Investigating the internal structure of four Azorean *Sphagnum* bogs using ground-penetrating radar

D. Pereira, E. Dias and M. Ponte

Institute of Agronomy and Environment Research and Technology (IITAA), University of the Azores, Portugal

SUMMARY

This study evaluates the applicability of ground penetrating radar (GPR) as a technique for determining the thickness and internal structure of four peat deposits on Terceira Island (Azores archipelago, mid-Atlantic region). The peatlands studied are all *Sphagnum* mires located above 500 m a.s.l., but they differ hydrogenetically and in their degree of naturalness. Radargrams for all four bogs, obtained using both 100 MHz and 500 MHz GPR antennae, are presented and compared. The radargram data were validated against peat characteristics (bulk density, von Post H, US method) obtained by direct sampling ('open cores') across the whole peat profile at each site. A scheme of 'soft scoring' for degree of naturalness (DN) of the peatland was developed and used as an additional validation factor. The GPR data were positively correlated with DN, and relationships between GPR data, peat bulk density and degree of humification (H) were also found. From the radargrams it was possible to distinguish the interface between the peat and the mineral substratum as well as some of the internal structure of the peat deposit, and thus to derive the total thickness of the peat deposit and (in some cases) the thicknesses of its constituent layers. The first evaluation of the propagation velocity of electromagnetic waves in Azorean peat yielded a value of 0.04 m ns^{-1} for 100 MHz and 500 MHz radar antennae. For one of the study sites, the GPR data were analysed using GIS software to produce tridimensional models and thus to estimate the volumes of peat layers. This type of analysis has potential utility for quantifying some of the ecosystem services provided by peatlands.

KEY WORDS: conservation, degree of naturalness, ecology, ecosystem services, GPR, stratigraphy

INTRODUCTION

The Azores archipelago (Mid-Atlantic region) comprises nine volcanic islands distributed across an area of approximately 1,000 km^2 at latitude 36º 56′–39º 42′ N and longitude 25º 5′–31º 12′ W (Dias & Mendes 2007). Terceira Island (~402 km^2) is located near its centre (Figure 1).

Due to high rainfall and humidity in the Azorean uplands, an impermeable (*Placic*) horizon tends to form in andosoils (Madruga 1995). This, in turn, induces creation of the basic conditions for peat formation - namely waterlogging, low pH and anoxia (McQueen 1990), in the absence of ice. In these environments, the activity of the soil microflora is limited and the decomposition of organic matter is very slow, so that layers of undecomposed or partially decomposed organic material accumulate (Dias 1996). The nature of the organic substrate formed is highly variable depending on the plant source material (*Sphagnum* spp., grasses, trees, etc.) (Moreira 1992) and its position in the profile. Under certain conditions it may develop into a mire.

Mires are typical structural elements of the Azorean landscape (Figure 2) and occupy about 40 % of the total area of NATURA 2000 (European nature protection network) sites on the islands. They host a range of protected habitats listed by the European Habitats Directive (EC 1992), and a wide variety of rare and protected species (Mendes & Dias 2002). *Sphagnum* peatlands also provide various ecosystem services including carbon sequestration and accumulation (Wetlands International 1999, Gruber *et al*. 2004, Parish *et al*. 2008), biodiversity maintenance, and water storage (e.g. Rodrigues 2002). Retention of the carbon stored in peatlands is a current global priority, in order to limit further emissions of greenhouse gases to the atmosphere; and efforts to reverse the widespread degradation of peatlands through past and present human activities (Strack 2008) are increasing around the world (e.g. McInnes 2007, Wood & Halsema 2008, Borges *et al*. 2010, Joosten *et al*. 2012, Maes *et al*. 2013). For this purpose, it will be necessary to prioritise peatlands for restoration. This might be done according to the quantity of peat carbon they contain, creating a requirement to assess the thickness of peat layers across large areas.

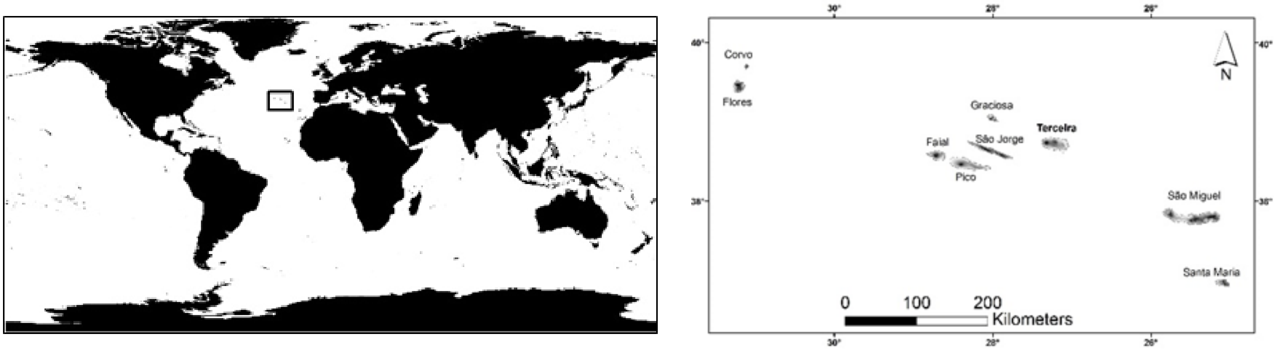

Figure 1. Location of the Azores in the world (left) and map of the Azores archipelago (right) showing the main islands: Corvo and Flores (Western Group); Faial, Graciosa, Pico, São Jorge and Terceira (Central Group); Santa Maria and São Miguel (Eastern Group).

Peat thickness (depth) has traditionally been estimated by manual probing, usually with metal rods (e.g. Worsfold *et al*. 1986, Buffam *et al*. 2010, Householder *et al*. 2012, Parry *et al*. 2012, Valpola *et al*. 2012). In the Azores, it has previously been determined by a variant of this classical technique, by probing with PVC tubes (Dias & Mendes 2007, Mendes & Dias 2008, Mendes & Dias 2009). Although successful, these methods are too costly, in terms of time and logistics, for easy application over large areas.

An alternative method involves the use of Ground Penetrating Radar (GPR), which is a non-destructive geophysical prospecting technique for exploring the shallow subsurface. It is based on the reflection of high-frequency electromagnetic pulses, directed into the ground from an antenna at the surface, by various materials and features below. The electromagnetic waves (EMW) are recaptured after reflection by a receiving antenna, also located at the ground surface. The GPR records two-way travel times (TWT) of the radar waves, from which the depths of subsurface reflectors can be estimated. Because travel times are influenced by the physical and chemical properties of the different materials traversed, these can be distinguished. It is often possible, for example, to identify the transition from organic to mineral sediment at the interface between the peat deposit and the mineral substratum (Baraniak 1983, Warner *et al.* 1990, Hänninen 1992, Slater & Reeve 2002, Comas *et al.* 2004, Comas & Slater 2005) and use its location to derive peat thickness.

In recent decades, GPR has been used to determine peat thickness in various locations (e.g. Doolittle & Collins 1995, Sheng *et al*. 2004, Comas *et al*. 2004, 2005a, 2005b; Comas & Slater 2005, Holden 2005, Szuch *et al*., 2006, Dallaire & Garneau 2008, Nolan *et al.* 2008, Comas & Slater 2009, Dallaire 2010, Howell *et al*. 2010). It has also been used to study the stratigraphy of peat bogs (Baraniak *et al.* 1983, Warner *et al.* 1990, Hänninen 1992, Holden *et al*. 2002, Moorman *et al*. 2003, Sheng *et al.* 2004, Bradford *et al.* 2005); to distinguish between stratigraphic units with different moisture content or bulk density (BD) and locate charcoal layers or soil pipes (Warner *et al*. 1990, Slater & Reeve 2002); and even to determine water availability (Holden *et al*. 2002).

In *Sphagnum* peatlands, GPR is used to study the peat layer to depths of several metres, depending on the EMW frequency used and the characteristics of the material. It allows continuous data collection in the field and reduces the degree of uncertainty associated with classical techniques for the study of deep peat. This technique provides a continuous image of the subsurface, and thus allows the connection of data through Geographical Information Systems (GIS) to create a regional upscaling methodology with faster and more effective logistics than can be achieved using traditional peat depthing techniques (Warner *et al*. 1990, Parry *et al*. 2014). Properly calibrated GPR data can be inserted into a GIS, allowing for fast tridimensional mapping and peat volume calculation when combined with other information (e.g. Sheng *et al*. 2004). However, these techniques need to be calibrated according to the type of substrate (e.g. Rosa *et al*. 2009, Parsekian *et al*. 2012).

It can be difficult to apply GPR techniques in wetlands because the EMW may suffer attenuation due to the electrical conductivity of the pore water, which reduces their penetration (e.g. Davis & Annan 1989). On the other hand, peat itself has favourable electrical characteristics, resulting in low attenuation and excellent results (Halleux 1990, Mellet 1995, Comas *et al.* 2004, 2005a, 2005b; Comas & Slater 2005, Comas & Slater 2009).

Figure 2. Typical landscape with peat bogs in the interior part of Terceira Island.

The relative dielectric permittivity of the materials traversed influences diffusion of the transmitted EMW. As the speed of EMW transmission varies with the material studied, depths from GPR will be inaccurate if EMW speed is not compensated for. One method for estimating EMW speed is by performing GPR common-midpoint (CMP) surveys (e.g. Warner *et al*. 1990, Theimer *et al*. 1994, Lapen *et al*. 1996, Slater & Reeve 2002, Comas *et al*. 2004, 2005b), with the dielectric constant of the peat sometimes being determined in the laboratory (e.g. Theimer *et al*. 1994). When applying GPR methodologies to substantial areas of bog, it is important to have a quick method for determining the speed of the EMW, such as a depth-to-target calibration with manual sampling points (e.g. Bjelm 1980, Worsfold *et al*. 1986, Welsby 1988, Theimer *et al.* 1994, Slater & Reeve 2002, Bradford *et al*. 2005, Comas *et al*. 2005b, Plado *et al*. 2011). Rosa *et al.* (2009) discussed this option and determined the number of manual measurements required to improve peat thickness estimations with GPR. However, the potential for application of this methodology in Azores peat bogs is limited by some of their characteristics; notably their small sizes, the heterogeneity of their microrelief, and large variations in their peat properties over short distances.

The objectives of the study described here were to:

1. calibrate the velocity of the EMW generated by GPR antennae to Azorean peat bogs by validation against open cores;
2. compare the ability of 100 and 500 MHz GPR antennae to distinguish peat layers in Azorean peat bogs, considering Placic or lava soils, the degree of saturation with water, and the ages of the bogs (Wieder & Vitt 2006);
3. investigate the applicability of GPR in comparing the internal stratigraphy of Azorean bogs in various natural states, allowing for management; and
4. explore the potential for using GPR in combination with GIS to estimate the peat reserves represented by different layers in various types of peat bogs, in relation to the provision of ecosystem services.

METHODS

Study sites

Four peat bogs were studied. All of them were located above 500 m a.s.l. on Terceira Island (Figure 3). Originally, they may all have been part of a single ancient mire, as inferred by Dias (1996),

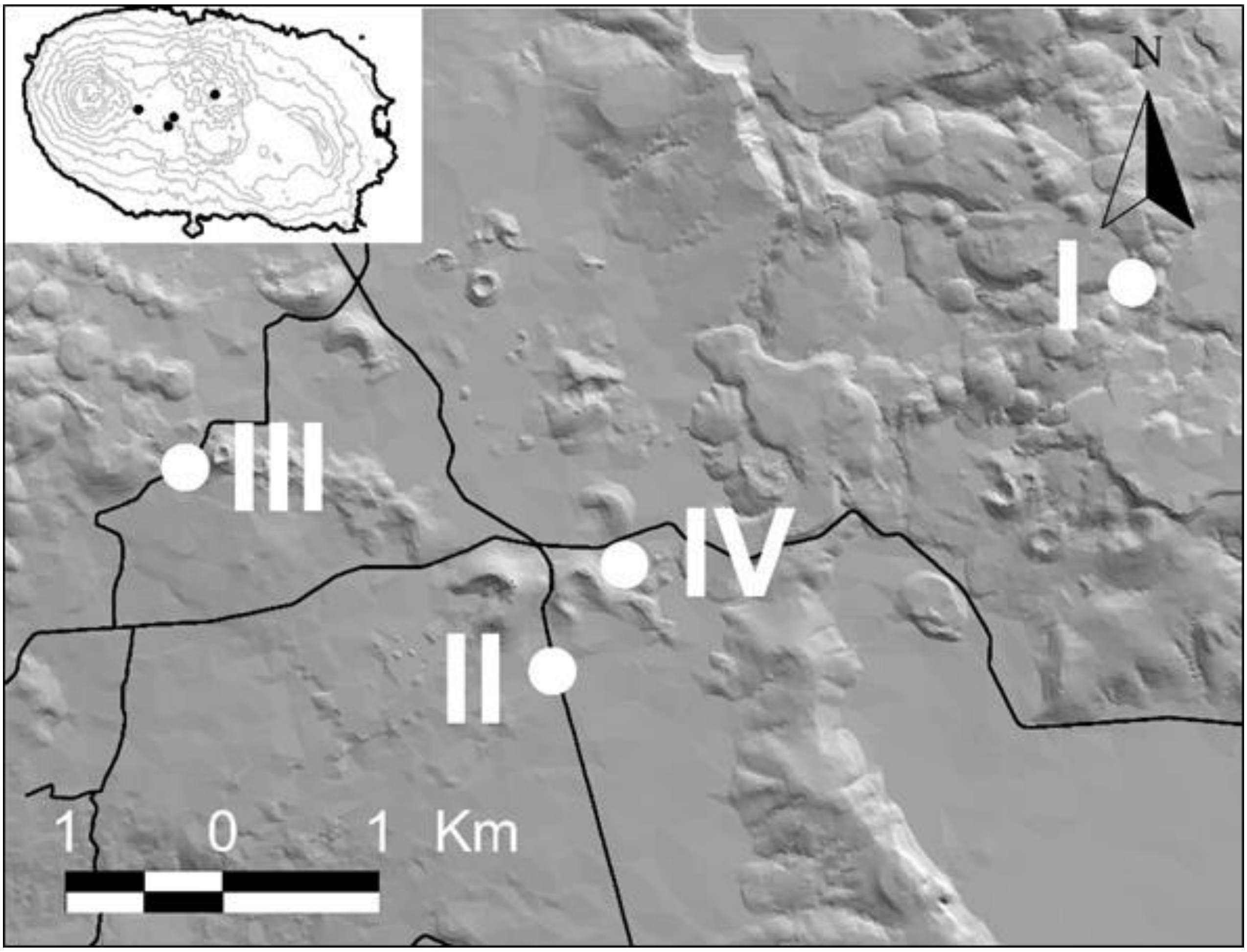

Figure 3. Locations of the four studied bogs, which all lie above 500 m a.s.l. on Terceira Island (inset).

but are now separate peatlands in different states of preservation, largely due to human activities (Mendes 1998, Mendes & Dias 2002).

Site I (3810 m^2) is an endorheic basin bog (Mendes 2010, Mendes & Dias 2013), classed as blanket bog (Habitat 7130 of the European Habitats Directive). It accumulates considerable runoff from the surroundings and remains full of water throughout the year. The vegetation of its interior is dominated by lawns of *Sphagnum* and *Eleocharis*, and there are small hummocks of *Carex* and *Politrychum*. A marginal community of *Juncus effusus* is surrounded by laurel forest (Dias 1996) dominated by *Laurus azorica*, *Juniperus brevifolia* and *Ilex azorica*, and a pastured *Callunetum*. Although classified as natural and subject to no significant pressures by Mendes (2010), the bog has been altered by historical grazing combined with burning (to improve pasture quality) around its margins.

Site II (19414 m^2) is classified by Mendes (2010) as active raised bog (Habitat 7110 of the European Habitats Directive), and is described in detail by Mendes & Dias (2013). It is quite poor in terms of plant communities (Mendes 2010) due to its ombrotrophic nature (fed exclusively by rainwater). Its central parts are essentially occupied by *Sphagnum palustre* and there are some patches of *Juncus effusus* communities in its margins, where temporary ponds frequently develop. There is also a small area of exotic trees arising from a recent planting trial of *Cryptomeria japonica*. Although the trial was deemed unsuccessful due to high sapling mortality, some of the trees continue to grow. Mendes (2010) reports that this bog is in a natural state, but it is currently subject to some pressure (mainly on its margins) due to the presence of animals in nearby pastures.

Site III (138468 m^2) is classified by Mendes (2010) as a blanket bog (Mendes & Dias 2013) and, like Site I, as Habitat 7130 of the European Habitats Directive. It is characterised by uneven terrain that can be associated with a previous afforestation attempt and its current use as pasture. This bog has an intense microrelief with small endorheic areas, but is dominated by hummock structures. Its floristic composition is heterogeneous and varies with the microrelief. Lower-lying areas (hollows and small pools) are dominated by communities of *Sphagnum* (mainly *S. palustre* and *S. auriculatum*) and *Eleocharis multicaulis*, whereas the hummocks are dominated by *Polytrichum* and *Pteridium* species. The highest and driest areas are favoured by animals, and are dominated by grasses such as *Agrostis* (*A. gracililaxa and A. azorica*) and *Holcus* (mainly *H. lanatus*) although there is a very low cover of *Sphagnum* species. This peatland is severely threatened (Mendes 2010), is under pressure for agricultural development, and is at an advanced stage of degradation.

Site IV (50296 m^2) is a basin bog belonging to a transition subtype (Mendes 2010) with narrow but pronouncedly endorheic margins that receive small amounts of runoff water (Mendes & Dias 2013), and is also classed as blanket bog (Habitat 7130 of the European Habitats Directive). It was partially ploughed 15 years ago and still drains through its margins when the water table is high, especially in winter. This peatland is dominated by *Callunetum* vegetation, which mainly develops on hummocks along with other bushes such as *Erica azorica* and *Frangula azorica*, which are both classified by the European Habitats Directive as endemic, rare and protected species. In hollows, communities of *Sphagnum palustre* and *Sphagnum centrale* prevail. There are also several ponds dominated by *Juncus effusus*. The most significant negative actions affecting this peat bog occurred approximately 15 years ago, when it was both grazed and partially planted with *Cryptomeria*. It appears to be recovering from ploughing, and only gradually losing water from its margins. It is classified by Mendes (2010) as natural.

GPR surveys

The GPR surveys, which covered a total distance of several kilometres, were conducted in 2013. The summer season was chosen because the water content of the peat should then be at its annual minimum, resulting in lower EMW attenuation than at other times of year. The irregular microrelief of the bog surfaces made it impossible to sample for internal structure across a grid of regularly spaced points. Instead, we established transects and surveyed tortuous paths along these. The surveys were located with a hand-held GPS (accuracy 3 m).

The GPR antennae used must be appropriate for the material and objectives of the study, and our choices were based on previous published studies (e.g. Theimer *et al*. 1994, Rosa *et al*. 2009). Two different antennae were employed. For deeper bogs we used a MALA ® 100 MHz unshielded RTA with a separation of 2.2 m and a maximum time window of 1377 ns, with a spacing of 0.1 m for the distance measurement by hip chain or by time. For shallow peat we used a MALA ® 500 MHz shielded antenna with a separation of 0.18 m and a maximum time window of 116 ns, again with a spacing of 0.1 m for the distance measurement by hip chain (distance) or by time. Depending on the material studied, the 500 MHz antenna may have a penetration of up to 5 m and a vertical resolution of 0.05 m, whereas the 100 MHz antenna can penetrate up to 20 m with a vertical resolution of 0.25 m. However, the resolution of the GPR theoretically decreases as depth increases, and depth of penetration may be limited by attenuation by peat moisture (e.g. Theimer *et al*. 1994), signal scattering from gas bubbles or small pieces of undecomposed material, and/or reflection losses from materials with potentially large reflection coefficients such as the *Placic* (iron and magnesium layer) or lava (a geological material rich in iron).

After obtaining the radargrams, it is important to determine which software filters should be applied to them; e.g. to eliminate interference, to highlight certain areas, to compensate for signal decay, or to discriminate between different types of reflections from the geological material (e.g. Neal 2004). The radargrams produced in our study were post-processed with the Reflexw seismic/GPR software (©1997–2010 Sandmeier V.7.0), with the filters (adapted from Sandmeier 1998–2012): *subtract-DC-shift*, *subtract-mean (dewow)*, *gain function (exp. damping)*, *background removal* and *fk migration (Stolt)*, all plotted in *Pointmode*.

Peat sampling

To validate the radargrams, depth profiles were examined in the various peat bogs and the depth and degree of decomposition of their various peat layers determined, using the von Post humification scale (von Post 1924, *op cit*. Paavilainen & Päivänen 1995) as a reference. In addition to coring (holes that were opened in the peatland with shovels and hoes), the depths of the peat layers were measured with a metal ruler inserted in the peat every 10 m of each transect. From each of the peat layers identified, we collected a sample of volume 1750 ml, or 750 ml if the layer was thin. To determine BD, organic matter content and ash content, the samples were dried in the laboratory at 100 °C, weighed, and then submitted to loss-on-ignition (Dean 1974) at 500 ºC before re-weighing. Because the mineral contents of some internal layers of the peat deposits were considerable, due to landslides (e.g. Elias & Dias 2009) or ploughing of the surrounding land (Mendes 2010), it was necessary to correct for ash content before calculating the BD of the organic portion (Nichols & Boelter 1984).

To establish the relationships between core-derived data and radargrams, we cored not only at our study sites but also at other bogs on Terceira Island. This enabled us to convert TWT to real depth, determine the speed of propagation of the EMW signal within the substrate, and thus obtain confirmation of the peat thickness indicated by the radargram.

Estimation of peat volume

For Site IV only, the reflections identified in the post-processed GPR data were integrated using GIS, to produce cartography of the surveys. To eliminate gaps in places where it was not possible to identify a reflector (R2 in Figures 4 and 10), layer thicknesses for such locations were derived by extrapolation using the average percent thicknesses of the layers in the cores. Available topographic data have a horizontal accuracy of 10 m, which means that the best resolution that could be achieved inside the bog was the accuracy of the GPS used (3 m).

The volume of each of identified peat layer was estimated using ArcGIS and Geomedia GIS software. Skidmore (2002) and Sheng *et al*. (2004) suggest that ordinary kriging is suitable for good interpolations to determine peat volume. However, we used simple kriging and a normal score transformation, which returned the best relationship between values for the stratigraphic layers observed in the radargrams and the cores, as well as the tridimensional information produced by that type of kriging (with R^2>0.80 in almost all cases). We also used information from Mendes (1998), who probed some of these peat bogs with PVC tubes, and actual depth measurements, and obtained a good relationship between these data and the output of kriging. The result is a raster with information about the depth of the peat bog within each spatial unit that can be converted into the tridimensional layer models that are used to estimate the volumes of individual peat layers.

Degree of naturalness (DN) of the peat bogs

The study sites were selected as standards for particular states of naturalness (or human disturbance); the condition of each one is actually a function of a characteristic type of disturbance. Because direct information about their grazing regimes, fertilisation and when trees were felled are not available, we developed an index of naturalness as a quantitative indicator of total anthropic pressure. The DN index is derived by scoring each site (1–5) for each of the six factors listed below (the total score for a pristine mire would be 30):

- Effective boundaries of the peat bog: percentage of the margin of each peat bog that is imposed by human structures such fences and walls, weighting that value. The higher the percentage of boundaries with human structures, the lower the score.
- Modification of the surrounding landscape: measured by the presence of grazing or man-made structures such as roads.
- Water circulation: a site with natural circulation of water within and around the bog scores 5. Lower scores are awarded to peatlands from which water is draining due to human actions, or have artificial obstructions to water movement.
- Grazing: the presence and annual duration of grazing within or on the periphery of the bog, verified from historical aerial photography. Sites with high grazing pressure receive low scores.
- Number of exotic species and extent of bog: the score weighs the number of exotic species occurring within the bog against its total area.
- Hummocks: presence or absence of hummocks and the degree to which they are disturbed by cattle trampling or non-natural drainage of water from the bog.

RESULTS

Cores

In general, the floors of the peat bogs investigated proved to be limited by various types of geological substrata which created irregularities such as changes in BD within the peat (as noted by Welsby 1998) (Figure 4). For the classified peat layers, the relationship between von Post Humification and BD had R^2=0.87 (Figures 4 and 5), suggesting the presence of various peat types in each bog. The BD of fibrous or white peat ranged from 0.01 to 0.05 g cm^{-3}, of hemic or dark peat from 0.04 to 0.07 g.cm^{-3}, and of sapric or black peat from 0.09 to 0.12 g.cm^{-3}.

According to the cores and laboratory data for the peat bogs studied, maximum peat BD is positively correlated with DN (Figure 6), indicating that the surface peat layer is the most sensitive to disturbance. One of the factors considered in deriving the DN is the artificial drainage of peat, which causes significant water losses in summer that accelerate mineralisation of the surface layer.

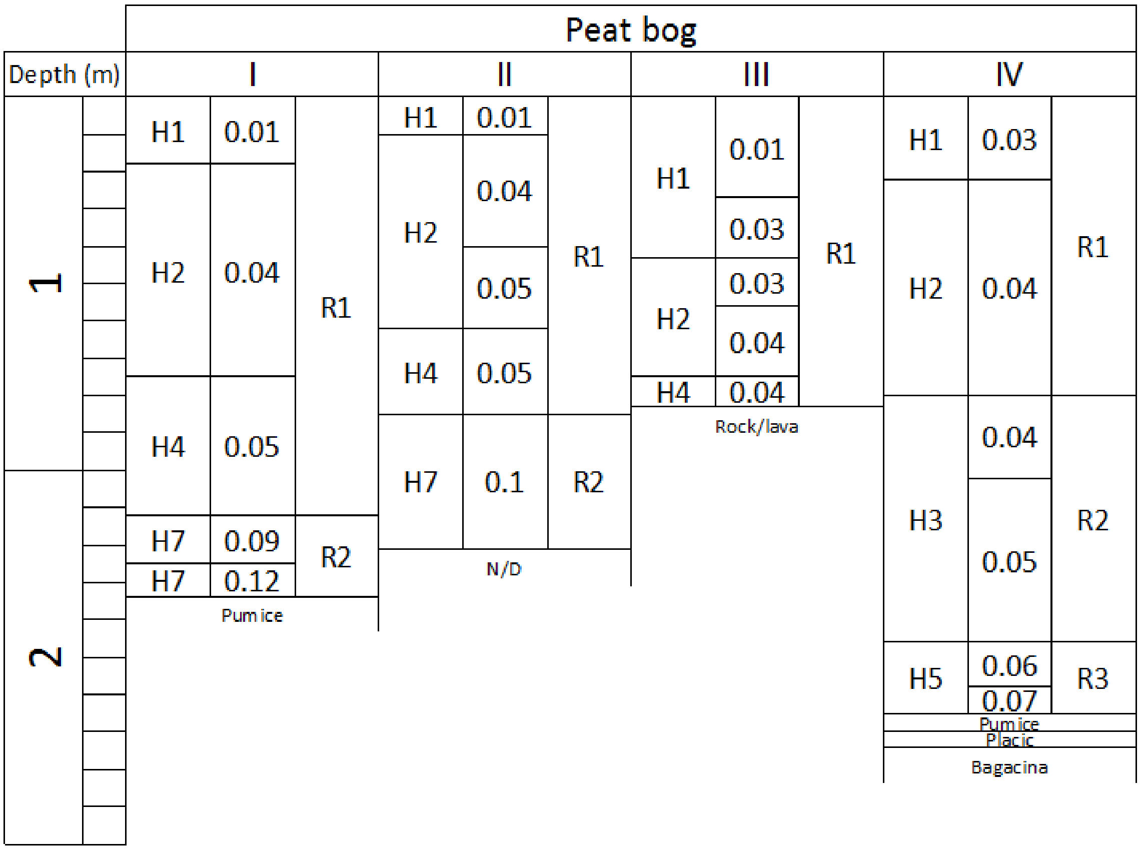

Figure 4. Depth and classification of layers identified in the profiles of the studied bogs. according to the von Post scale (Paavilainen & Päivänen 1995) (H1 to H3 - fibrous or white peat, H4 to H6 - hemic or dark peat, H7 to H10 - sapric or black peat), BD (g cm^{-3}), and identified reflectors in the radargrams (R = reflector).

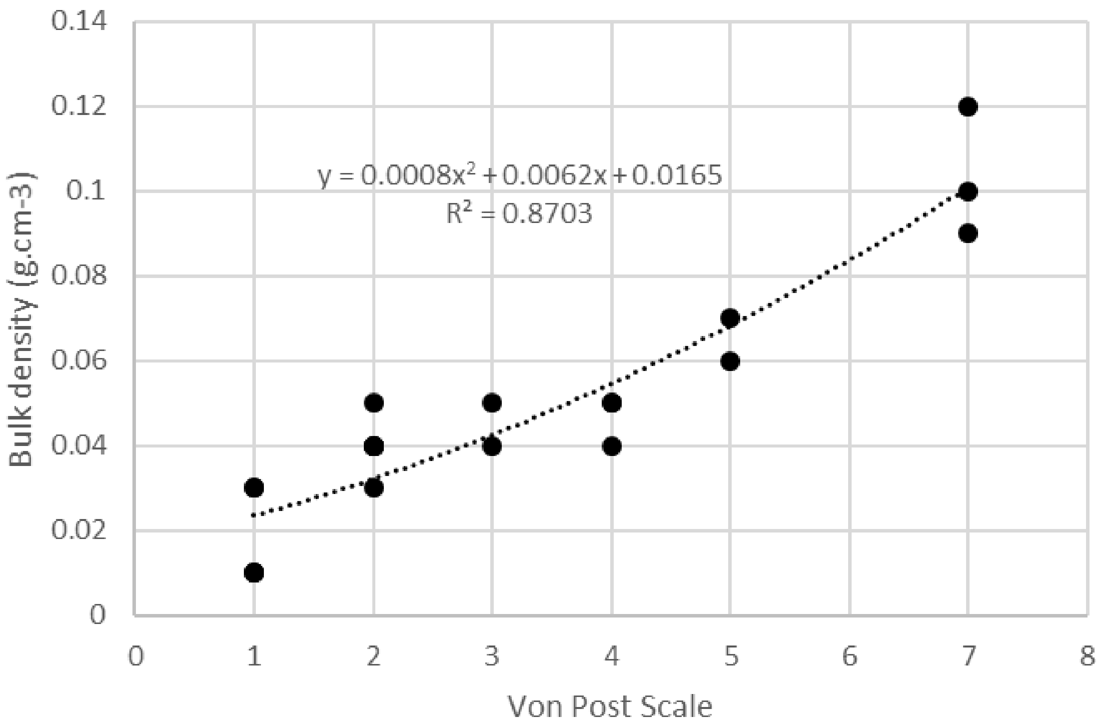

Figure 5. Relationship between BD and von Post huification of the layers identified.

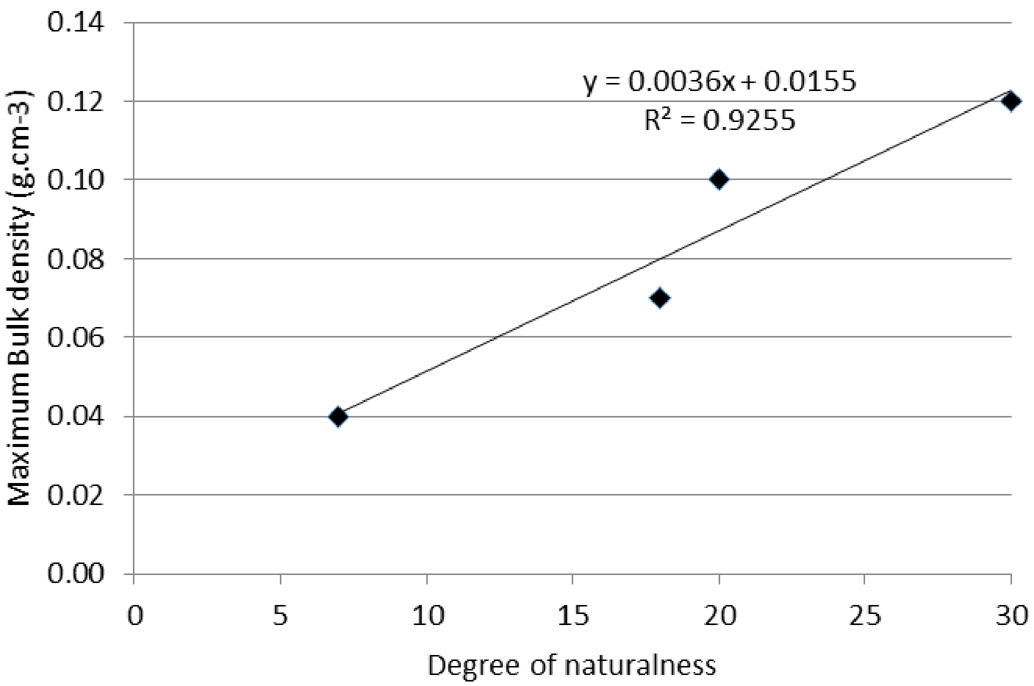

Figure 6. Degree of naturalness (DN) *versus* maximum bulk density (BD) of the studied bogs.

GPR radargrams

Radargrams from the four study sites are shown in Figures 7 to 10. In each case, two radargrams (for 100 MHz and 500 MHz antennae, respectively) are presented for the transect that included the location of the profiled peat core. These peat bogs have prominent surface microrelief that changes rapidly over distances of a few metres (generally, less than half a metre), and correspondingly variable layers in their interiors (as observed by Warner *et al*. 1990). It was possible to distinguish layers in the radargrams which could be linked to the information collected from the profile cores (Figures 4 and 5). Figures 7 to 10 are annotated with dashed lines indicating the positions of the reflectors identified.

At Site I (DN = 30), the profile revealed a thick layer of fibrous peat overlying a smaller deposit of hemic peat, a considerable layer of sapric peat and pumice. It was not possible to identify the *Placic*. BD was highest for the sapric layer, which contained wood, with a value between 0.09 and 0.12 g cm^{-3}. The presence of pumice may indicate potential landslides, which are typical phenomena in the Azorean volcanic islands (Elias & Dias 2009). Regarding the GPR surveys, the 100 MHz antenna just allowed the interface between the peat and mineral substrate, and the hemic and sapric peat layers, to be distinguished. With this antenna it was possible to distinguish a reflector in an area with BD 0.12 g cm^{-3}, which is interpreted as the transition between hemic and sapric peat (Figure 4). Although the transects were surveyed in summer (the driest time of year), the 500 MHz antenna did not differentiate the major materials. The iron/mineral content may be responsible for a higher than usual attenuation of the GPR signal. By probing with PVC tubes, Mendes (1998) recorded a maximum depth of 4.1 m for this bog; deployment of the GPR antennae increased this estimate to 4.2 m.

At Site II (DN = 20), the profile showed fibrous, hemic and sapric peat (von Post 1924, *op cit*. Paavilainen & Päivänen 1995), with a maximum BD value of 0.10 g.cm^{-3}. This is a raised bog in which water moves to the lowest possible level, forming pools, so there is a lower presence of surface water in summer than at Site I. The 100 MHz antenna located the interface between peat and mineral substratum, but did not differentiate any other peat layers. The 500 MHz antenna distinguished between the two layers of less-decomposed (hemic and fibrous) and sapric peat, and identified the reflector at the transition between peat and the mineral substratum. The GPR survey also indicated that the peat layers identified were continuous across the bog. (Figure 4). In view of the relatively unstable geology and geomorphology (Elias & Dias 2009), the existence of a fossil bog between two *Placic* layers was suspected, but it was not possible to prove this. The relationship between the radargrams and the geological interface from coring yielded a value for EMW velocity of 0.04 m ns^{-1} (also in the other studied sites) which is similar to a value

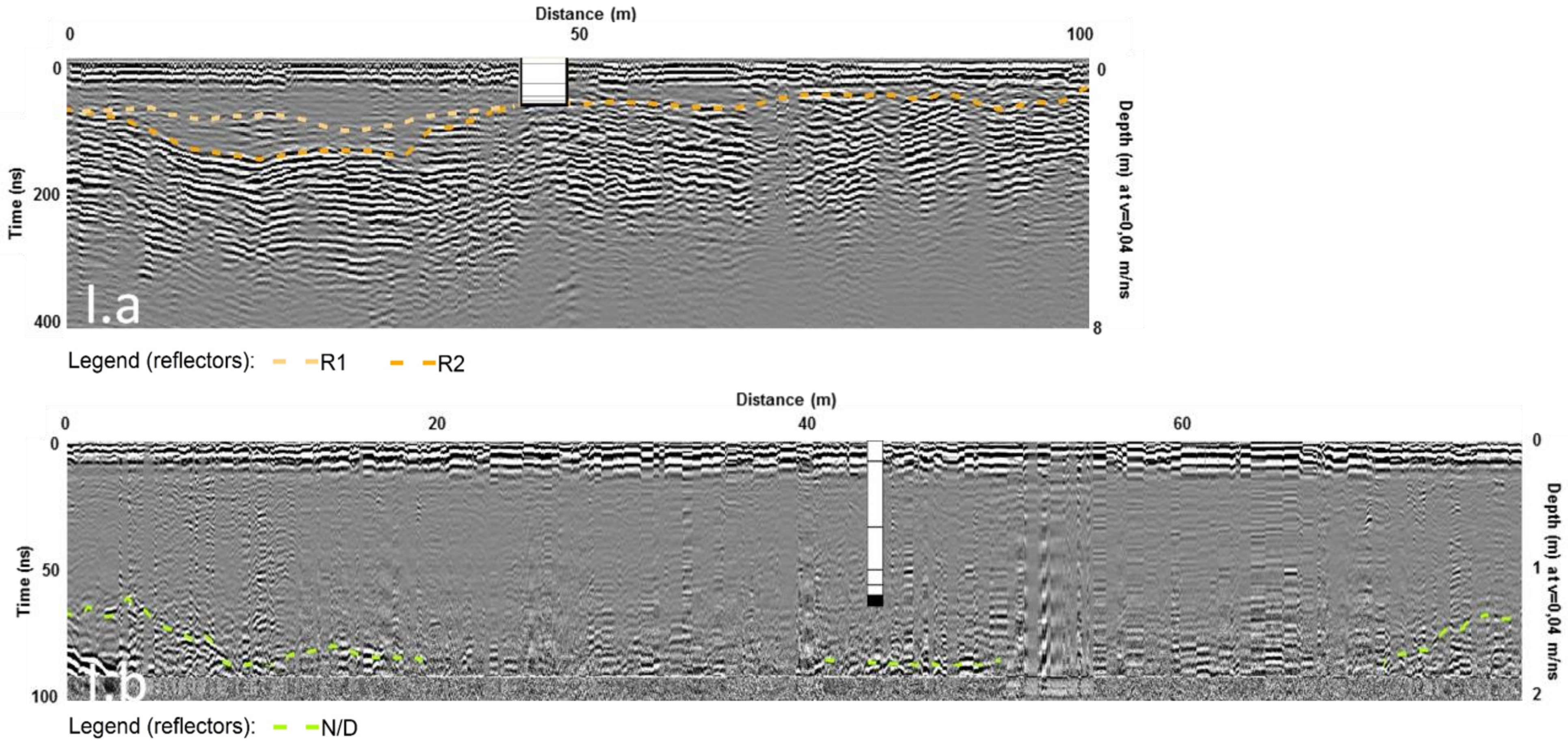

Figure 7. Peat Bog I: example radargrams produced using the 100 MHz antenna (above) and the 500 MHz antenna (below). The transect selected includes the open core (see Figure 4 for more information). The dashed lines indicate interpreted reflections in the GPR signal.

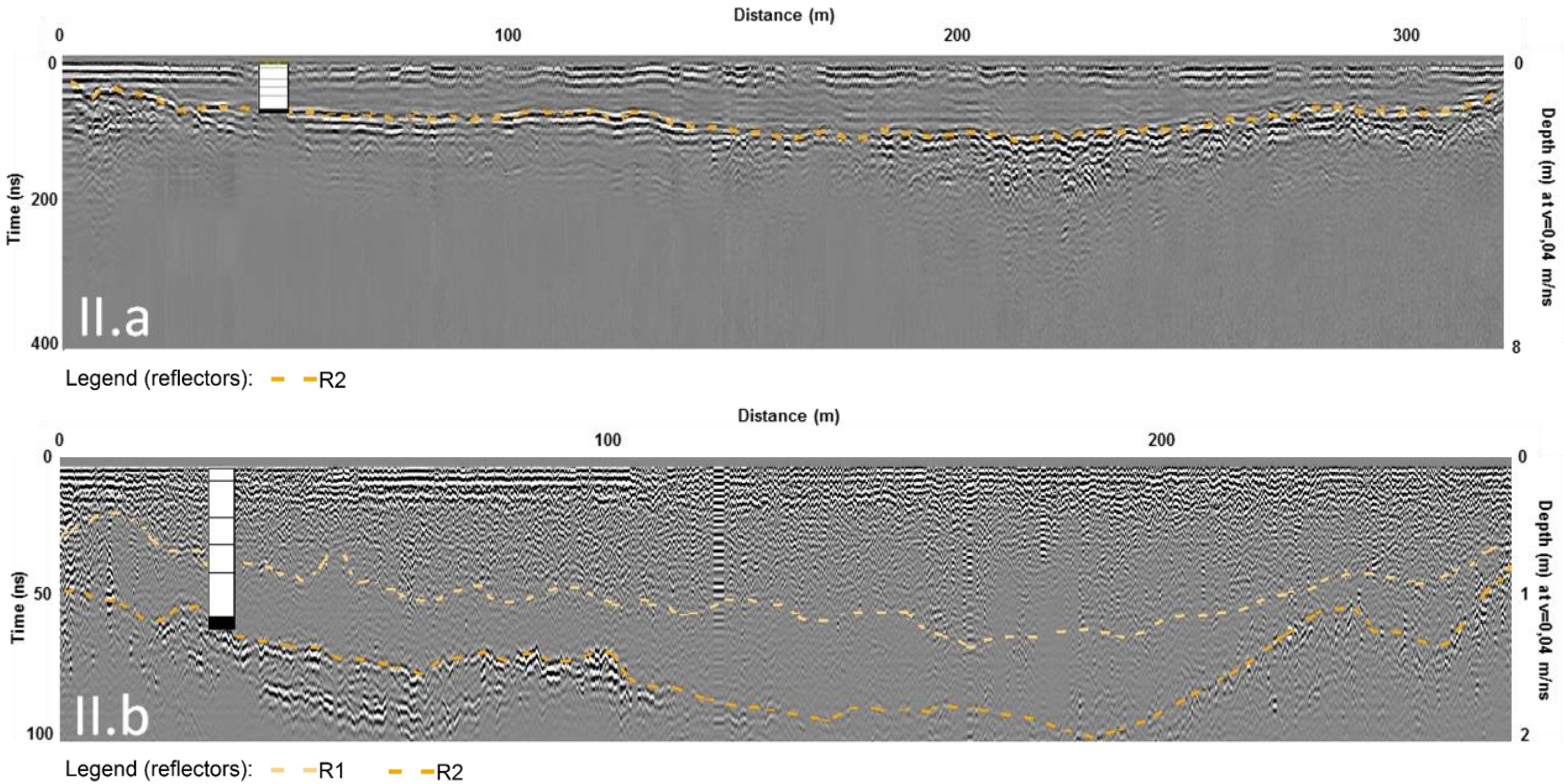

Figure 8. Peat Bog II: example radargrams produced using the 100 MHz antenna (above) and the 500 MHz antenna (below). The transect selected includes the open core (see Figure 4 for more information). The dashed lines indicate interpreted reflections in the GPR signal.

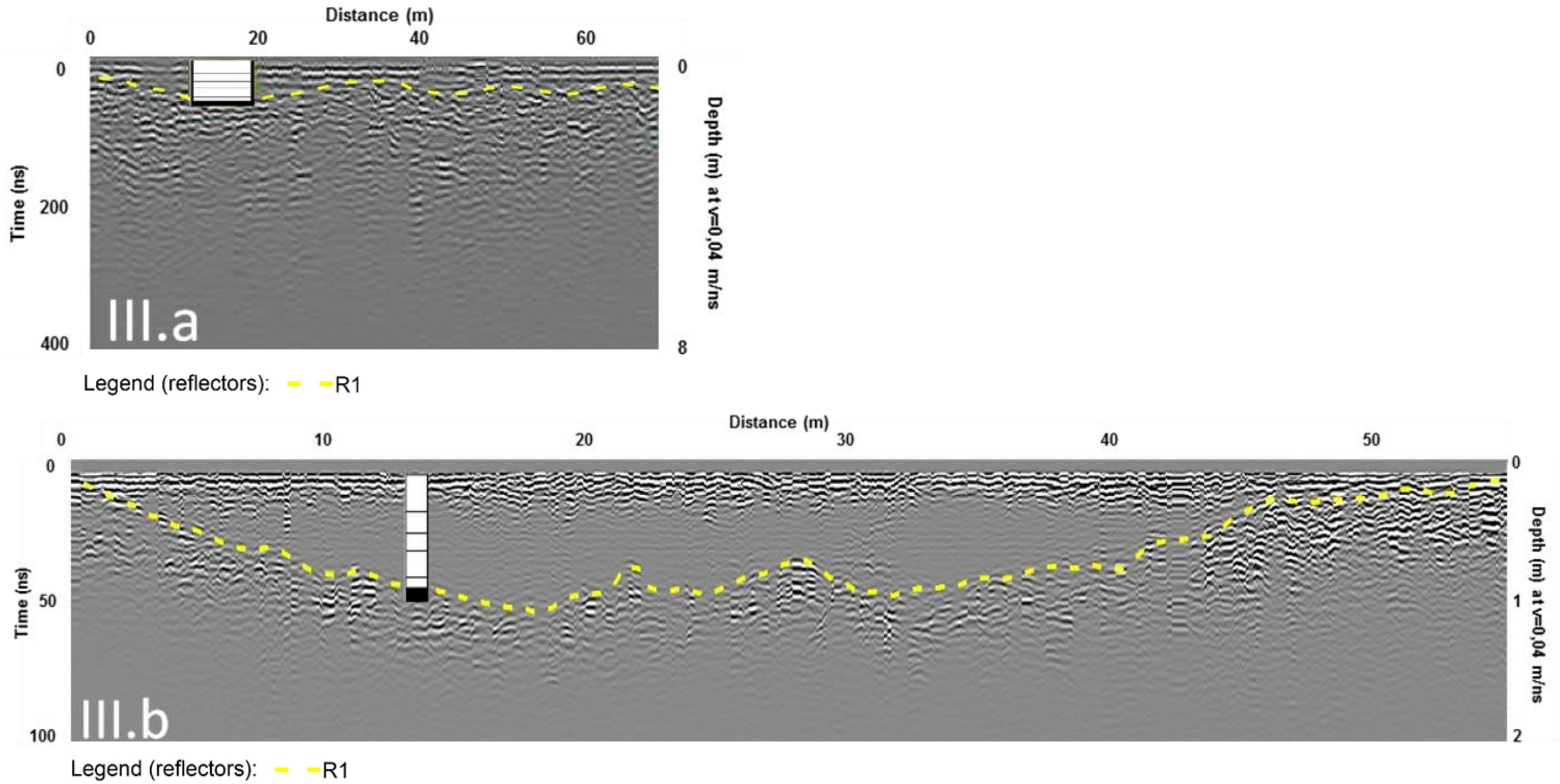

Figure 9. Peat Bog III: example radargrams produced using the 100 MHz antenna (above) and the 500 MHz antenna (below). The transect selected includes the open core (see Figure 4 for more information). The dashed lines indicate interpreted reflections in the GPR signal.

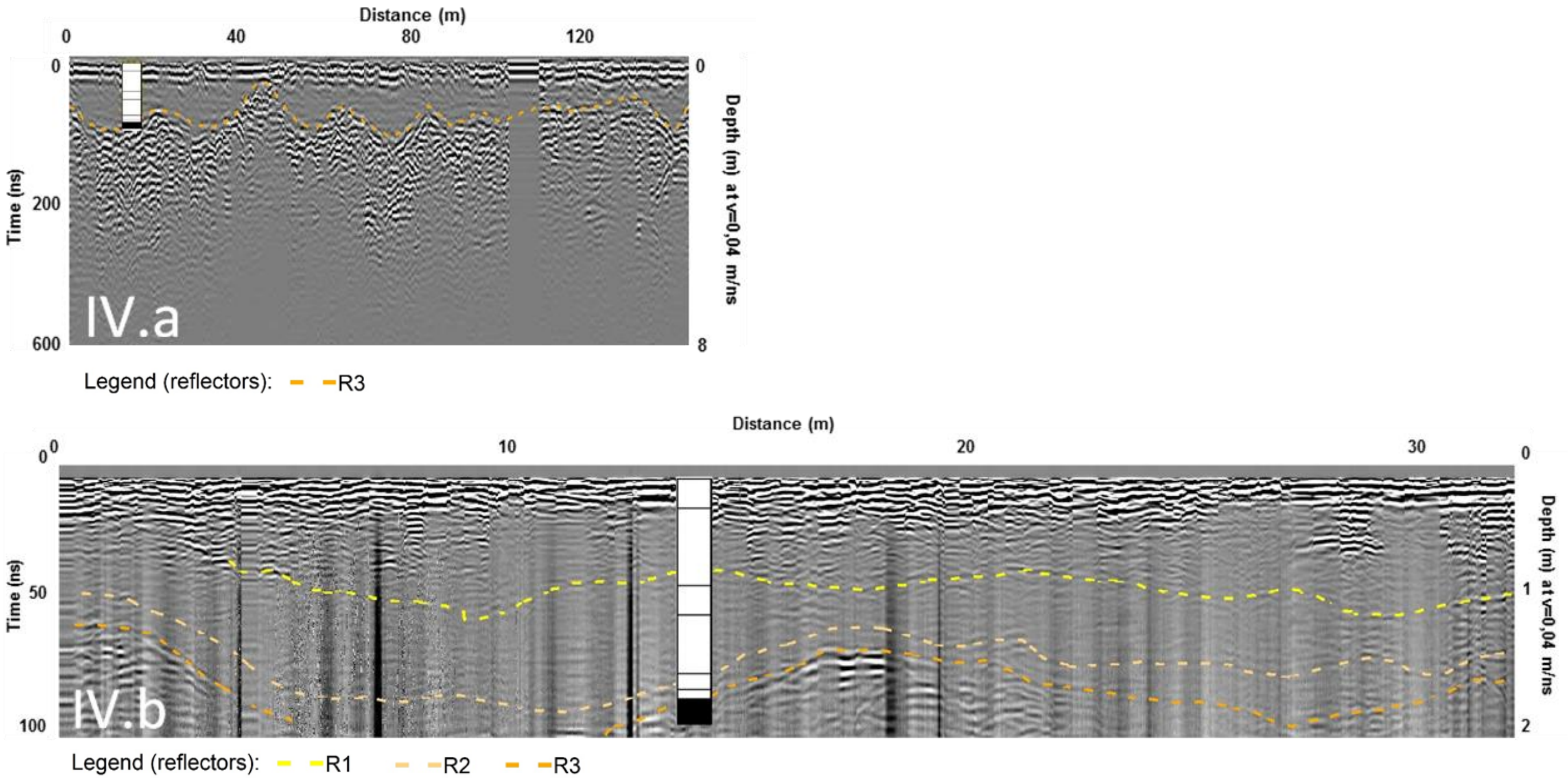

Figure 10. Peat Bog IV: example radargrams produced using the 100 MHz antenna (above) and the 500 MHz antenna (below). The transect selected includes the open core (see Figure 4 for more information). The dashed lines indicate interpreted reflections in the GPR signal (the R2 reflector was derived by interpretation of the results of the depth cores and GPR reflections for only parts of the radargram).

derived by Rosa *et al*. (2009) for some peat bogs. The GPR surveys indicated that the maximum depth of the bog was 2.00 m, whereas the maximum depth derived by Mendes (1998) using PVC tubes was 1.80 m.

The surroundings and margins of Site III (DN = 7) were ploughed, so that peat and bog vegetation persisted only in the deepest parts of the basin. This site was in a state of great perturbation (Mendes 2010), although in the process of recovery. Peat layers are not evident in the radargrams produced with the 100 MHz GPR antenna. On the other hand, the radargrams from the 500 Mhz antenna could be related to the profile (Figure 4), revealing continuous layers of younger peat including a considerable layer of fibrous peat and a thin layer of hemic peat. This can be seen in the BD data, for which the maximum value was 0.04 g cm^{-3}. No evidence of sapric peat was found, indicating the possibility that this is a young peat bog. Applying the filters of the Reflex software also revealed the presence of rock and lava under the peat, and *Placic* was not detected in either the radargrams or the profile. The maximum depth of peat indicated by the GPR antennae was about 1.20 m, and the only reflector distinguished was that between peat and mineral substrate. *Placic* was not detected in either the radargrams or from coring (Figure 4).

Site IV (DN = 18) is disturbed, although less so than Site III. This was evidenced by the profiles. Figure 10 shows a thick layer of fibrous peat and a thin layer of hemic peat, limited by a deposit of pumice and another of *Placic*. The BD indicates that the peat was more decomposed than at Site III, with a maximum value of 0.07 g cm^{-3}. Coring elsewhere in this bog revealed the presence of a thin layer of sapric peat. The inconstant presence of this layer may be due to either the accumulation of black peat in the most endorheic parts of the rugged microrelief or the spatial patchiness of existing disturbance to the bog. The radargrams show a continuous thick layer of fibrous peat. The maximum peat depth determined by GPR was 3.0 m, whereas Mendes (1998) reported 2.3 m. It was not possible to identify a reflector at the transition from fibrous to hemic peat at 0.04/0.05 g cm^{-3} (between the von Post H2 and H3 layers) or even, in part of the transect, the transition between peat and the mineral substrate. It was possible to identify a layer with poor reflection, visible in only some parts of the radargrams, which was also hemic peat but with a BD of 0.06/0.07 g cm^{-3} (Figure 4).

Peat volume

The peat volume calculation for Peat Bog IV is summarised in Figure 11 and Table 1. The calculation indicates that this bog contains 32,059 m^3 of fibrous peat and 13,028 m^3 of hemic peat. For areas of thinner peat, it was also possible to identify a trend in the tridimensional models that could be related to the presence of *Calluna vulgaris*.

DISCUSSION

Properties of Azorean peats

The bulk density values for peat collected from the four study sites are quite similar to values determined by other authors such as Boelter (1968), who reports BD values for several *Sphagnum* moss peat layers in northern Minnesota. These are: 0.010 g.cm^{-3} for living, undecomposed mosses; 0.040 g.cm^{-3} and 0.052 g.cm^{-3} for undecomposed mosses; and 0.153 g.cm^{-3} for moderately decomposed peat with wood inclusions. In central Finland, *Sphagnum* peat has again been shown to exhibit lower BD values than woody peat (Verry *et al*. 2011). In the research reported here, the highest BD value determined for Site I (0.13 g.cm^{-3}) is for peat layers with woody debris, and is similar to the above literature value for woody peat in Minnesota. The maximum peat BD value for the Azores sites (0.13 g.cm^{-3}) is lower than the value of 0.23 g.cm^{-3} reported for several woody peats in northern Ontario (Canada) by Silc & Stanek (1977). Because the Azores sites are *Sphagnum* peat bogs, the result that BD increases with von Post humification (Figure 5) was expected.

The potential of GPR for revealing the internal structure of Azorean peat deposits

GPR is a non-destructive, continuous and rapid technology which, in this study, has produced better information about Azorean peat deposits than was previously obtained by manual probing. However, it should be validated using cores or drilling.

Although several authors have determined the speed of GPR EMW propagation in different peats (e.g. Slater & Reeve 2002, Emili *et al*. 2006, Dallaire & Garneau 2008, Rosa *et al*. 2009), we found no literature that considered how the calculation should allow for the presence of strong EMW reflectors like the *Placic* or lava, as found in Azorean *Sphagnum* peatlands. In the specific case of the four *Sphagnum* peatlands studied here, the relationship between core and radargram data gave a best-fit EMW propagation velocity of 0.04 m ns^{-1}. This result is consistent with values found in the literature; for example, Parsekian *et al*. (2012) present a table of electromagnetic wave velocity

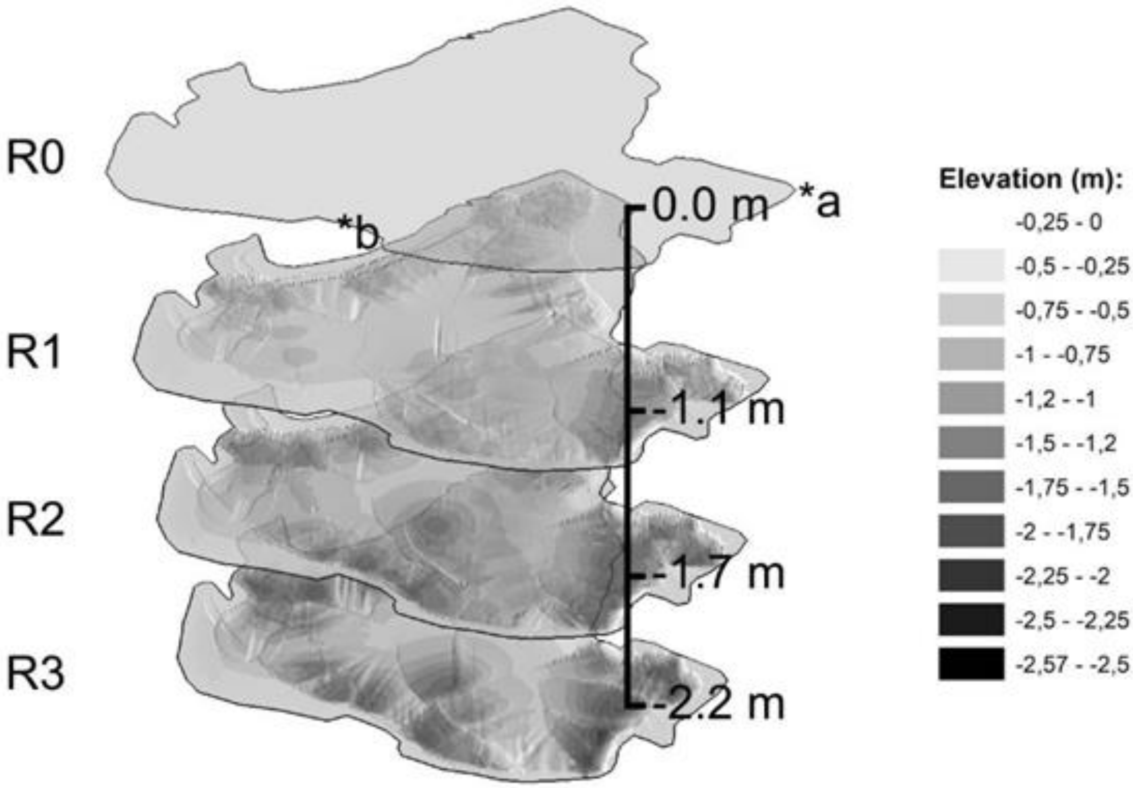

Figure 11. View across Peat Bog IV (above) and tridimensional GIS models of the reflectors/layers identified using the 500 MHz GPR antenna (below).

Table 1. Estimated values from the tridimensional models, for the peat layers identified in Peat Bog IV.

Bulk density (g.cm^{-3})	Von Post scale of humification	Vol. (m^3)	Von Post classification	Vol. (m^3)	GPR reflector	Vol. (m^3)
0.03	H1	5246	Fibrous peat	32059	R1	19075
0.04	H2	13829				
0.04	H3	4328			R2	12984
0.05	H3	8656				
0.06	H5	8228	Hemic peat	13028	R3	13028
0.07	H5	4800				

values for peat soils determined in different places by various authors, with a velocity range of 0.033–0.049 m.ns^{-1}. Similar values have also been reported from Canada, for example 0.046 m ns^{-1} from Québec (Dallaire & Garneau 2008) and 0.039–0.040 m ns^{-1} from Southern Québec (Rosa *et al*. 2009).

With the two GPR antennae used in this work, it was possible to determine the depths of major reflectors such as the interface between peat and the mineral substratum. The 100 MHz antenna proved to be more suitable for deeper and wetter peat bogs, whereas the 500 MHz antenna was a better solution for bogs without these limitations because it produced better resolution.

Depending on the naturalness (DN) and wetness of the peatlands, as well as the presence or absence of strong reflectors such as the *Placic*, it was also possible to locate stratigraphic layers within the peat that differed in terms of bulk density (BD) and, in some cases (e.g. Site IV), von Post humification (H) as verified by the examination of coincident peat cores. The von Post H value may be related to the BD of the material (e.g. Silc & Stanek 1977, Damman & French 1987) as well as to the radargrams. However, the results always retain some degree of uncertainty (Rosa *et al*. 2009, Parsekian *et al*. 2012).

It was also possible to find a dominance of fibrous peat and hemic peat (in smaller proportions) for degraded *Sphagnum* peatlands, even in recovery (Peat Bog III), unlike older or less disturbed peat or peat with localised disorders, which show the presence of sapric peat (Peat Bogs II, IV and I - the latter was not distinguishable by the GPR). It was also possible, in the tridimensional models and the areas with less peat, to relate it to the presence of *Calluna vulgaris*.

Figure 11 illustrates how the results can be processed *via* GIS to yield volume estimates for individual layers of peat and for the peat deposit as a whole. This provides a basis for quantifying ecosystem services that are provided by the bog, such as the accumulation and storage of both carbon and water. Such information might usefully be integrated into the national strategies of, for example, the Portuguese Carbon Fund and Fund for the Protection of Water Resources; and even the carbon and water strategies of international bodies like the European Commission and the Food and Agriculture Organization (FAO) of the United Nations.

ACKNOWLEDGEMENTS

This research was carried out as part of a PhD scholarship of the Portuguese Foundation for Science and Technology (SFRH/BD/66357/2009) financed by the Ministry of Education and Science, and the European Social Fund. For their helpful suggestions we thank: the Plant and Applied Ecology Group and the project Wetrest (Insular Wetland Restoration: Renaturalization Processes and Biodiversity Valorization in Environmental Management), Centre for Climate, Meteorology and Global Change, Institute of Agronomy and Environment Research and Technology (IITAA), University of the Azores; the Regional Secretariat for Science, Technology and Equipment; Intergraph; Cândida Mendes; Pierre-Luc Dallaire;

ECOPRISMA (Engenharia e Gestão, Lda.); Jukka Laine and Harri Vassander (Helsinki University); and Andrew Parsekian (University of Wyoming). We also thank Isabel Silva and Meredith Cannella for English revision; and Olivia Bragg (University of Dundee, UK, Editor-in-Chief of *Mires and Peat*) and Neil Terry (Postdoctoral Research Hydrologist, US Geological Survey) for the revision and helpful comments.

REFERENCES

Baraniak, D.W. (1983) Exploration for surface peat deposits using ground penetrating radar. In: Fuchsman, C.H. & Spigarelli, S.A. (eds.) *Proceedings of the International Symposium on Peat Utilization, Bemidji, Minnesota*, Bemidji State University, 105–121.

Bjelm, L. (1980) Geological interpretation with subsurface interface radar in peat lands. In: *Proceedings of the 6th International Peat Congress (Duluth, Minnesota)*, International Peat Society, Jyväskylä, Finland, 7–8.

Boelter, D.H. (1968) Important physical properties of peat materials. In: *Proceedings of the 3rd International Peat Congress (Quebec, Canada)*, International Peat Society, Jyväskylä, Finland, 150–154.

Borges, P., Azevedo, E., Borba, A., Dinis, F., Gabriel, R. & Silva, E. (2010) Ilhas Oceânicas (Oceanic islands). In: *Ecossistemas e o Bem-estar Humano. Avaliação para Portugal do Millenyum Ecosystem Assessment* (*Ecosystems and Human Well-being. Millennium Ecosystem Assessment for Portugal*). Escolar Editora, Lisboa, 461–508 (in Portuguese).

Bradford, J.H., McNamara, J.P., Bowden, W. & Gooseff, M.N. (2005) Measuring thaw depth beneath peat-lined arctic streams using ground-penetrating radar. *Hydrological Process*, 19, 2689–2699.

Buffam, I., Carpenter, S.R., Yeck, W., Hanson, P.C., & Turner, M.G. (2010) Filling holes in regional carbon budgets: Predicting peat depth in a north temperate lake district, *Journal of Geophysical Research*, 115, G01005, doi:10.1029/2009JG001034.

Comas, X. & Slater, L. (2005) Geophysical and hydrological evaluation of two bog complexes in a northern peatland: Implications for the distribution of biogenic gases at the basin scale. *Global Biogeochemical Cycles*, 19, GB4023, doi: 10.1029/2005GB002582.

Comas, X. & Slater, L.D. (2009) Noninvasive field-scale characterization of gaseous-phase methane dynamics in peatlands using the ground-penetrating radar method. In: Baird, A.J., Belyea, L.R., Comas, X., Reeve, A.S. & Slater, L.D. (eds.) *Carbon Cycling in Northern Peatlands*, Geophysical Monograph Series 184, the American Geophysical Union, Washington DC, 159–171 .

Comas, X., Slater, L. & Reeve, A. (2004) Geophysical evidence for peat basin morphology and stratigraphic controls on vegetation observed in a Northern Peatland. *Journal of Hydrology*, 295, 173–184.

Comas, X., Slater, L. & Reeve, A. (2005a) Spatial variability in biogenic gas accumulations in peat soils is revealed by ground penetrating radar (GPR). *Geophysical Research Letters*, 32, L08401, doi: 10.1029/2004GL022297.

Comas, X., Slater, L. & Reeve, A. (2005b) Stratigraphic controls on pool formation in a domed bog inferred from ground penetrating radar (GPR). *Journal of Hydrology*, 315, 40–51.

Dallaire, P.-L. (2010) *Utilisation d'un Géoradar afin de Caractériser la Stratigraphie de la Tourbe et Estimer le Carbone Organique Accumulé dans une Tourbière Boréale, Région d'Eastmain, Baie James, Québec* (*The Use of Ground Penetrating Radar to Characterise Peat Stratigraphy and Estimate the Organic Carbon Accumulated in a Boreal Peatland, Eastmain Region, James Bay, Quebec*). Mémoire (Maîtrise en Géographie), Université du Québec à Montréal, Canada, 132 pp. (in French). Online at: http://www.archipel.uqam.ca/3912/1/M11747.pdf, accessed 04 Jly 2017.

Dallaire, P.-L. & Garneau, M. (2008) The use of a ground-penetrating radar (GPR) to characterize peat stratigraphy and estimate the carbon pool in a boreal peatland, Eastmain region, James Bay, Québec, Canada. *Proceedings of the 12th International Conference on Ground Penetrating Radar, June 16–19, 2008, Birmingham, UK*, 9 pp. Online at: https://declique.uqam.ca/upload/files/conference/Dallaire_etal%20GPR2008.pdf, accessed 04 Jly 2017.

Damman, A. & French, T. (1987) *The Ecology of Peat Bogs of the Glaciated Northeastern United States: a Community Profile*. Biological Report 85(7.16), Fish and Wildlife Service, US Department of the Interior, Washington DC, 100 pp.

Davis, J.L. & Annan, A.P. (1989) Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. *Geophysical Prospecting*, 37, 531–551.

Dean, W.E. (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology*, 44(1), 242–248.

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, Universidade dos Açores, Angra do Heroísmo, XI+299 pp. (in Portuguese).

Dias, E. & Mendes, C. (2007) Characterisation of a basin mire in the Azores archipelago. *Mires and Peat*, 2(08), 1–11.

Doolittle, J.A. & Collins, M.E. (1995) Use of soil information to determine application of ground penetrating radar. *Journal of Applied Geophysics*, 33, 101–108.

EC (1992) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Official Journal of the European Communities*, No L 206, 7–50.

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

Emili, L.A., Price, J.S. & Fitzgerald, D. (2006) Hydrogeological influences on forest community type along forest-peatland complexes, coastal British Columbia. *Canadian Journal of Forest Research*, 36, 2024–2037, doi:10.1139/x06-104.

Gruber, N., Friedlingstein, P., Field, C.B., Valentini, R., Heimann, M., Richey, J.E., Romero-Lankao, P., Schulze, D. & Chen, C.T.A. (2004) The vulnerability of the carbon cycle in the 21st century: an assessment of carbon-climate-human interactions. In: Field, C.B. & Raupach, M.R. (eds.) *The Global Carbon Cycle: Integrating Humans, Climate and the Natural World.* Island Press, Washington DC, 45–76.

Halleux, L. (1990) Ground penetrating radar applied to the study of peat bogs and moors. *Annales de la Société Géologique de Belgique*, 113(2), 115–123.

Hänninen, P. (1992) *Application of Ground Penetrating Radar and Radio Wave Moisture Probe Techniques to Peatland Investigation*. Bulletin 361, Geological Survey of Finland, Espoo, 71 pp.

Holden, J. (2005) Controls of soil pipe frequency in upland blanket peat. *Journal of Geophysical Research*, 110, F01002, doi: 10.1029/2004JF000143.

Holden, J., Burt, T.P. & Vilas, M. (2002) Application of ground-penetrating radar to the identification of subsurface piping in blanket peat. *Earth Surface Processes and Landforms*, 27, 235–249.

Householder, J.E., Janovec, J., Tobler, M., Page, S. & Lähteenoja, O. (2012) Peatlands of the Madre de Dios River of Peru: Distribution, geomorphology, and habitat diversity. *Wetlands*, 32(2), 359–368.

Howell, D., Astin, T., Branch, N.P. & Young, D.S. (2010) Using ground-penetrating radar to image features within peatlands: a feasibility study from four Irish bogs. *Wetland Archaeology in Ireland and Beyond, Conference 6th–7th February 2010, Abstracts of Papers*, University College Dublin, Ireland, 10–11. Online at: https://www.ucd.ie/t4cms/s003_abstracts_wetland_archaeology_in_ireland_and_beyond.pdf, accessed 04 Jly 2017.

Joosten, H., Tapio-Biström, M.L. & Tol, S. (eds.) (2012) *Peatlands - Guidance for Climate Change Mitigation Through Conservation, Rehabilitation and Sustainable Use*. Second edition. Mitigation of climate change in agriculture series 5, Food and Agriculture Organization of the United Nations (FAO) and Wetlands International, Rome, 100 pp. Online at: http://www.fao.org/3/a-an762e.pdf, accessed 03 Jly 2017.

Lapen, D.R., Moorman, B.J. & Price, J.S. (1996) Using ground-penetrating radar to delineate subsurface features along a wetland catena. *Soil Science Society of America Journal*, 60, 923–931.

Madruga, J. (1995) *Caracterização e Génese do Horizonte Plácico em Solos Vulcânicos do Arquipélago dos Açores* (*Characterisation and Genesis of the Placic Horizon in Volcanic Soils of the Azores Archipelago*). PhD thesis, Departamento de Ciências Agrárias, Universidade dos Açores, Angra do Heroísmo, XVI+244 pp. (in Portuguese).

Maes, J., Teller, A., Erhard, M., Liquete, C., Braat, L., Berry, P., Egoh, B., Puydarrieux, P., Fiorina, C., Santos, F., Paracchini, M.L., Keune, H., Wittmer, H., Hauck, J., Fiala, I., Verburg, P.H., Condé, S., Schägner, J.P., San Miguel, J., Estreguil, C., Ostermann, O., Barredo, J.I., Pereira, H.M., Stott, A., Laporte, V., Meiner, A., Olah, B., Royo Gelabert, E., Spyropoulou, R., Petersen, J.E., Maguire, C., Zal, N., Achilleos, E., Rubin, A., Ledoux, L., Brown, C., Raes, C., Jacobs, S., Vandewalle, M., Connor, D. & Bidoglio, G. (2013) *Mapping and Assessment of Ecosystems and their Services. An Analytical Framework for Ecosystem Assessments Under Action 5 of the EU Biodiversity Strategy to 2020*. Publications office of the European Union, Luxembourg, 57 pp. Online at: http://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/MAESWorkingPaper2013.pdf, accessed 03 Jly 2017.

McInnes, R.J. (2007) *Integrating Ecosystem Services Within a 50-year Vision for Wetlands.* Report to the England Wetland Vision Partnership, Wildfowl & Wetlands Trust, Slimbridge, 36 pp. Online at: http://www.wetlandvision.org.uk/userfiles/file/annex2_ecosystemservicesscopingreport.pdf, accessed 03 Jly 2017.

McQueen, C.B. (1990) *Field Guide to the Peat Mosses of Boreal North America*. University Press of New England, Hanover, USA, 138 pp.

Mellet, J.S. (1995) Profiling of ponds and bogs using ground-penetrating radar. *Journal of Paleolimnology*, 14, 233–240.

Mendes, C. (1998) *Contributo para a Caracterização de Turfeiras de Sphagnum spp. na ilha Terceira. (Contribution to the characterisation of the* Sphagnum *mires of Terceira Island)*. Relatório de estágio (Internship Report), Universidade dos Açores, Angra do Heroísmo, 168 pp. (in Portuguese).

Mendes, C. (2010) *Critérios de identificação das zonas húmidas protegidas na Directiva Habitats nos ZEC terrestres dos Açores* (*Criteria for the Identification of Protected Wetlands in the Habitats Directive Terrestrial SACs of the Azores*). Tese de Mestrado em Gestão e Conservação da Natureza (Master’s thesis in nature conservation and management), Universidade dos Açores, Angra do Heroísmo, 148 pp. (in Portuguese).

Mendes, C. & Dias, E. (2002) *Ecologia e Vegetação das Turfeiras de* Sphagnum *spp. da ilha Terceira (Açores)* (*Ecology and Vegetation of the* Sphagnum *peatlands of Terceira Island (Azores)*). Cadernos de Botânica 5, Herbário da Universidade dos Açores, Angra do Heroísmo (in Portuguese). Online at: https://www.researchgate.net/publication/299514443_Ecologia_e_vegetacao_das_Turfeiras_de_Sphagnum_spp_da_ilha_Terceira, accessed 05 Aug 2017.

Mendes, C. & Dias, E. (2008) Characterization of a basin mire in Terceira Island: Tamujal case study. *Boletim Museu Municipal Funchal*, 58(321), 37–52.

Mendes, C. & Dias, E. (2009) Characterization of Sanguinhal Mire, Terceira Island (Azores): a protected quaking bog habitat. *Acta Botanica Brasilica*, 23(3), 812–819.

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

Moorman, B., Robinson, S. & Burgess, M. (2003) Imaging periglacial conditions with ground-penetrating radar. *Permafrost and Periglacial Processes*, 14, 319–329.

Moreira, J.C.B. (1992) Contribuição para o conhecimento de turfas. Ocorrência de turfas em Portugal: sua caracterização (Contribution to the knowledge of peat. Occurrence of peat in Portugal: its characterisation). *Boletim das Minas*, 29(1), 3–26 (in Portuguese).

Neal, A. (2004) Ground-penetrating radar and its use in sedimentology: principles, problems and progress. *Earth-Science Reviews*, 66, 261–330.

Nichols, D.S. & Boelter, D.H. (1984) Fiber size distribution, bulk density, and ash content of peats in Minnesota, Wisconsin, and Michigan. *Soil Science Society of America Journal*, 48, 1320–1328.

Nolan, J.T., Parsekian, A.D., Slater, L.D. & Glaser, P.H. (2008) Geophysical characterization of the Red Lake Peatland Complex, Northern Minnesota. In: Kaufmann, R. (ed.) *Symposium on the Application of Geophysics to Engineering and Environmental Problems* (*21st SAGEEP)*, Environment and Engineering Geophysical Society, 858–861.

Paavilainen, E. & Päivänen, J. (1995) *Peatland Forestry: Ecology and Principles*. Ecological Studies 111, Springer-Verlag Berlin Heidelberg, XI+250 pp., doi: 10.1007/978-3-662-03125-4.

Parish, F., Sirin, A., Charman, D., Joosten, H., Minaeva, T. & Silvius, M. (eds.) (2008) *Assessment on Peatlands, Biodiversity and Climate Change: Main Report*. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen, 179 pp.

Parry, L.E., Charman, D.J. & & Noades, J.P.W. (2012) A method for modelling peat depth in blanket peatlands. *Soil Use and Management*, 28(4), 614–624.

Parry, L.E., West, L.J., Holden, J. & Chapman, P.J. (2014) Evaluating approaches for estimating peat depth. *Journal of Geophysical Research: Biogeosciences*, 119(4), 567–576.

Parsekian, A.D., Slater, L., Ntarlagiannis, D., Nolan, J., Sebesteyen, S.D., Kolka, R.K. & Hanson, P.J. (2012) Uncertainty in peat volume and soil carbon estimated using ground-penetrating radar and probing. *Soil Science Society of America Journal*, 76, 1911–1918.

Plado, J., Sibul, I., Mustasaar, M. & Jõeleht, A. (2011) Ground-penetrating radar study of the Rahivere peat bog, eastern Estonia. *Estonian Journal of Earth Sciences*, 60(1), 31–42, doi: 10.3176/earth.2011.1.03.

Rodrigues, F.C. (2002) *Hidrologia da ilha Terceira (Açores - Portugal)* (*Hydrology of Terceira Island (Azores, Portugal)*). PhD thesis, Universidade dos Açores, Angra do Heroísmo, XXVIII+418 pp. (in Portuguese).

Rosa, E., Larocque, M., Pellerin, S., Gagné, S. & Fournier, B. (2009) Determining the number of manual measurements required to improve peat thickness estimations by ground penetrating radar. *Earth Surface Processes and Landforms*, 34(3), 377–383.

Sandmeier, K.J. (1998–2012) *Reflexw Version 7.0.* Manual, Sandmeier Geophysical Research, Karlsruhe, Germany. Online at: http://www.sandmeier-geo.de.

Sheng, Y., Smith, L.C., MacDonald, G.M., Kremenetski, K.V., Frey, K.E., Velichko, A.A., Lee, M., Beilman, D.W. & Dubinin, P. (2004) A high-resolution GIS-based inventory of the Siberian peat carbon pool. *Global Biogeochemical Cycles*, 18, p. 1–14.

Silc, T. & Stanek, W. (1977) Bulk density estimation of several peats in northern Ontario Canada using the von Post humification scale. *Canadian Journal of Soil Science*, 57(1), 75–76.

Skidmore, A. (2002) *Environmental Modelling with GIS and Remote Sensing*. Taylor and Francis, New York, 268 pp.

Slater, L.D. & Reeve, A. (2002) Investigating peatland stratigraphy and hydrogeology using integrated electrical geophysics. *Geophysics*, 67(2), 265–378.

Strack, M. (ed.) (2008) *Peatlands and Climate Change*. International Peat Society, Jyväskylä, Finland, 223 pp. ISBN 978-952-99401-1-0.

Szuch, R.P., White, J.G., Vepraskas, M.J. & Doolittle, J.A. (2006) Application of ground-penetrating radar to aid restoration planning for a drained Carolina Bay. *Wetlands*, 26(1), 205–216.

Theimer, B.D., Nobes, D.C. & Warner, B.G. (1994) A study of the geoelectrical properties of peatlands and their influence on ground-penetrating radar surveying. *Geophysical Prospecting*, 42, 179–209.

Valpola, S., Harju, A., Herranen, T., Toivonen, T., Valo, O. & Vahakuopus, T. (2012) The peat investigations in the Geological Survey of Finland. In: *Proceedings of the 14th International Peat Congress (Stockholm, Sweden)*, International Peat Society, Jyväskylä, Finland, 4 pp.

Verry, E.S., Boelter, D.H., Päivänen, J., Nichols, D.S., Malterer, T. & Gafni, A. (2011) Physical properties of organic soils. In: Kolka, R.K., Sebestyen, S.D., Verry, E.S. & Brooks, K.N. (eds.) *Peatland Biogeochemstry and Watershed Hydrology at the Marcell Experimental Forest*. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, 135–176.

von Post, L. (1924) Das genetische System der organogenen Bildungen Schwedens (The genetic system of the organogenic formations of Sweden). In: Comité International de Pédologie, IVème commission (commission pour la nomenclature et la classification des sols, commission pour l'Europe, président: B. Frosterus) (ed.) *Mémoires sur la Nomenclature et la Classification des Sols*, Helsingfors/ Helsinki, 287–304 (in German).

Warner, B.G., Nobes, D.C. & Theimer, B.D. (1990) An application of ground penetrating radar to peat stratigraphy of Ellice Swamp, southwestern Ontario. *Canadian Journal of Earth Sciences*, 27, 932–938.

Welsby, J. (1988) The utilisation of georadar in monitoring cutover peatlands. In: *Proceedings of the 8th International Peat Congress (Leningrad, USSR)*, International Peat Society, Jyväskylä, Finland, Volume 1, 99–107.

Wetlands International (1999) *Wetlands and Climate Change Phase 1: The Potential for Crediting Wetland Conservation as Carbon Sinks*. Wetlands International - Americas, North American Wetlands Conservation Council (Canada), International Institute for Sustainable Development and Ducks Unlimited Canada, 51 pp. Online at: http://www.creditvalleyca.ca/wp-content/uploads/2011/02/wtlnds_cc.pdf, accessed 03 Jly 2017.

Wieder, R.K. & Vitt, D.H. (eds.) (2006) *Boreal Peatland Ecosystems*. Ecological Studies 188, Springer-Verlag, Berlin Heidelberg, 429 pp.

Wood, A. & Halsema, G. (eds.) (2008) *Scoping Agriculture - Wetland Interactions. Towards a Sustainable Multiple-response Strategy*. FAO Water Reports 33, Food and Agriculture Organization of the United Nations, Rome, 155 pp.

Worsfold, R.D., Parashar, S.K. & Perrott, T. (1986) Depth profiling of peat deposits with impulse radar. *Canadian Geotechnical Journal*, 23, 142–186.

Submitted 20 Oct 2016, final revision 13 Jun 2017
Editor: Olivia Bragg

Author for correspondence:
Dinis Pereira, Instituto de Investigação e Tecnologia da Agronomia e Meio Ambiente (IITAA), Universidade dos Açores, Rua Capitão João d'Ávila, 9700-042 Angra do Heroísmo, Portugal.
Tel: +351295402200; Email: dinisacores@sapo.pt or dinispereira@dinispereira.com