominated bogs began much earlier in the Policarpo region than in areas farther to the west be explained?

*Astelia* and other cushion plants occupy a very narrow ecological niche determined by a combination of low summer temperatures, frost-poor winters, high rainfall (causing extremely low nutrient availability by heavy leaching), shallow water table, absence of prolonged flooding, and episodic desiccation by strong winds (Fritz 2012). Impeded growth of competing bog plants like *Sphagnum* seems to be compulsory for the success of cushion plants due to their own low growth rates, which may result from their large investment in

Table 2. Major ecological changes in mires, moving from west to east along the Atlantic coast of Peninsula Mitre. See also Figure 14.

Mire complex	La Chaira	Leticia	Río Bueno	Policarpo
<i>Sphagnum magellanicum</i>				
<i>Caltha dionaeifolia</i>				
<i>Astelia pumila</i>				
Peat thickness (typical)	4 m	4 m	4.5 m	4 m
Bogs: start of <i>Sphagnum</i> peat below surface (n)	0 cm (1)	10 cm (1)	10–15 cm (2)	90 cm (1)
Bogs: total thickness of <i>Sphagnum</i> peat (n)	2.5 m (1)	3 m (1)	1.5–5.0 m (2)	0.8 m (1)
Indications of water level drop	desiccation	gully erosion, soil piping	beach ridges, lowered lake level, truncated pools/rivers, bog bursts	soil piping
Impacts of beavers	+	+	++	+
Impacts of cattle	+	++	++	+



Figure 14. From top left to bottom right, these pictures show possible sequential stages in *Sphagnum magellanicum* degradation and its replacement by *Caltha dionaeifolia* then (finally) *Astelia pumila*, in the landscape of Peninsula Mitre.

producing root biomass to access nutrients (Fritz *et al.* 2011). We argue that episodic water shortage may offer *Astelia pumila* a ‘window of opportunity’ to invade *Sphagnum* bogs. Once established, it is persistent (Heusser 1995, Teltewskaja 2010).

Water shortage may have been caused by changes in the depth of regional drainage relative to the peat surface. In the mire landscape of Peninsula Mitre we found a range of evidence for deepening of the regional drainage (e.g. incised riverbeds) that has probably been caused by land uplift (Isla & Bujaleski 2008) and eustatic sea level fall (Mörner 1991, Costa *et al.* 2006, Bujalesky 2007, Torres Carbonell *et al.* 2011, Shellman & Radtke 2010, González Bonorino *et al.* 2012). From recent decades we also observed frequent indications of beaver dam failures resulting in gully erosion which has increased the fraction of the peat body that is directly connected to the regional drainage network.

Hydroclimatic conditions may also have changed. The intensification of westerly winds around 2800 cal BP (Borromei *et al.* 2010, cf. Chambers *et al.* 2007) has been linked to vegetation changes in bogs such as the replacement of *Sphagnum* by *Astelia* (Heusser 1995, Teltewskaja 2010). An aspect that deserves further investigation is the role of cooler climate between 680 and 300 cal BP (Little Ice Age, cf. Borromei *et al.* 2010) in triggering the dominance of cushion bog vegetation.

The calcareous mires in the Río Leticia and Río Policarpo areas also seem to have a recent origin, as we found peat underneath a rather shallow layer of travertine/tufa (Figure 8). This phenomenon may be explained by an increase in local groundwater discharge and travertine deposition on pre-existing groundwater fed fens, arising from uplifting of their infiltration areas (cf. Grootjans *et al.* 2012).

#### **Effect of overgrazing and introduced beavers**

In addition to the natural processes described above, 100 years of cattle grazing and 40 years of beaver activity have contributed to the degradation that we observed in these mires.

In most of the coastal area of Peninsula Mitre, excessive numbers of wild cows and horses cause much damage to fens and calcareous spring mires. The forests are the main source of food for cows and guanaco in winter because grasslands on mineral soils are scarce, occurring only in a narrow strip along the coast. Overgrazing inhibits tree regeneration so that tree species are being replaced by thorn bushes like *Berberis buxifolia*. A regional-scale increase of livestock grazing in Chile and Argentina may increase nutrient deposition (Martines-Lagos *et al.* 2010), and this may be especially significant for the extremely nutrient-poor

bogs and fens of Peninsula Mitre.

The introduction of Canadian beaver has already caused substantial damage to Fuegian mires by erosion and flooding with nutrient-rich and alkaline surface water (Fritz 2012). The building of beaver dams negatively impacts on the forest, both by direct tree felling and by flooding. Gallery forests along watercourses, e.g. those that separate mire massifs, are particularly vulnerable and most of them have already been destroyed. The effects of beaver at landscape scale are more difficult to evaluate. Depending on the local situation, damming of watercourses by beavers may flood parts of a mire, increase water storage on the mire surface or raise the water level in the mire. On the other hand, beavers also drain mires and pools by excavating channels to facilitate their own movements, and bursting of their dams may initiate erosion events that substantially lower the drainage base (see above). Both flooding and drainage arising from beaver activity generate rapid changes in local hydrology and vegetation. In view of the high rates of beaver colonisation, the cumulative changes could be very substantial and, given that beaver ponds are often abandoned, we anticipate a desiccating effect in the long term.

#### **Comments on the bipolar distribution of species**

Many mire plant genera and species have bipolar distributions, with occurrences in Tierra del Fuego. Most of these taxa are found in rich fen and spring vegetation. Species that are common to Peninsula Mitre and the boreal fens of Europe (e.g. Moen *et al.* 2012) include, for example, *Carex canescens*, *C. microgloch*, *Cystopteris fragilis* and *Triglochin palustre*. A very large number of vascular plant genera occur in both areas, e.g. *Blechnum*, *Caltha*, *Empetrum*, *Juncus*, *Primula*, *Schoenus* and *Viola*.

The situation is similar for bryophytes. Two of the three *Sphagnum* species in Peninsula Mitre (*Sphagnum magellanicum* and *S. fimbriatum*) also occur in Europe. *Sphagnum falcatulum* is closely related to the northern hemisphere species *S. cuspidatum*. As few bipolar/biboreal species have so far been studied using modern genetic methods, geographic taxonomic differences may exist between taxa regarded as one species today. However, recent studies of *Cinclidium stygium* and *Sphagnum fimbriatum* from fens distributed across the world, including collections from Tierra del Fuego (gathered during the IMCG excursion of 2005) and from boreal areas of the northern hemisphere, show no genetic or leaf morphological differences (Pineiro *et al.* 2012, Shaw *et al.* 2012). Studies of *Sphagnum magellanicum* give the same result (Kjell Ivar Flatberg pers. comm. 2013).

## SUMMARISING CONCLUSIONS

The peatlands of Peninsula Mitre are of global significance. They are impressive, peculiar, extensive and largely pristine mires which have developed in a climatic zone (the oceanic-boreal) that is extremely rare globally; and in the southern hemisphere is restricted to parts of Tierra del Fuego, southern Chile, Tasmania and New Zealand (Godley 1960, Kottek *et al.* 2006). Also, the biogeographical context is special. The mire types are arranged along a west-east gradient, with *Sphagnum* bogs most common in the more continental western part of the peninsula (La Chaira mires) and “Polstermoore” dominated by *Astelia pumila* with only scattered occurrences of *Sphagnum magellanicum* in the more oceanic east (Policarpo mires). The transitions between these types are highly variable in both space and time. The west–east gradient is less clearly defined along the south coast of Tierra del Fuego, where *Astelia* mires occur at Moat, west of Peninsula Mitre (Roig & Collado 2004, Fritz 2012, Iturraspe *et al.* 2013), as a consequence of more oceanic climate and the additional effect of the discontinuous mountain relief. Further studies of the distribution of mire types across the entire region are necessary.

The mires of Peninsula Mitre are embedded in a wild and naturally dynamic landscape. Long-term changes in ocean water levels and tectonics have influenced and will continue to influence mire landscape dynamics, leading to both significant natural erosion processes and the formation of new types of mires. A fascinating current phenomenon is the temporally differentiated expansion of stenoecious and globally extremely rare cushion mires, which is probably due to the interplay of climate change, climatic gradients and tectonics.

The damaging impact of free-roaming cattle on mires and upland vegetation is, however, conspicuous. In particular, the cattle do much damage to calcareous mires and prevent the regeneration of forest on the mineral hills. This disproportionate damage needs urgent control.

Several initiatives in the Parliament of Tierra del Fuego to declare Peninsula Mitre a provincial protected area have hitherto failed. Recent regulations do prohibit peat mining in the area, but a policy for integrated land management oriented to the conservation of these globally unique ecosystems is an urgent necessity.

Peninsula Mitre clearly deserves the highest possible protection at both provincial and national levels and, in view of its global importance, as a World Heritage Site.

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