Description of a peatland complex in an agricultural landscape on Terceira Island (Azores): Criação do Filipe Case Study

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SUMMARY

The Criação do Filipe peatland complex on Terceira Island (Azores) includes a fragmented network of inter-connected peatlands that have persisted over time within an agriculture-dominated landscape. This study identifies a number of human pressures including cattle grazing in and around the mire, a high population density of rabbits, high cover of exotic plant species and the presence of infrastructure (stone walls, electricity poles, etc.). The peatland complex has 44 plant species including four *Sphagnum* species, ten endemic vascular plants and eight plant communities. The maximum peat depth is seven metres. The peatlands receive inputs of water from streams entering at their northern margins, particularly from two pumice-extravasated cones, in addition to precipitation and intercepted fog. Accumulated water feeds other wetlands downstream. The complex shows increasing cover of aggressive and natural woody species, and water table levels are lower now than they were in 1998. Given its importance as one of the largest peatland complexes within Terceira Island's anthropic landscapes, which is partially protected by the European Habitats Directive and located within a Natura 2000 network area as well as in Terceira Natural Park, the Criação do Filipe area should be the target of an active restoration/conservation plan.

KEY WORDS: degradation, European Habitats Directive, heather (*Calluna vulgaris*), pasture, *Sphagnum*, surface hydrology, vegetation

INTRODUCTION

The earliest records of peatlands in the Azores are provided by Sjögren (1973) and the phytosociological system of Lüpnitz (1975). Dias (1996) developed the first classification of Azorean wetland vegetation and Mendes (1998) distinguished five *Sphagnum* peatland types. These include: basin, transition, raised, hillside and blanket peatlands, described in the international literature by Mendes & Dias (2013). Since then, several aspects of peatlands have been studied in the Azores, including a number of ecosystem services (Pereira 2015, Pereira *et al*. 2019), distribution (Mendes & Dias 2017, Mendes *et al*. 2019), regeneration (Mendes *et al*. 2020) and restoration (Mendes 2017).

Terceira currently has 3,011 ha of peatland, of which 44 % is forested (Table 1). It has been estimated that, in the past, there were 35,000 ha of Azores peatlands of which less than 30 % persist at present; and more than 50 % of these are degraded (Mendes 2017).

In the Azores, the main threat to these habitats is inappropriate land use, because large areas of peatland have been transformed into pastures or production forests (Mendes 2017). Nevertheless, Azorean peatlands continue to have numerous ecological, hydrological (Pereira *et al*. 2019) and biochemical functions and societal values. In particular, the Criação do Filipe peatland complex has persisted for decades, even though it is located within an agricultural area where the peatlands and their hydrological catchments are used as pasture for cattle. The density of grazing animals appears not to be high, but cows and bulls can be observed in the area almost year-round.

Table 1. Extent of different land cover types on the current total area of peatlands in Terceira Island. Based on Mendes *et al*. (2019).

Cover type	Area (ha)	% of total area
Forested	1,324.84	44
Bog	421.54	14
Fen	90.33	3
Degraded	1,174.29	39
Total	3,011.00	100

The descriptions of Azorean peatlands so far published in international literature (e.g. Mendes & Dias 2007, 2009) have considered peatlands located in natural areas, meaning that the potential resistance of peatlands to anthropogenic pressures has not been reviewed previously. The sensitivity of peatlands to disturbance is a complex topic, since it depends on innumerable facets of the disturbance such as type, magnitude, duration, spatial extent, frequency and timing, as well as on site ecological conditions and the way the peatlands respond. Bacon *et al*. (2017) discuss the fragility of peatland ecosystems and, on the basis of an exhaustive literature search, conclude that opinions diverge but generally support the notion that the concepts of resistance and resilience capacity are relevant to peatlands. Disturbance is a major force that influences, or even determines, the structure and functions of ecological components (populations, communities, ecosystems); and the capacity to survive the effects of a disturbance is resistance (Lake 2013).

Peatlands have developed due to positive feedback mechanisms that promoted their expansion under favourable climatic and waterlogged conditions (Jones & Yu 2010). The preservation of anoxic conditions is the result of internal negative feedbacks between ecological, hydrological and biogeochemical processes that stabilise shallow water tables for long periods and promote the growth of peat-forming vegetation (Waddington *et al*. 2015). Still, many peatlands have been modified by humans for several purposes including agriculture, habitat management, forestry, fuel and horticultural growing media (Limpens *et al*. 2008, Page & Hooijer 2016, Mendes 2017). These can combine with natural disturbances such as fire and erosion (Tallis 1985, Turetsky *et al*. 2002, Elias & Dias 2009) to destabilise the carbon (C) store through the lowering of water tables and a subsequent shift away from peat-forming vegetation, leading to an increase in gaseous and fluvial C fluxes (Kettridge *et al*. 2015). These negative effects suggest that peatlands are fragile ecosystems, as highlighted by Maltby (1997) and Minayeva *et al*. (2008). This is further supported by the fact that about 50 % of European peatlands have ceased to accumulate peat and almost 20 % of the original area no longer exists (Rochefort & Lode 2006). On the other hand, peatlands have persisted across the globe, accumulating and storing atmospheric carbon, for millennia (Kettridge *et al*. 2019). Stabilising feedbacks that regulate the water content / retention / storage of peatland have been instrumental in achieving this persistence (Belyea & Baird 2016). While the loss of peat carbon is likely to occur because of short-term pressures, an understanding of the long-term (100–200 years) response of peatlands to these disturbances needs to take internal adaptive mechanisms into account (Laiho 2006). For example, Swindles *et al*. (2016) demonstrated that peatlands can be resilient to disturbance by human activities such as repeated phases of peat cutting (since the Iron Age), by resuming peat accumulation over longer timescales. Mendes *et al*. (2020) showed that grazed peatlands in the Azores might regenerate after the removal of cattle. Evans & Warburton (2005) reported that degraded UK blanket peatlands have revegetated autogenically after drainage. However, in some locations, the combined effects of pollution, grazing, burning and gullying have resulted in large areas of persistently bare peat that show little sign of recovery without intervention (Evans *et al*. 2014).

The aim of this study was to build an integrated understanding of the Criação do Filipe peatland and its dynamics, and thereby develop an understanding of local peatland degradation effects, in the context of possible dynamics and/or historical factors that enable peatlands to resist anthropogenic pressures. Our approach involves the description of multiple ecological attributes such as floristic diversity, vegetation, hydrology and peat depth, along with ongoing and historical threats arising from human activities. The data presented here provide a temporal reference (baseline) for future assessment of the effects of ongoing disturbance; and, thus, a foundation for further research and publications.

METHODS

Study area

The Azores is the northernmost Macaronesian archipelago, located between 36º 56' N, 25º 5' W and 39º 42' N, 31º 12' W, about 1,400 km from the European continent (distance between Sta. Maria Island and Lisbon) and 1,900 km from the American continent (distance between Flores Island and St John’s Newfoundland, the most easterly city in North America) (Figure 1A). The archipelago has nine islands (Figure 1B), distributed in three groups. Terceira Island belongs to the central group (Figures 1B, 1C) and has an area of about 402 km^2. The altitude of its highest mountain peak (Santa Bárbara volcano, in the western part of the island) is 1,023 m a.s.l. (above sea level).

The Criação do Filipe peatland complex (Figure 1D and Figure 2) includes several connected peatlands of different types, located at an altitude of 450 metres a.s.l. within the Special Conservation Area (SCA; EU Natura 2000 network area) and

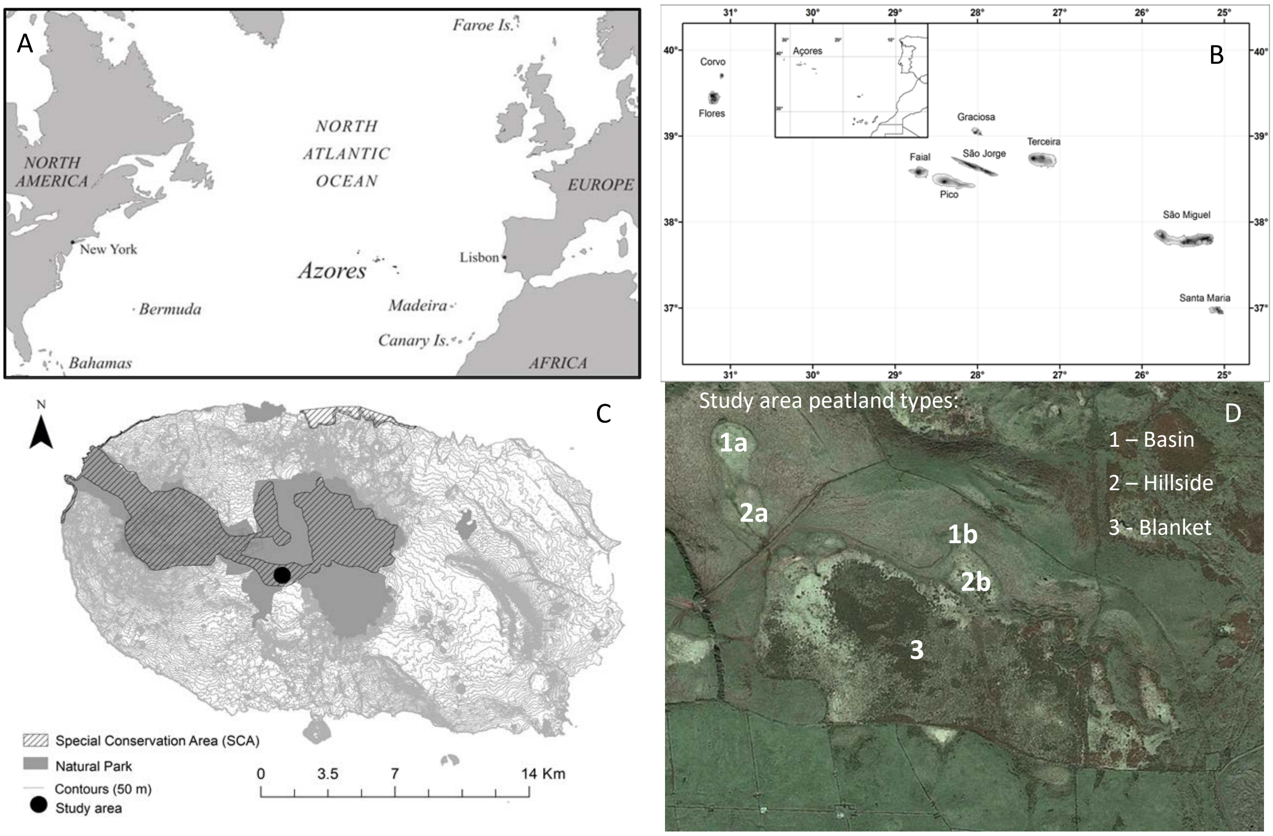

Figure 1. A: map of the North Atlantic region, showing the location of the Azores archipelago; B: map of the Azores archipelago; C: map of Terceira Island identifying the study area inside the Special Conservation Area (SCA) and Natural Park; D: aerial image of the Criação de Filipe peatland complex, distinguishing different peatland types (1, 2 and 3). Aerial photo by Google Earth, 2011.

Natural Park of Terceira Island (Figure 1C). The European Habitats Directive protects the most extensive peatland type within the study area under the designation of 'blanket bogs' (code 7130, a priority habitat).

The soil type of the study area is predominantly Histosol (see Montanarella *et al*. 2006), yet there is an important diversity of organic soils as a consequence of both drainage-induced mineralisation and anthropogenic mixing with mineral soils because a secondary transformation of the peat has occurred in large areas of former peatland under agricultural use (as described by Säurich *et al*. 2019). The dominant soils at the margins of the peatland are classified as Andosols with placic horizons. These are modern soils with high organic matter content, developed from volcanic pyroclastic material in a wet temperate Atlantic climate (Pinheiro 1990, Madruga 1995). The presence of a placic horizon (Bsm horizon characterised by the accumulation of iron and magnesium, also known as an 'iron pan' or 'iron band') is an important ecological factor because it restricts soil drainage.

Figure 2. View across the Criação de Filipe peatland complex.

Precipitation class at the study site is 2,600–3,000 mm yr^{-1} (Azevedo 2005a), humidity is 96–100 % (Azevedo 2005b) and the annual average temperature is 13–14 ºC (Azevedo 2005c).

Dias (1986) suggests that the transformation of this area by grazing occurred prior to the first reliable records of land use (historical aerial images from 1930). The complex margins and parts of adjacent areas (wherever ground conditions allowed machinery to operate) were ploughed in the 1980s and subsequently used as pasture, at spatially uniform intensity and frequency, causing the disappearance of several shallow peatlands and the general degradation of remaining peatlands. The Criação do Filipe peatland complex persisted because the thick peat layer and wet ground conditions made the use of machinery impossible, but the peatland has nonetheless been affected by all of the changes on adjacent land, from decreasing water quantity to altered flora and natural dynamics associated with marginal grazing.

Data collection and data analysis

Peatland complex mapping and description of types
The peatland types of the complex were classified as in Mendes & Dias (2013), and its cartographic limits were demarcated using a WorldView multispectral image (2017/12/21 satellite image courtesy of DigitalGlobe Foundation), based on colour gradient. Boundaries were adjusted in the field using peat depth (minimum considered was 30 cm, as in Mendes 2017). Maps were completed in ArcGIS 10.6.1.

Peatland complex vegetation mapping and description of flora
For the vegetation classification, the same WorldView multispectral image was used. The satellite image was clipped to the complex boundary obtained previously. To distinguish different vegetation units, we used Iso Cluster Unsupervised Classification software in ArcMap 10.6.1. Field inventories were carried out in November 2018, to improve and validate the classification obtained (ground-truthing). Floristic inventories were carried out in 16 plots (5 m × 5 m) and included all of the vegetation types identified. The same cover classes of Braun Blanquet (Westhoff & Van der Maarel 1978) as in Mendes (1998) were used in order to obtain comparable information for assessing trends in vegetation evolution. Nomenclature of vascular plants was based on Silva *et al*. (2010), while naturalness and status followed Dias (2016). Nomenclature of mosses was based on Gabriel *et al*. (2010). Designation of the vegetation types was based on the dominant cover species.

Description of surface hydrology and water properties
An analysis of surface water movement was carried out using Arc Hydro Tools in ArcGIS 10.1.6., defining flowlines, main watersheds and flow direction. In November 2018, water depth was measured in each vegetation type, using adapted piezometers made from PVC tubes. Sixty-five samples of water were collected simultaneously and several properties measured in the field including pH, conductivity and TDS, using a portable WTW pH meter.

Peat depth/volume
Ground Penetrating Radar (GPR) was used to collect information on peat depth across several peatlands within the complex. This information was used to assess the maturity of the peatland complex and to evaluate its importance as a carbon source. The GPR surveys followed the methodology of Pereira *et al*. (2017), using a MALA ® 100 MHz unshielded RTA GPR. The radargrams were made as shown in Figure 3. They were post-processed with Reflexw seismic/GPR software (©1997–2010 Sandmeier V.7.0). To validate the radargrams, peat depth was measured by probing with a metal pipe at intervals of 10 m along each transect.

To estimate peat volume, the reflections identified in the post-processed GPR data were integrated in ArcGIS 10.6.1 to produce cartography of the surveys. The volume was estimated using simple kriging and a normal score transformation (Pereira *et al*. 2017), which returned the best relationship between values for the stratigraphic layer observed in the radargrams and validation (with $R^2 > 0.80$ in almost all cases). As a result, a three-dimensional raster of the bottom of the peatland was developed.

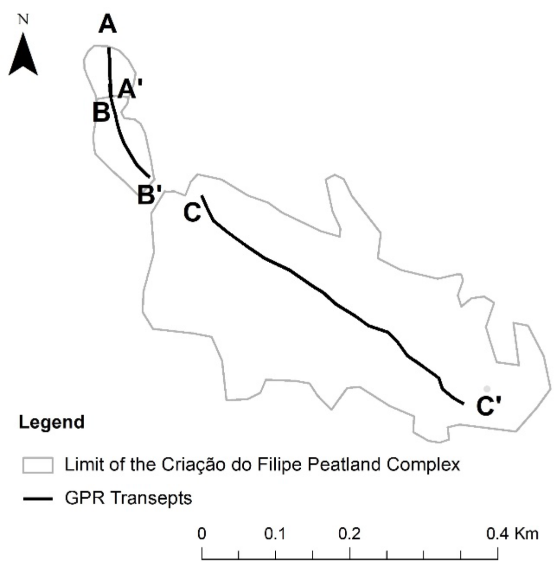

Figure 3. Location of the peat depth transepts (Figure 6) made using a MALA ® 100 MHz unshielded RTA GPR on the Criação do Filipe peatland complex.

Active threats and historical landscape changes (1958–2018)

For this study, we described threats based on local observation. To evaluate historical changes within the Criação do Filipe complex as well as in its surrounding area, a buffer of 200 ha (to guarantee similar ecological conditions) was considered and peatland occupation was defined for the years 1958 and 2018 using aerial photos.

RESULTS

Peatland complex mapping and description of types

The Criação do Filipe peatland complex covers an area of 12.57 ha. It includes basin, hillside and blanket peatland types (described in Mendes & Dias 2013). The basin type (two patches) occupies an area of 0.5 ha, the hillside type (two patches) 0.4 ha and the blanket type (one patch) 11.67 ha. The two basin peatlands developed in the bases of endorheic valleys of pumice-extravasated cones, connecting with the blanket peatland via the two hillside peatlands. In the basin peatlands (Figure 1D-1), the hummock area is very limited and the plant cover of hummocks is restricted to graminoid species due to extreme trampling by cattle, in and around the peatland. The water table is close to the peatland surface in the basins, which quite commonly overflow following rainfall events, the excess water moving along central soakways into other peatlands downstream (e.g. from 1A to 2A in Figure 1D).

In May 2015, Dr Hervé Cubizolle from Université de Lyon (France) visited the Azores and collected peat samples for ^{14}C dating from one of the basin bogs (peatland 1A in Figure 1D). The samples were collected at 4.12 m depth and yielded a calibrated age 14BP of 885 ± 30. As described later, there are greater depths of peat in this basin bog, meaning it should be older than the reported ^{14}C age.

The hillside peatlands (Figure 1D-2) occur on sloping areas (always exorheic). Although the water supply in hillside peatlands is predominantly meteoric, arriving as precipitation and intercepted thick fog (Mendes & Dias 2013), in these cases water is also supplied from the basin peatlands. The margins of these peatlands are rich in hummocks dominated by graminoid species, whose development can be attributed to the entrance of water enriched in oxygen and nutrients from the surrounding mineral catchment area.

The blanket peatlands (Figure 1D-3) occur on the plateaux of mountain peaks or on extended flat areas (Mendes & Dias 2013). They are characterised by an accentuated microrelief, especially at their margins, which are also reached by oxygen- and nutrient-enriched water. Woody-plant communities of *Calluna vulgaris* dominate the hummock areas of the blanket peatland, whereas mainly *Sphagnum* species develop in the wetter areas. This blanket peatland is protected by the EU Habitats Directive (code 7130), with priority status when active. The term "active" infers that the peatland still supports a significant area of vegetation that is typically peat forming, as is the case for this peatland.

Peatland complex vegetation mapping and flora description

Our surveys of the Criação do Filipe peatland complex recorded 44 species (Table 2) including four *Sphagnum* species. One species, *Erica azorica* Hochst, is listed in Annex II of the EU Habitats Directive and another four (*Sphagnum* species) are listed in Annex V of the same Directive. Eight vegetation community types were distinguished (Figure 4, Table 2). The study area is dominated by shrub vegetation, mostly *Calluna vulgaris.* In the basin and hillside peatland, the dominant functional type is mosses (Figure 4.). The *Calluna vulgaris* vegetation type (Table 2, 3) has the highest richness, with 32 species identified. This covers 12 % of the peatland, predominantly in hummock areas. It corresponds to the less wet area inside the peatland. The *Calluna vulgaris* with *Sphagnum* spp. vegetation type occupies 14 % of the complex, presenting 30 species. A mixed *C. vulgaris* and *P. aquilinum* vegetation type was also defined. The *Sphagnum* spp. community, found in wetter areas within the complex, occupies 13 % of the area. The genus *Sphagnum* is represented by four species, the commonest being *S. palustre*. This community forms remarkably homogeneous lawns, which are perennially waterlogged, and has low vascular plant cover. *S. auriculatum* and *S. cuspidatum* occur in small pools. In the complex boundaries, behind the ecotone line, the vegetation consists of *Sphagnum* mixed with graminoids, namely *Eleocharis multicaulis*, *Holcus rigidus* and *H. lanatus*. This is the most widespread community, occurring in 20 % of the complex area. The vegetation with lowest richness is the pure *Pteridium aquilinum* type, owing to the high cover of this plant, which tends to shade out other plants - apart from *Sphagnum* species - from the ground layer. The *Holcus lanatus* vegetation type occurs at the ecotone trampled margins of the peatland and covers 10 % of the complex area. The remaining vegetation type is dominated by *Juncus effusus* and contains 29 species. It occupies small depressions in the extremely waterlogged portion of the site, and covers 11 % of the mire complex area.

Table 2. Plant species in each community of the Criação do Filipe peatland complex. Species cover according to Braun-Blanquet classes. Designation of vegetation types is based on the dominant species. For each species, status and naturalness for the Azores is defined according to Dias (2016). Species listed in annexes II and V of the EU Habitats Directive are also indicated.

	Calluna vulgaris	*C. vulgaris_Sphagnum* spp.	*C. vulgaris_P. aquilinum*	*P. aquilinum*	*Sphagnum* spp._*graminoids*	*Juncus effusus*	*Holcus lanatus*	*Sphagnum* spp.			
	Hummock	Hummock	Hummock	Hummock	Lawn	Lawn	Lawn	Hollow	*Naturalness*	*Status in Azores*	*Habitats Directive*
Agrostis castellana Boiss. & Reut.	1	1	1	.	1	1	.	+	Endemic	NE	.
Anthoxanthum odoratum L.	+	+	+	.	+	+	+	.	Naturalised	Not defined	.
Deschampsia foliosa Hack	2	+	1	1	+	1	.	.	Endemic	NE	.
Blechnum spicant (L.) Sm.	+	2	+	.	.	+	+	.	Native	NE	.
Calluna vulgaris (L.) Hull	5	4	4	+	.	.	.	.	Native	NE	.
Cladonia azorica Ahti	1	+	+	.	.	.	.	.	Endemic	Not defined	Annex B-V
Cryptomeria japonica (L.f.) D.Don	+	.	.	.	.	.	.	.	Introduced	Not defined	.
Dryopteris azorica (Christ) Alston	+	.	.	.	.	.	.	.	Endemic	NE	.
Duchesnea indica (Andr.) Focke	+	+	.	.	.	+	.	.	Naturalised	Not defined	.
Eleocharis multicaulis (Sm.) Desv.	.	+	+	.	2	3	+	1	Native	Not defined	.
Erica azorica Hochst.	1	+	+	.	.	.	.	.	Endemic	NE	Annex B-II
Hedychium gardneranum Ker-Gawl.	+	.	.	.	.	.	+	.	Naturalised/Invasive	Not defined	.
Holcus lanatus L.	+	+	+	.	2	1	5	.	Naturalised/Invasive	Not defined	.
Holcus rigidus Hochst. ex Seub.	2	+	.	1	+	+	+	.	Endemic	LR	.
Hydrangea macrophylla (Thunb.) Ser.	+	.	.	.	.	.	.	.	Naturalised/Invasive	Not defined	.
Hydrocotyle vulgaris L.	+	+	.	.	1	1	+	+	Native	NE	.
Juncus bulbosus L.	.	.	.	.	.	.	.	+	Native	LC	.
Juncus effusus L.	+	1	.	1	+	5	+	+	Native	LC	.
Juniperus brevifolia (Seub.) Antoine	+	.	.	.	.	.	.	.	Endemic	NE	.
Leucobryum glaucum (Hedw.) Angstr.	+	+	.	.	.	.	.	.	Native	Not defined	Annex B-V
Lotus pedunculatus Cav.	+	+	.	.	+	+	+	+	Native	LR	.
Luzula purpureo-splendens Seub.	.	+	.	+	+	+	+	.	Endemic	LR	.
Lysimachia azorica Hornem. ex Hook.	.	+	+	+	.	.	.	.	Endemic	LR	.
Metrosideros excelsa Banks ex Gaertn.	.	+	.	.	.	.	.	.	Introduced	Not defined	.
Osmunda regalis L.	+	+	+	.	.	.	.	.	Native	Not defined	.
Polygonum hydropiperoides Michx.	.	.	.	.	.	.	.	+	Native	Not defined	.
Polytrichum commune Hedw.	.	2	.	+	.	+	.	.	Native	Not defined	.
Potentilla anglica Laich.	+	+	+	+	+	+	.	.	Native	LR	.
Potentilla erecta (L.) Räusch.	.	+	.	.	.	+	+	.	Native	LR	.
Prunella vulgaris L.	+	1	+	.	+	+	+	+	Naturalised	LR	.
Pteridium aquilinum (L.) Kuhn	+	+	4	5	+	.	.	+	Native	LR	.
Ranunculus repens L.	+	+	.	.	.	.	+	+	Not defined	Not defined	.
Rhytidiadelphus squarrosus (Hedw.) Warnst.	+	.	+	+	1	.	2	.	Native	Not defined	.
Rubus ulmifolius Schott	+	.	1	+	.	.	+	.	Not defined/Invasive	Not defined	.
Rumex conglomeratus Murr.	+	.	+	.	+	.	+	+	Native	Not defined	.
Pseudoscleropodium purum (Hedwig) M. Fleischer ex Brotherus	1	1	1	.	.	.	+	.	Native	Not defined	.
Sibthorpia europaea L.	.	+	+	+	+	+	+	.	Native	LR	.
Sphagnum auriculatum Schimp.	.	.	.	.	.	.	.	+	Native	Not defined	Annex B-V
Sphagnum cuspidatum Ehrh. ex Hoffm.	.	.	.	.	.	.	.	1	Native	Not defined	.
Sphagnum capillifolium (Ehrh.) Hedw.	+	2	+	.	.	.	.	.	Native	Not defined	.
Sphagnum palustre L.	2	4	4	5	5	5	2	5	Native	Not defined	Annex B-V
Trifolium repens L.	.	.	.	.	+	.	1	.	Naturalised	Not defined	.
Thuidium tamariscinum (Hedw.) Schimp.	2	2	2	1	+	1	1	.	Native	Not defined	.
Vaccinium cylindraceum Sm.	+	.	.	.	.	.	.	.	Endemic	NE	.

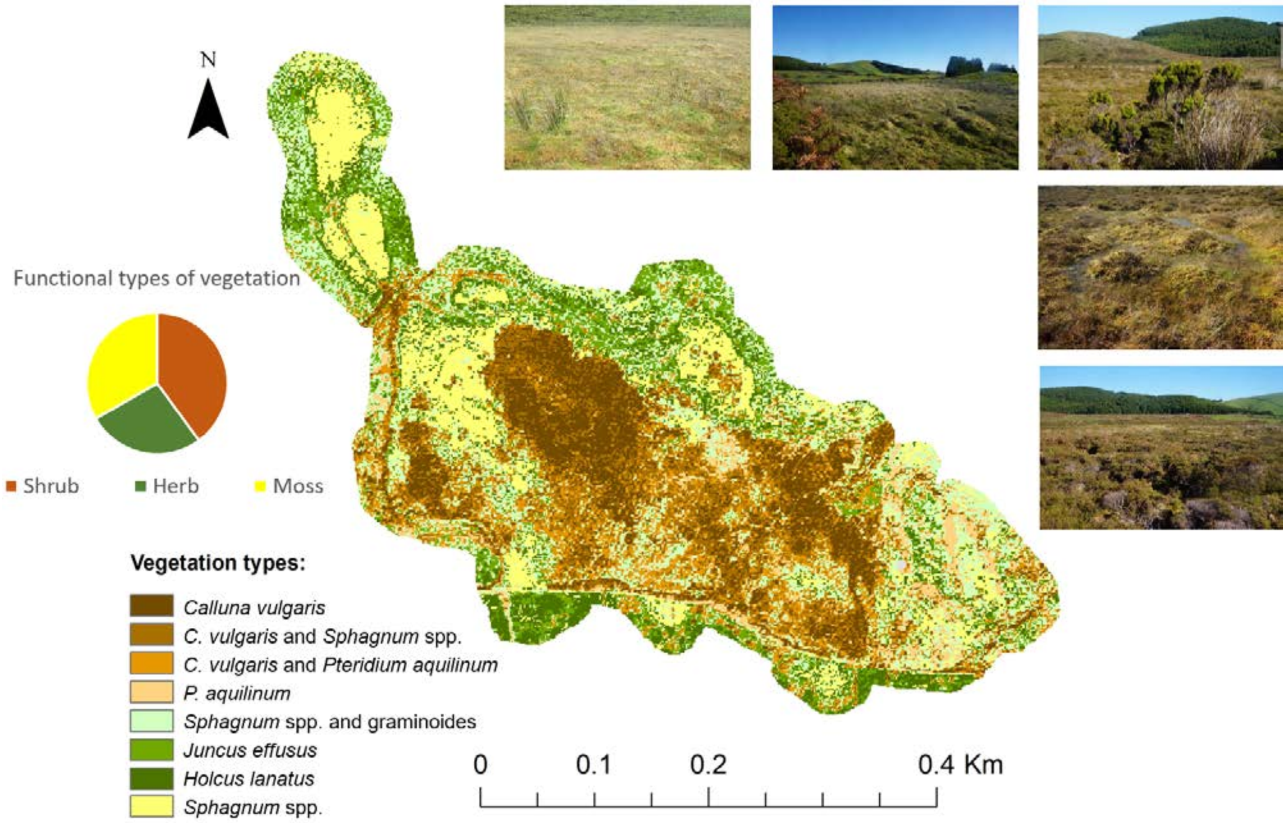

Figure 4. Vegetation map of the Criação do Filipe Peatland Complex. To distinguish between different vegetation units, we use Iso Cluster Unsupervised Classification, software ArcMap 10.6.1. The designation of vegetation types is based on the dominant cover species.

Description of surface hydrology and water properties

Analysis of the surface hydrology of the peatland complex revealed the presence of flowlines that run through several peatland types (Figure 5). Water moves from both basin peatlands (at the bases of two pumice domes) to lower-level formations until it reaches the blanket peatland. The blanket peatland is exorheic (draining) to the south, releasing water for the surrounding pastures and downstream wetlands.

The water level varies inside this complex (Table 3), from the surface to more than 50 cm depth. Wetter communities are *Sphagnum* dominated, in hollow and lawn structures; and drier communities are associated with *Calluna vulgaris* dominance, always in hummocky areas. Average pH ranges from 6.52 in the *H. lanatus* community (an ecotone community under bovine trampling) to 4.53 in the *Sphagnum* spp. community (Table 3). Average conductivity varies between 146 mV in *C. vulgaris* communities and 44 mV in *Sphagnum* spp. communities. Both pH and conductivity increase with water depth, as described by Mendes & Dias (2009).

Peat depth/volume

The maximum peat depth obtained by the GPR transepts (Figure 6) was 5.41 m in the north basin peatland. However, in the radargram there was a second level of reflection at about 7 m and this was, in fact, the depth measured by Mendes (1998). A maximum depth of 3.68 m was identified in the blanket peatland (Figure 6C). The average depth was 2.34 m on the axis of the deepest mire (Transect A–A'), 0.54 m on the axis of the shallowest mire (Transect B–B') and 2.26 m on the third transect (Transect C–C').

Active threats and historical changes (1958–2018)

All of the catchment areas of this complex have been disturbed by human activities (Figure 7). These can be described as:

- The continuous presence of cattle.
- The construction of roads and walking trails that pass through the complex may be responsible for serious hydrological changes.
- Presence of infrastructure such as stone walls and electricity poles.

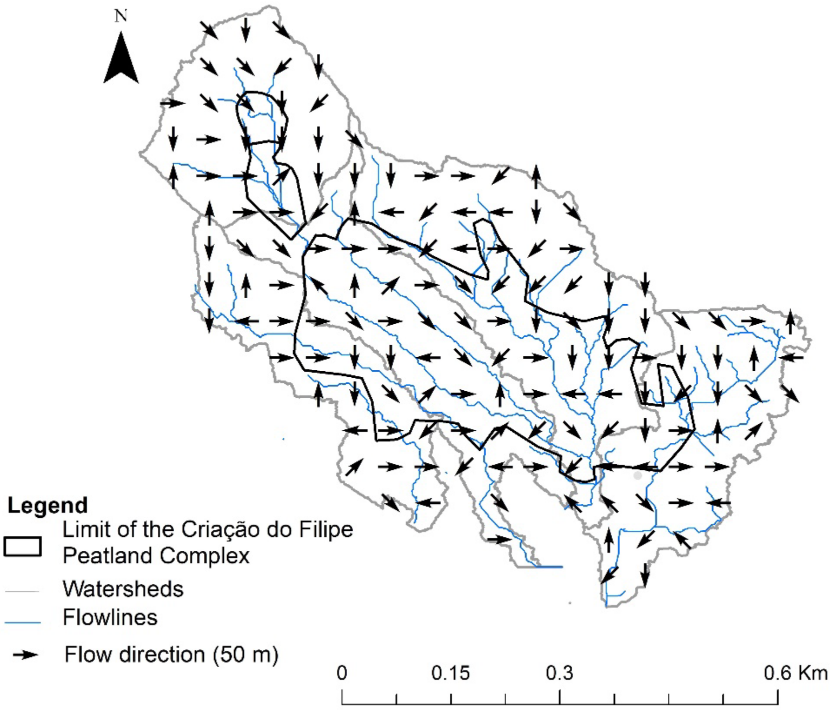

Figure 5. Watersheds, flowlines and flow direction in the Criação do Filipe peatland complex and surrounding catchment area, derived using Arc Hydro Tools in ArcGis 10.1.6.

Table 3. Average water table depth in each vegetation type identified in Criação do Filipe peatland complex. Parameters measured using a portable WTW pH meter, presenting average values. The dominant microrelief of each vegetation type marked and recorded the types of peatland where each vegetation is present. Information collected in November 2018.

Vegetation community	Peatland type	Microform	Water table depth (cm)	Number of samples	pH	Conductivity (mV)	TDS (mg ml^{-1})
Calluna vulgaris	*Blanket*	hummock	> 50	5	6.35	146	355
Calluna vulgaris Sphagnum spp.	*Blanket*	hummock	15	10	5.24	84	136
Calluna vulgaris Pteridium aquilinum	*Blanket*	hummock	40	5	6.32	141	326
Pteridium aquilinum	*Blanket*	hummock	30	5	6.01	124	212
Sphagnum spp. graminoids	*Blanket/ Hillside/ Basin*	lawn	7	10	5.13	55	121
Juncus effusus	*Blanket/ Hillside/ Basin*	lawn	10	10	5.42	65	95
Holcus lanatus	*Blanket/ Hillside/ Basin*	hummock	20	10	6.52	139	402
Sphagnum spp.	*Blanket/ Hillside/ Basin*	hollow/lawn	0	10	4.53	44	28

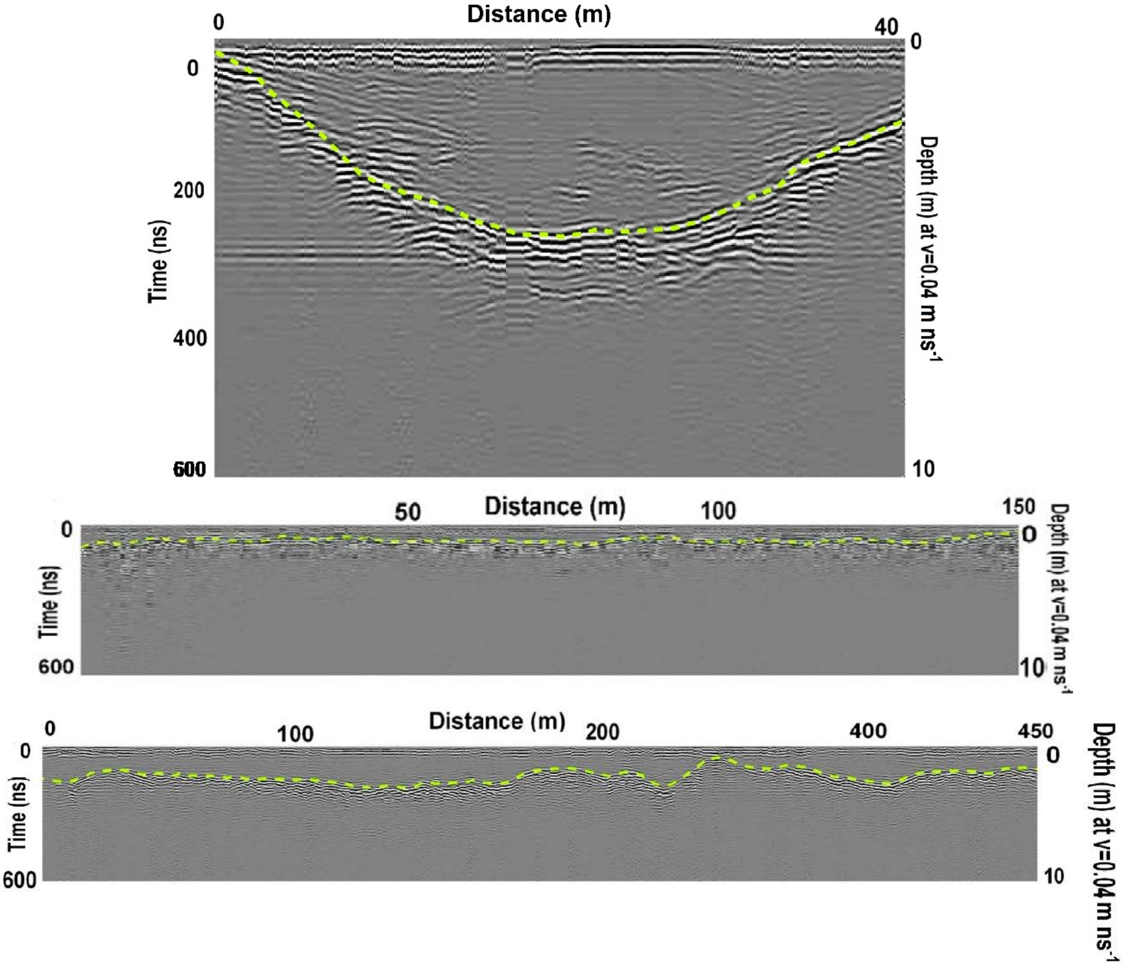

Figure 6. Peat depth profiles of the Criação do Filipe peatland complex on the three transects shown in Figure 3: A–A' (top), B–B' (middle), C–C' (bottom).

- An increase of non-peatland species such as *Rubus ulmifolius*. This member of the *Rosacea* is used for food and shelter by another invasive species, *Oryctolagus cuniculus* (Moore 2017).
- *Oryctolagus cuniculus* (the European rabbit) is one of the major threats to nature in the Azores, according to Portugal's 2007–2012 Natura 2000 monitoring report (Dias *et al*. 2012).
- The landscape outside the water catchment also presents small patches occupied by peatlands, ponds, *Cryptomeria japonica* (an introduced tree used for wood production) forests, and sedges.

The analysis of historical changes (Figure 8), using a buffer of 200 ha, showed that the total area occupied by peatlands was 64 ha in 1958, decreasing to 21 ha in 2018. During these years there were several attempts to mechanically transform the study area into pasture which failed, mainly because the peat depth caused difficulties for machinery access. Nonetheless, the marginal pasture and trampling by livestock represent serious threats, linked to the advance of invasive species.

Figure 7. Part of the Criação do Filipe peatland complex showing evidence of disturbance caused by animal trampling as well as by the passage of vehicles including vans and tractors. Some clearly apparent consequences are vegetation change, alteration of the pattern of water movement, and peat erosion.

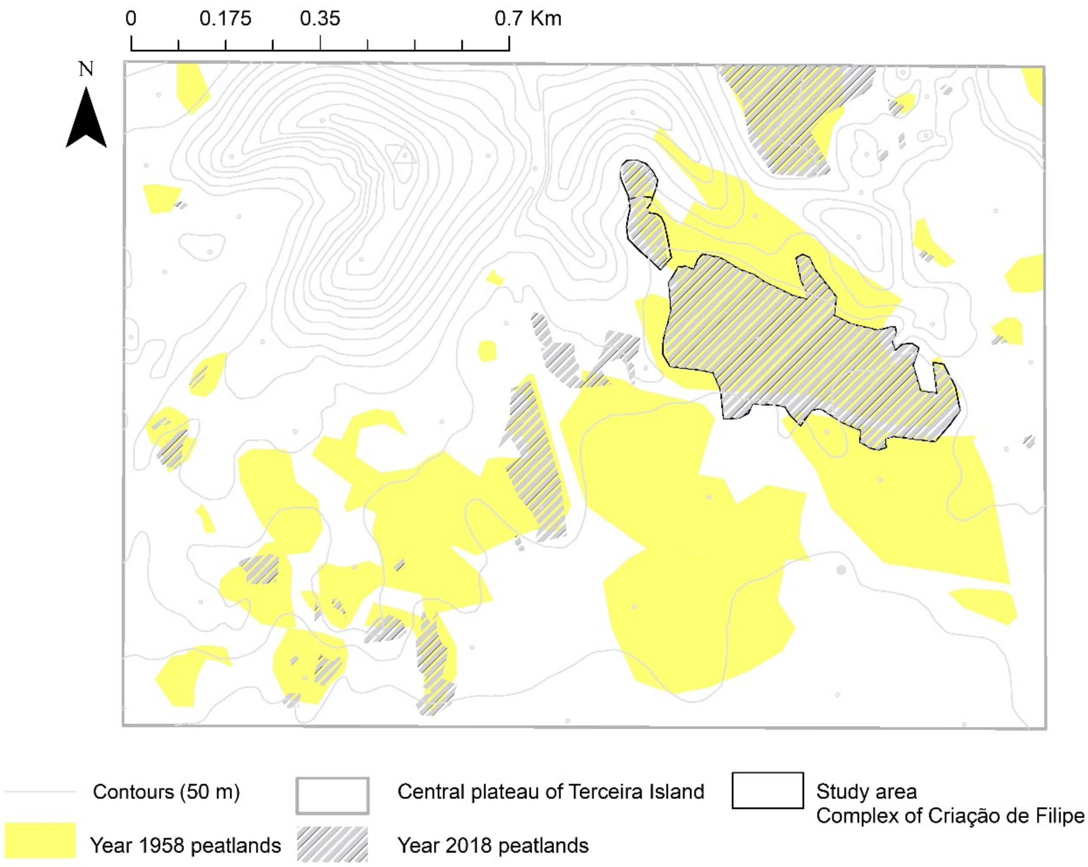

Figure 8. Comparison of the extent of peatlands in 1958 and 2018 within a defined section of the central plateau of Terceira Island drawn in ArcGIS 10.6.1, based on historical aerial photos.

DISCUSSION

In terms of floristics and plant communities, the Criação do Filipe peatland complex is currently important for the presence of protected species and several endemics. It also has the deepest layer of peat known on the island, which retains carbon and water. By comparing information collected during the course of this study with a characterisation made by one of the authors in 1998, some major changes can be identified (Tables 4 and 5). The first of these is an increase in species richness (as described by Grabovik *et al*. 2021); wetland plant species were retained but their prevalence and percentage cover declined, while ruderal/invasive species expanded. One example of this tendency was the reduction in cover of endemic grass species (e.g. *Deschampsia foliosa*, *Holcus rigidus*) and a very clear increase of *Holcus lanatus* (considered an invasive species; Mendes 2017). The only exception was an increase in cover of the endemic heather *Erica azorica*, although it remains sparse on the blanket peatland. This species typically behaves as a pioneer species in colonising lava fields and bagacin slopes (Sousa 2002) and is atypical for Azorean peatlands. Another notable change was the increase of vegetation community diversity from 5 to 8. Two communities dominated by *C. vulgaris* and one community of

Table 4. Comparison of some attributes of the Criação do Filipe peatland complex between surveys 21 years apart. Data from Mendes (1998) and this study (2019).

Attribute	Year	
	1998	2019
Plant species (total no.)	40	44
Sphagnum species (no.)	4	4
Community types (no.)	5	8
C. vulgaris area (%)	30	60
Water table depth (cm)	0–30	0–50
pH	4.13–4.27	4.53–6.35
Total dissolved solids	17–46	95–402

Table 5. Comparison of the vegetation communities recorded at the Criação do Filipe peatland complex between surveys 21 years apart. Data from Mendes (1998) and this study (2019).

Vegetation community	Dominant species	Extent in 2019 (%)	Change since 1998
Calluna vulgaris	*C. vulgaris/D. foliosa/T. tamariscinum*	12	Increase
Calluna vulgaris Sphagnum spp.	*C. vulgaris/S. palustre/P. commune*	14	New
Calluna vulgaris Pteridium aquilinum	*C. vulgaris/P. aquilinum/S. palustre*	12	New
Pteridium aquilinum	*P. aquilinum/S. palustre/J. effusus*	8	Stable
Sphagnum spp. graminoids	*S. palustre/E. multicaulis/H. lanatus*	20	Decrease
Juncus effusus	*J. effusus/ S. palustre/E. multicaulis*	11	Increase
Holcus lanatus	*H. lanatus/R. squarrosus/S. palustre*	10	New
Sphagnum spp.	*S. palustre/S. cuspidatum/S. auriculatum*	13	Decrease

H. lanatus emerged (Table 4). In 1998 *C. vulgaris* was present in 30 % of the peatland area and currently covers more than 60 % (essentially in the blanket peatland). The presence of heather on natural peatlands is atypical but not rare (Wallèn 1987, Morton & Heinemeyer 2019). In the Azores, this species is present in natural peatlands but more common on historically pastured land. In highly natural peatlands, it is associated with intense hydrological erosion that has transformed the environment by creating extremely nutrient-poor conditions and thus inhibiting the establishment of other vegetation types (Mendes *et al*. 2020). Therefore, the increase of *C. vulgaris* on the Criação do Filipe peatland in a quite short period indicates changes within the complex that suggest degradation (Doyle 1990, Renou-Wilson *et al*. 2011) such as reduced water table and increased nutrient input (Large 2001). Hammond (1981) states that *C. vulgaris* grows in the drier parts of peatlands, and we also verify a tendency for water level drop within these peatlands (Table 4) as well as an increase of pH and TDS (total dissolved solids).

The *Holcus lanatus* community, which now forms part of the vegetation on these peatlands, is waterlogged for most of the winter; but in summer the water table falls and the substrate dries, allowing some peat decomposition which releases plant nutrients. Allelopathy may play a role in the dominance of *Holcus lanatus* over other grasses (Remison & Snaydon 1980). Formerly, *H. lanatus* occurred in the *Juncus effusus* community with maximum cover of two on the Braun-Blanquet scale, increasing to the maximum class of five in the *H. lanatus* community. This grass is an introduced species in the Azores and presents a serious threat to peatlands, especially when they are grazed. Mendes (2017) described the aggressiveness of this plant in restricting restoration success on formerly grazed peatlands. Given the nature of this species, its advance at Criação do Filipe should be a cause of concern.

The *Juncus effusus* community occupies small depressions in the extremely waterlogged portion of the site and covers 11 % of the mire complex area, showing a tendency to increase its range.

The community of *Pteridium aquilinum* (L.) Kuhn remained stable, but a new combined community of *C. vulgaris* and *P. aquilinum* emerged. This fern is indicative of nitrous soil conditions arising from organic decomposition, which is probably attributable to hydrological changes associated with animal trampling in the peatland boundaries. *Pteridium aquilinum* is an annual plant, so it disappears during the coldest season in the Azores, when this vegetation type (*P. aquilinum* community) becomes floristically identical to the *Sphagnum* spp. type.

In this study a tendency for water level to decrease and for pH to increase was noted. Previous data indicate a maximum water table depth of 30 cm. The phreatic level is now at the surface in small ponds and more than 50 cm below ground level in areas with nearly pure stands of *C. vulgaris*. This may have contributed to the advance of *C. vulgaris* and the decrease in the area occupied by *Sphagnum*. A similar trend was observed in relation to average acidity.

From the GPR transepts, the estimated volume of peat accumulated is about 207,910 m^3, underlining the importance of this complex as a carbon sink and for water storage (Pereira 2015, Pereira *et al*. 2017). Although peat depth profiling was done in 1998, the method was more rudimentary, so no comparisons were made.

In terms of the nature of threats and their degree of intensity, there is no change. However, in some cases the resulting changes in the peatlands are more visible as an increase in cover of invasive species such as *Rubus ulmifolius*. Grazing and associated trampling causes physical damage to the peatland system and/or changes to the typical peatland vegetation (Pellerin *et al*. 2006, Preez & Brown 2011, Mendes *et al*. 2020). It also shifts the vegetation communities away from species that would typically characterise peatlands towards negative indicator species that are more tolerant of grazing, such as *H. lanatus*. The result is the loss of inherent peatland ecosystem services such as water regulation and carbon sequestration (Lindsay *et al*. 2014, Pereira *et al*. 2019).

This peatland complex is nowadays an expression of its own resistance and a series of disturbances related to the history of the island itself. The central plateau of Terceira Island, where this complex is located, was formerly a more extensive area of wetlands, mainly peatlands, in the past. This peatland complex has persisted through time, but is gradually changing (using historical aerial photos dated 1958 and 2000 for reference). In terms of peatland distribution, the analyses from this study showed very similar results for 2000 (based on aerial photos) and currently, whereas other adjacent peatlands were more intensively ploughed or grazed and transformed into pastures.

Based on our local knowledge, we consider that originally (without human intervention), the most important component of the peatlands within this complex would be *Sphagnum* in the wettest areas and a mixture of *Sphagnum* with endemic and native herbs in its moderately wet parts and in the margins (lower wetness); combined with different mosaics of woody / shrubby communities dominated by the endemic shrub / tree *Juniperus brevifolia* (also on the shallower peat), as shown in Figure 9.

This is an extremely important peatland complex for the Azorean Natura 2000 network and for Terceira Island Natural Park because it is one of the largest (12.57 ha) peatlands in the Central Island plateau, where agriculture activity prevails. In this agricultural area, the persistence of natural and semi-natural patches are quite important as biological and genetic reservoirs. Furthermore, this complex is located within a corridor that connects the two main

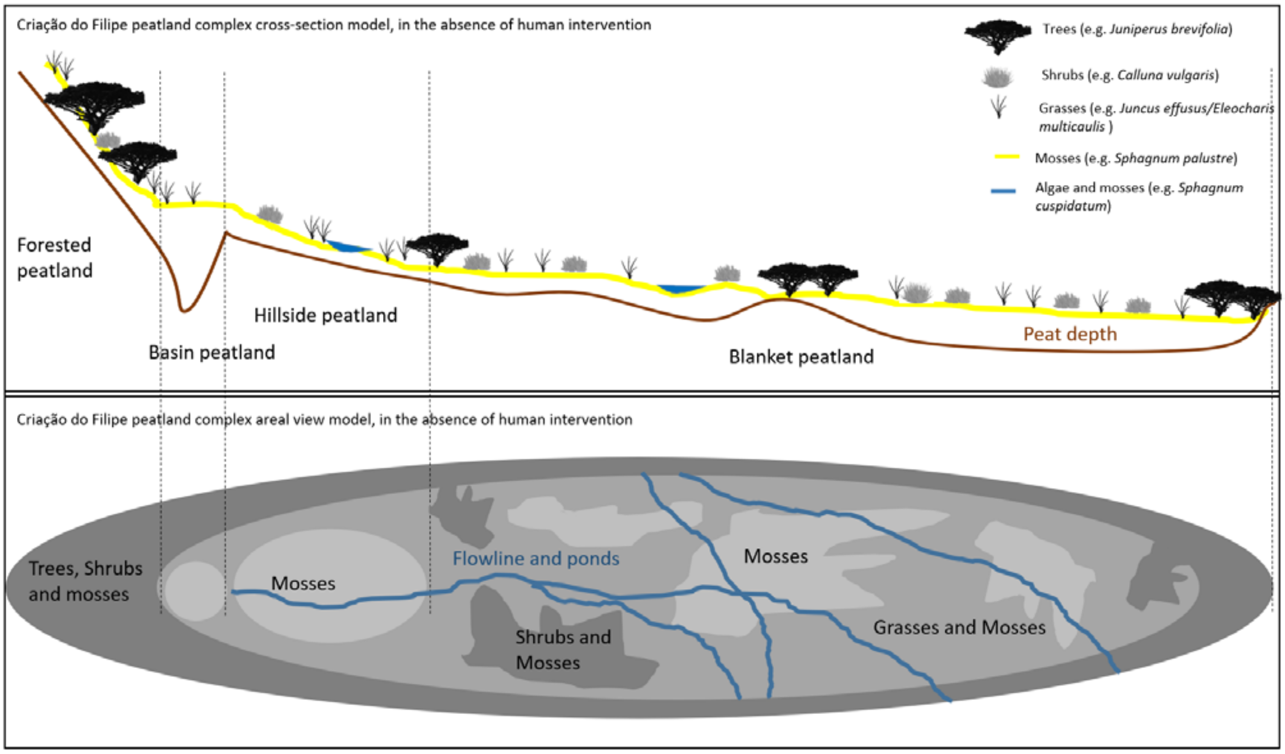

Figure 9. Pico da Criação do Filipe peatland complex before human intervention, based on theoretical modelling. From A to C' (left to right) considering Figure 3.

natural areas in Terceira Island (Santa Barbara Mountain and Pico Alto) (Dias *et al*. 2021). Based on this and other studies (Mendes 1998), this complex possesses the deepest peat found on the island and this has helped to preserve its characteristic features. The relevance of the area is further reinforced as it is a habitat for ten endemic species, including Habitats Directive protected species, as well as a priority habitat type listed in Annex I of the EU Habitats Directive.

Recognising the value of the area, local authorities must address the moderation and/or the removal of pressure factors from these peatlands. The most significant is cattle, which should be removed from the complex as well as from its water catchment areas to maintain water quantity and quality. This would apply not only to the peatland complex itself but also for the other dependent wetlands downstream. This area, under the management responsibility of Regional Environmental Services, should be the object of an active conservation/restoration plan.

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AUTHOR CONTRIBUTIONS

CM and ED conceived and designed the research; CM performed the experiments, analysed the data and wrote the manuscript; CM edited the manuscript; and DP was responsible for the GPR and SIG data presented. All authors commented on all versions of the manuscript.

REFERENCES

Azevedo, E. (2005a) *Model Cielo. Precipitação acumulada Ilha Terceira* (*Accumulated Precipitation Terceira Island*). Centro do Clima, Meteorologia e mudanças globais da Universidade dos Açores (CMMG), Angra do Heroísmo (in Portuguese). Online at: http://www.climaat.angra.uac.pt/CD/imprimir/Terceira_Prec.pdf, accessed 06 Dec 2019.

Azevedo, E. (2005b) *Model Cielo. Humidade relativa anual Ilha Terceira* (*Relative Humidity Terceira Island*). Centro do Clima, Meteorologia e mudanças globais da Universidade dos Açores (CMMG), Angra do Heroísmo (in Portuguese). Online at: http://www.climaat.angra.uac.pt/CD/pages/terceira_hum.htm, accessed 06 Dec 2019.

Azevedo, E. (2005c) *Model Cielo. Temperatura média anual Ilha Terceira (Annual Average Temperature Terceira Island)*. Centro do Clima, Meteorologia e mudanças globais da Universidade dos Açores (CMMG), Angra do Heroísmo (in Portuguese). Online at: http://www.climaat.angra.uac.pt/CD/pages/terceira_temp.htm, accessed 06 Dec 2019.

Bacon, K., Baird, A., Blundell, A., Bourgault, M-A., Chapman, P., Dargie, G., Dooling, G., Gee, C., Holden, J., Kelly, T., McKendrick-Smith, K., Morris, P., Noble, A., Palmer, S., Quillet, A., Swindles, G., Watson, E.J., Young, D.M. (2017) Questioning ten common assumptions about peatlands. *Mires and Peat*, 19(12), 23 pp.

Belyea, L., Baird, A. (2016) The limits to peat bog growth: Cross-scale feedback in peatland development. *Ecological Monographs*, 76, 299–322.

Dias, E. (1986) *Estudo Bio-Ecológico da Bacia da Lagoa do Negro* (*Bio-Ecological Study of Lagoa do Negro Watershed*). Communications and Reports of the Biology Department 16, Azores University, Angra do Heroísmo, 131 pp. (in Portuguese).

Dias, E. (1996) *Vegetação Natural dos Açores. Ecologia e Sintaxonomia das Florestas Naturais* (*Natural Vegetation of the Azores. Ecology and Syntaxonomy of Natural Forests*). PhD thesis, Department of Agricultural Sciences, Azores University, Angra do Heroísmo, 289 pp. (in Portuguese).

Dias, E. (2016) *Livro Vermelho da Flora Vascular dos Açores com Status por Ilha* (*Red Book of Vascular Flora of the Azores, with Status by Island*). Gabinete de Ecologia Vegetal e Aplicada (GEVA), Faculdade de Ciências Agrárias e do Ambiente, Azores University, Angra do

Heroísmo, 14 pp. (in Portuguese). Online at: http://eduardodias.com.pt/Lista/Lista_Vermelha_Flora_A%C3%A7ores.pdf, accessed 18 Dec 2019.

Dias, E., Mendes, C., Pereira, D. (2012) *Relatório de Monitorização da Rede Natura 2000 dos Açores - Áreas Terrestres* (*Monitoring Plan of Azores Nature 2000 - Terrestrial Areas*). Institute for Nature Conservation and Forests (ICNF), Lisbon. Online at: http://www2.icnf.pt/portal/pn/biodiversidade/rn2000/dir-ave-habit/rel-nac/rel-nac-07-12, accessed 21 May 2020 (in Portuguese).

Dias, E., Mendes, C., Pereira D., Bettencourt S. (2021) Conservação da conectividade: manter as conexões para a natureza (Conserving connectivity: maintaining connections for nature). *Atlântida*, LXVI, 383–408 (in Portuguese).

Doyle, G. (1990) Phytosociology of Atlantic blanket bog complexes in North-West Mayo. In: Doyle G. (ed.) *Ecology and Conservation of Irish Peatlands*, Royal Irish Academy, Dublin, 75–90.

Elias, R.B., Dias, E. (2009) Effects of landslides on the mountain vegetation of Flores Island, Azores. *Journal of Vegetation Science*, 20, 706–717.

Evans, C., Bonn, A., Holden, J., Reed, M., Evans, M., Worrall, F., Couwenberg, J., Parnell, M. (2014) Relationships between anthropogenic pressures and ecosystem functions in UK blanket bogs: Linking process understanding to ecosystem service valuation. *Ecosystem Services*, 9, 5–19.

Evans, M., Warburton, J. (2005) Sediment budget for an eroding peat-moorland catchment in northern England. *Earth Surface Processes and Landforms*, 30, 557–577.

Gabriel, R., Sjögren, E., Schumacker, R., Sérgio, C., Aranda, S., Claro, D., Homem, N., Martins, B. (2010) List of bryophytes (Anthocerotophyta, Marchantiophyta, Bryophyta). In: Borges, P.A.V., Costa, A., Cunha, R., Gabriel, R., Gonçalves, V., Martins, A.F., Melo, I., Parente, M., Raposeiro, P., Rodrigues, P., Santos, R.S., Silva, L., Vieira, P., Vieira, V. (eds.) *A List of the Terrestrial and Marine Biota from the Azores*, Princípia Editora Lda, Cascais, 99–115.

Grabovik, S., Kantserova, L., Ananyev, V. (2021) Changes in plant cover of a mire in southern Karelia, Russia over 50 years following drainage. *Mires and Peat*, 27, 24, 11 pp.

Hammond, R. (1981) *The Peatlands of Ireland: To Accompany Peatland Map of Ireland, 1978*. Soil Survey Bulletin 35 (second edition), An Foras Taluntais, Dublin, 60 pp. Online at: https://www.teagasc.ie/media/website/environment/soil/Peatlands-of-Ireland.pdf, accessed 27 Nov 2019.

Jones, M., Yu, Z. (2010) Rapid deglacial and early Holocene expansion of peatlands in Alaska. *Proceedings of the National Academy of Sciences*, 107, 7347–7352.

Kettridge, N, Turetsky, M., Sherwood J., Thompson D., Miller, C., Benscoter, B., Flannigan, M., Wotton, B., Waddington, J. (2015) Moderate drop in water-table increases peatland vulnerability to post-fire regime shift. *Scientific Reports*, 5, 8063, 4 pp.

Kettridge, N., Lukenbach, M., Hokanson, K., Devito, K., Petrone, R., Mendoza, C., Waddington, J. (2019) Severe wildfire exposes remnant peat carbon stocks to increased post-fire drying. *Scientific Reports*, 9, 3727, 6 pp.

Laiho, R. (2006) Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology & Biochemistry*, 38, 2011–2024.

Lake, P. (2013) Resistance, resilience and restoration. *Ecological Management & Restoration*, 14(1), 20–24.

Large, A. (2001) Reversing spontaneous succession to protect high-value vegetation: Assessment of two Scottish mires using rapid survey techniques. *Applied Vegetation Science*, 4, 103–110.

Limpens, J., Berendse, F., Blodau, C., Canadell, J., Freeman, C., Holden, J., Roulet, N., Rydin, H., Schaepman-Strub, G. (2008) Peatlands and the carbon cycle: from local processes to global implications - a synthesis. *Biogeosciences*, 5, 1475–1491.

Lindsay, R., Birnie, R., Clough, J. (2014) *Peat Bog Ecosystems: Grazing and Trampling*. Briefing Note No. 7, IUCN UK Committee Peatland Programme, International Union for the Conservation of Nature (IUCN), Edinburgh, 4 pp.

Lüpnitz, D. (1975) Geobotanische Studien zur Natürlichen Vegetation der Azorean unter Berücksichtigung der Chorologie innerhalb Makaronensis (Geobotanical studies of the natural vegetation of the Azores in the context of the chorology of Macaronesia). *Beiträge zur Biologie der Pflanzen*, 51, 149–317 (in German).

Madruga, J. (1995) *Caracterização e génese do horizonte plácico em solos vulcânicos do arquipélago dos Açores* (*Characterization and Genesis of Placic Horizon in Volcanic Soils of Azores Archipelago*). PhD thesis, Department of Agricultural Sciences, Azores University, Angra do Heroísmo, XVI+244 pp. (in Portuguese).

Maltby, E. (1997) Developing guidelines for the integrated management and sustainable utilization of tropical lowland peatlands. In: Rieley, J., Page, S. (eds.) *Biodiversity and Sustainability of*

Tropical Peatlands, Samara Publishing Limited, Cardigan, UK, 9–18.

Mendes, C. (1998) *Caracterização das turfeiras de Sphagnum spp. da Ilha Terceira* (*Classification of the Sphagnum Bogs on Terceira Island*). Final Course thesis, Department of Agricultural Sciences, Azores University, 110 pp. (in Portuguese).

Mendes, C. (2017) *Study of the Ecological Processes Promotors of Regenerative Succession of Azorean Peatlands, after Anthropogenic Pressure, as a Model of Ecological Restoration*. PhD thesis, University of Azores, 258 pp.

Mendes, C., Dias, E. (2007) Characterisation of a basin mire in the Azores archipelago. *Mires and Peat*, 2, 08, 11 pp.

Mendes, C., Dias, E. (2009) Characterisation of a directive habitat protected quaking bog: Sanguinhal Mire, Terceira Island (Azores). *Acta Botanica Brasílica*, 23(3), 812–818.

Mendes, C., Dias, E. (2013) Classification of *Sphagnum* peatlands in Azores—cases from Terceira Island. *Suo*, 64(4), 147–163.

Mendes, C., Dias, E. (2017) Azores. In: Joosten, H., Tanneberger, F., Moen, A. (eds.) *Mires and Peatlands of Europe: Status, Distribution and Conservation*, Schweizerbart Science Publishers, Stuttgart, 282–287.

Mendes, C., Dias, E., Ponte M., Mendes, A., Rochefort, L. (2019) The distribution and naturalness of peatland on Terceira Island (Azores): instruments to define priority areas for conservation and restoration. *Mires and Peat*, 24, 35, 16 pp.

Mendes, C., Dias, E., Rochefort, L., Azevedo, J. (2020). Regenerative succession of Azorean peatlands after grazing: vegetation path to self-recovery. *Wetlands Ecology and Management*, 28, 177–190.

Minayeva, T., Bragg, O., Cherednichenko, O., Couwenberg, J., van Duinen, G.-J., Giesen, W., Grootjans, A., Grundling, P.-L., Nikolaev, V., van der Schaaf, S. (2008) Peatlands and biodiversity. In: Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M., Stringer, L. (eds.) *Assessment on Peatlands, Biodiversity and Climate Change: Main Report*, Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen, 60–98.

Montanarella, L., Jones, R., Hiederer, R. (2006) The distribution of peatland in Europe. *Mires and Peat*, 1, 01, 10 pp.

Moore, L. (2017) *Rabbit Nutrition and Nutritional Healing*. Third edition, Evonne's Art Creations Inc., Lusby MD, USA, 246 pp. Online at: https://www.evonnesartcreations.com/doc/Rabbit%20Nutrition%20pdf.pdf, accessed 07 Apr 2019.

Morton, P., Heinemeyer, A. (2019) Bog breathing: The extent of peat shrinkage and expansion on blanket bogs in relation to water table, heather management and dominant vegetation and its implications for carbon stock assessments. *Wetlands Ecology and Management*, 27(4), 467–482.

Page, S., Hooijer, A. (2016) In the line of fire: the peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B*, 371, 20150176, 9 pp.

Pellerin, S., Huot, J., Côté, S. (2006) Long-term effects of deer browsing and trampling on the vegetation of peatlands. *Biological Conservation*, 128(3), 316–326.

Pereira, D. (2015) *Avaliação do Valor dos Ecossistemas de Turfeiras dos Açores, com Recurso a Modelação em Sistemas de Informação Geográfica* (*Evaluation of Azorean Peatlands using Geographic Information Systems*). PhD thesis, Department of Agricultural Sciences, Azores University, Angra do Heroísmo, 138 pp. (in Portuguese).

Pereira, D., Dias, E., Ponte, M. (2017) Investigating the internal structure of four Azorean *Sphagnum* bogs using ground-penetrating radar. *Mires and Peat*, 19, 03, 19 pp.

Pereira, D., Mendes, C., Dias, E. (2019) The importance of land cover planning on climatic events: evaluation of peatlands' buffer impact on the mountains of Terceira and Flores Islands (Azores, Portugal). In: Fernandes, F., Malheiro, A., Chaminé, H. (eds.) *Advances in Natural Hazards and Hydrological Risks: Meeting the Challenge*, Proceedings of the 2nd International Workshop on Natural Hazards (NATHAZ'19) Pico Island—Azores, Springer Nature, Cham, Switzerland AG, 91–95.

Pinheiro, J. (1990) *Estudo dos Principais Tipos de Solos da Ilha Terceira (Açores)* (*A Study of the Major Soil Types of Terceira Island (Azores)*). PhD thesis, Department of Agricultural Sciences, Azores University, Angra do Heroísmo, 256 pp. (in Portuguese).

Preez, P., Brown L. (2011) Impact of domestic animals on ecosystem integrity of Lesotho high altitude peatlands. In: Grillo, O., Venora, G. (eds.) *Ecosystems Biodiversity*, InTech, Rijeka, Croatia, 249–271.

Remison, S.U., Snaydon, R.W. (1980) A comparison of root competition and shoot competition between *Dactylis glomerata* and *Holcus lanatus*. *Grass and Forage Science*, 35, 183–187.

Renou-Wilson, F., Bolger, T., Bullock, C., Convery, F., Curry, J., Ward, S., Wilson, D., Müller, C. (2011) *Bogland: Sustainable Management of Peatlands in Ireland*. STRIVE Report No. 75, Environmental Protection Agency, Johnstown Castle, Co. Wexford, Ireland, 157 pp.

Rochefort, L., Lode, E. (2006) Restoration of degraded boreal peatlands. In: Wieder, R.K., Vitt, D.H. (eds.) *Boreal Peatland Ecosystems*, Ecological Studies 188, Springer, Germany, 382–423.

Säurich, A., Tiemeyer, B., Don, A., Fiedler, S., Bechtold, M., Amelung, W., Freibauer, A. (2019) Drained organic soils under agriculture—The more degraded the soil the higher the specific basal respiration. *Geoderma*, 355, 113911, 12 pp.

Silva, L., Moura, M., Schäfer, H., Rumsey, F., Dias, E. (2010) List of vascular plants. In: Borges, P., Costa, A., Cunha, R., Gabriel, R., Gonçalves, V., Martins, A., Melo, I., Parente, M., Raposeiro, P., Rodrigues, P., Santos, R., Silva, L., Vieira, P., Vieira, V. (eds.) *A List of the Terrestrial and Marine Biota from the Azores*, Princípia Editora Lda, Cascais, 122–146.

Sjögren, E. (1973) *Recent Changes in the Vascular Flora and Vegetation of the Azores Islands*. Memórias da Sociedade Broteriana 22, Instituto Botânico da Universidade de Coimbra, 453 pp.

Sousa, S. (2002) *A Importância da* Erica azorica *no Planeamento Ambiental Regional. Contributo para a determinação do papel desempenhado por esta espécie nos ecossistemas naturais das Ilhas Terceira e Pico* (*The Importance of* Erica azorica *in Regional Environmental Planning. Contribution for the Determination of the Role Played by this Species in the Natural Ecosystems of Terceira and Pico Islands*). Final Degree thesis, Department of Agricultural Sciences, Azores University, Angra do Heroísmo, 133 pp. (in Portuguese).

Swindles, G., Morris, P., Wheeler, J., Smith, M., Bacon, K., Turner, T., Headley, A., Galloway, J. (2016) Resilience of peatland ecosystem services over millennial timescales: evidence from a degraded British bog. *Journal of Ecology*, 104, 621–636.

Tallis, J. (1985) Mass movement and erosion of a Southern Pennine blanket peat. *Journal of Ecology*, 73, 283–315.

Turetsky, M., Wieder, K., Halsey, L., Vitt, D. (2002) Current disturbance and the diminishing peatland carbon sink. *Geophysical Research Letters*, 29, 7–10.

Waddington, J., Morris, P., Kettridge, N., Granath, G., Thompson, D., Moore, P. (2015) Hydrological feedbacks in northern peatlands. *Ecohydrology*, 8, 113–127.

Wallèn, B. (1987) Growth pattern and distribution of biomass of *Calluna vulgaris* on an ombrotrophic peat bog. *Holartic Ecology*, 10(1), 73–79.

Westhoff, V., Van der Maarel, E. (1978) The Braun-Blanquet approach. In: Whittaker, R. (ed.) *Classification of Plant Communities*, Dr W. Junk bv Publishers, The Hague, 289–398.

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