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An archaeology and environmental history journal focusing on the peoples of the North Atlantic, their expansion into the region over time, and their interactions with their changing environments.

“Skálholt Map” courtesy of The Royal Library, Copenhagen, Denmark

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Early Neolithic Agriculture in County Mayo, Republic of Ireland: Geoarchaeology of the Céide Fields, Belderrig, and Rathlackan

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Abstract - The Céide Fields, Belderrig, and Rathlackan are extensive early Neolithic field systems in County Mayo, Republic of Ireland. The Céide Fields are thought to be the earliest field systems in Europe, and as such they are listed as a potential World Heritage site. For this project, the buried soils of the 3 sites were analyzed in order to determine the nature and extent of the prehistoric land use within the field systems. The aims were twofold: to identify material added as fertilizer, and to determine whether the land was used for pasture or for arable agriculture. Soil phosphates and bile acids from the Neolithic soils indicate low levels of input of herbivore dung, and also some human fecal material in the Céide Fields. The results suggest that the soils may have been fertilized with animal manure.

Introduction

The Céide Fields in County Mayo, Republic of Ireland, are thought to be the earliest field systems in Europe (Fig. 1; Caulfield et al. 1998). The Early Neolithic co-axial fields are delineated by stone walls that are now buried beneath up to 4 m of peat (ibid.), which also seals an extensive buried mineral soil. This geoarchaeological project was set up to investigate the nature of prehistoric agriculture and land use in these fields, and to compare the Irish evidence with that of Britain and Continental Europe.

The origin of farming in Europe and the nature of the social changes which accompanied it have been the subject of considerable debate. Early arable agriculture in Britain was once thought to have taken place in small fields within temporary clearings in the woodland (e.g., Case 1969), but subsequent models suggested that Neolithic populations were more sedentary (e.g., Barker 1985). The nature of Neolithic settlement and subsistence was radically reconsidered in the 1990s, when it was once again suggested that settlement in Neolithic Britain was shifting and impermanent (Thomas 1991, 1999; Whittle 1996). The argument was largely based on the absence of evidence for a sedentary lifestyle in SW England. The Scottish and Irish evidence contrasts with the mobile Neolithic model, and more recent thinking is that there are strong regional variations with differing degrees of mobility (Bradley 2003, Cooney 2003, Gibson 2003).

The Scottish evidence was reviewed by Barclay (1997), who rejected the suggestion that the Neolithic population in this region was anything but permanent. Stone field boundaries, clearance cairns, and long-lived settlement evidence suggest that there was little movement about the landscape, unless it was the seasonal movement of small groups. The geoarchaeological evidence from Scotland suggests that Neolithic agriculture took place in small plots of very fertile land that were more like gardens than fields (Guttmann 2005, Guttmann et al. 2004).

In NW Ireland, there is evidence for long-term settlement and substantial ties to the land, including many chambered tombs and extensive Neolithic field systems bounded by stone walls. The Céide Fields are the most well known of these sites, and their 12-ha extent has been painstakingly surveyed using steel probes to follow the walls beneath the peat (Caulfield et al. 1998); the site is now a visitor attraction and is currently under consideration to become a World Heritage site. Other field systems in the area have been revealed in peat cuttings, and there are fields and house structures to the east of the Céide Fields at Rathlackan (Byrne 1990) and to the west at Belderrig (also called Belderg) (Caulfield 1978, Caulfield et al. 2009).

Pollen analyses from Belderrig suggest pastoral land-use ending at around 3425 cal BC (Verrill and Tipping 2010), but pollen analyses from around the Céide Fields have demonstrated the presence of cereal-type pollen in a cleared landscape from the Early Neolithic, between ca. 3800–3250 cal BC (O'Connell and Molloy 2001). The extent of the field systems suggests that agriculture took place on a large scale in this region. It has been suggested that the land was used largely for pasture and to a lesser

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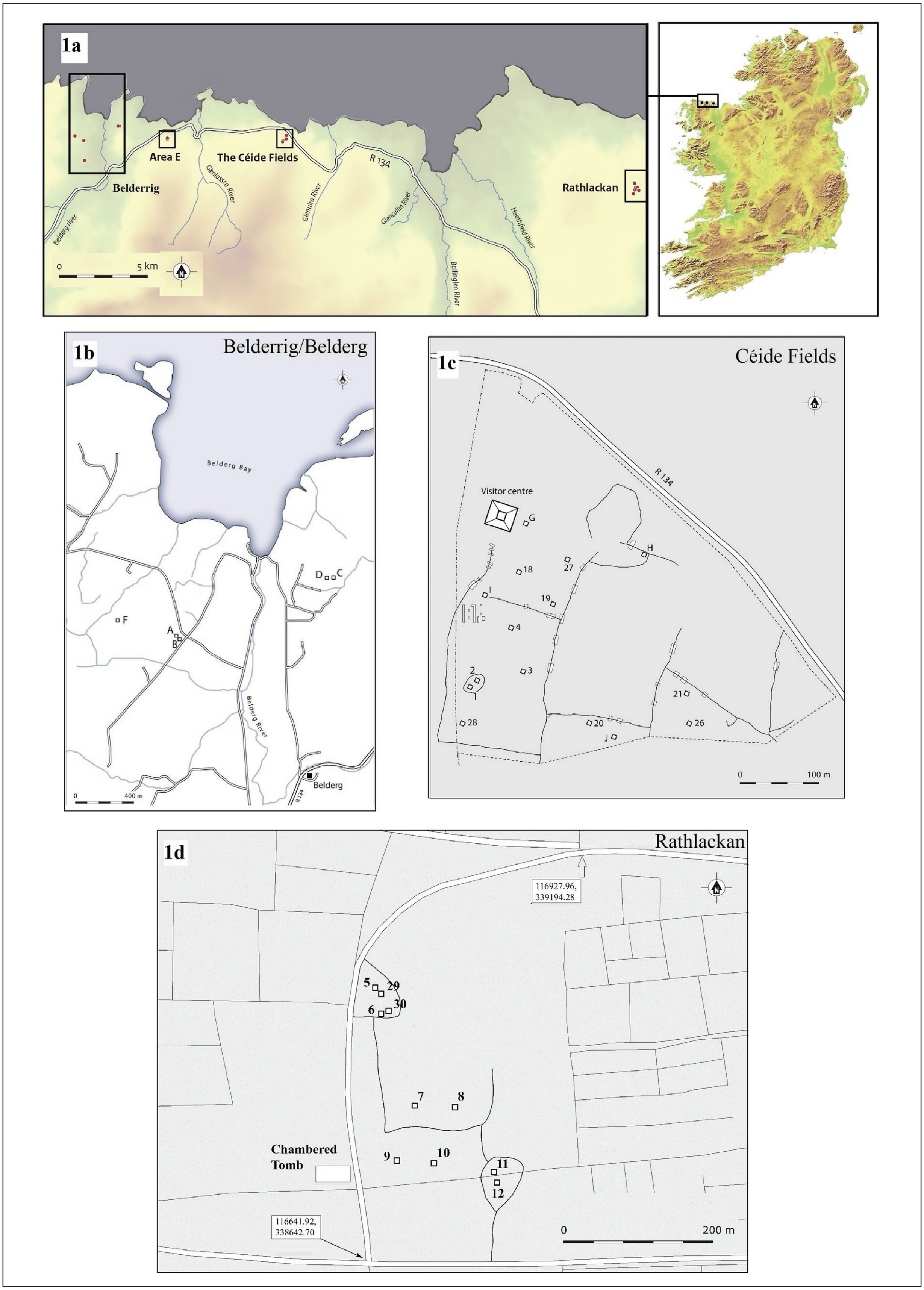

Figure 1. Location of the study area, sites, and test pits.

degree for arable cultivation (Caulfield 1983). Caulfield's original argument for pasture was based on the large size of the fields and the great extent of the enclosed land, but the later discovery of ard marks and stone ard shares within the fields demonstrate that they were also used, at least in part, for arable production (Byrne 1991, Byrne et al. 2009a). The extent of the ploughed land is unknown, because open-area excavation has been limited. Lazy beds (hand dug ridge and furrow) were found to the west at Belderrig, although these seem to be later, dating to the Bronze Age (Caulfield 1978, Herity and Eogan 1977:50).

Our new research aimed to determine how intensively the Neolithic fields were used. Cultivation within the fields could have been long term, or arable plots could have been shifting in order to fallow the land. Crop production could have been improved by adding locally available fertilizers such as domestic waste (including food remains and hearth ash), organic-rich sediments (such as peat and seaweed), or animal dung (Bakels 1997). The Céide Fields, Belderrig, and Rathlackan are all located by the sea, so seaweed would have been available, and organic-rich materials such as mud and peat (also potential fertilizers) occurred in basins in and around the fields (O'Connell and Molloy 2001). Domestic waste would have been available if there were permanent settlements in or around the fields, and animal manure would have been available if the fields were used for pasture, as Caulfield (1983) suggests. Peat development began in this region before the elm decline at 5840 cal BP, and continued to expand during the use of the fields, but peat did not develop within the fields until after they went out of use around 3250 cal BC (O'Connell and Molloy 2001). This history would suggest that manuring might have taken place to keep the soil fertile in the face of acidification and the spread of blanket bog.

The application of different materials would have made differing contributions to the fertility of the soil. The key elements necessary for plant growth are nitrogen, phosphorus, and potassium, and in addition there are a number of micronutrients that are required in smaller quantities. The addition of hearth ash and kitchen waste would have improved the soil nutrient availability, as hearth ash contains calcium and potassium (Canti 2003). The addition of ash to the soil would also have raised the soil pH. Animal bone and food residues would have added phosphate and nitrogen to the soil.

Animal dung is a better fertilizer than ash and kitchen waste, as it contains all 3 of the macronutrients required by plants, together with calcium, magnesium, and other micronutrients (Wild 1993:156). It is particularly rich in nitrogen, which is the key nutrient required by cereal crops. Organic manures such as animal dung also improve the soil structure by encouraging earthworms, which aerate the soil and enhance soil cohesion. Soil organic matter also retains water and enhances the availability of plant nutrients (Brady and Weil 1999:468; Dungait et al. 2008, 2012). The introduction of animal dung as an agricultural fertilizer therefore represents a considerable advance in agricultural land management, and it is an important indicator for the intensification of arable production and perhaps also for the emergence of long-lived (as opposed to shifting) fields.

Different stages of agricultural intensification can be traced back into prehistory, and a review of prehistoric soils in England and Scotland has suggested that Neolithic agriculture took place in small plots which are more like gardens than arable fields (Guttmann 2005, Guttmann et al. 2005). Macrobotanical evidence indicates that the same was true in Continental Europe (Bogaard 2004, 2005). Soils were fertilized with domestic or kitchen waste in the British Bronze Age, but animal manures were probably not widely used until the Iron Age (Guttmann et al. 2005). By contrast, animal manures were used in Switzerland as early as the Neolithic (e.g., Nielsen et al. 2000), and there are many records of its use in the Bronze Age in Western Europe (Bakels 1997).

The aims of the project presented here were to determine the intensity and extent of agricultural production within the Céide Fields, and to determine whether the land was used for pasture or arable agriculture. We tested the hypothesis that the arable soils in the Neolithic fields may have been fertilized, and given the extent of enclosed land—which suggests a large amount of pasture—that they were fertilized with animal manures. Such a finding would indicate the area followed an agricultural model closer to that currently accepted for Continental Europe than to that which has been presumed to apply to Britain.

Our specific objectives were: (1) To sample areas thought to have been arable and pasture within the Neolithic Fields, and to identify added cultural materials in the soils such as charcoal, charred peat, animal bone, animal dung, human excrement, and seaweed; and (2) To compare soils within the Neolithic field systems with "control" buried soils dating to the Mesolithic. This comparison would demonstrate the degree of enhancement in the arable soils.

Geology and soils

The geology of northern County Mayo is largely made up of metamorphic and sedimentary rocks. Belderrig is located on Dalradian rocks, which are mainly metamorphosed sedimentary rock (Long et al. 1992). The Céide Fields are on carboniferous rocks of the Downpatrick formation, which is a complicated interbedding of mudstones, siltstones, alluvial and deltaic sandstones, limestones, and shales. Moving west to Rathlackan, the geology is carboniferous sandstone and siltstones of the Mullaghmore formation. The solid geology is covered by drift made up of till (boulder clay). The soils in the region are peat, with areas of podzolic soils and acid brown earths.

Methods

In order to determine whether the soils were fertilized, it was necessary to identify material added to the soil. We used a range of analytical methods including thin-section micromorphology, macrobotanical analysis, and measurements of soil phosphates, soil magnetism, and lipid biomarkers. The point of using this wide range of methods was to ensure that there were no false positives, and to enable correlation between methods, e.g., phosphate data can be correlated with the lipid biomarkers analysis, which provides more specific information about the added material.

In order to determine whether the soils were used for arable or pasture, we took samples from the buried soils for analysis of insect remains. This did not produce results, probably because the soils were too oxidized. The second method we used for distinguishing arable and pasture was the analysis of compound-specific stable isotopes that are linked with particular amino acids in the soil. The method was developed by Simpson et al. (1999a, 1997) and was based on samples from experimental farms in Northumberland, the Paris Basin in France, and North Wyke, Devon. Simpson et al.'s work successfully distinguished manured grassland, unmanured grassland, and land used for long-term cereal cultivation, and also demonstrated that the signatures were still evident in soils from Bronze Age Orkney (ibid.). For the current project, we aimed to carry on the research of Simpson et al. by conducting further control studies at Rothamsted Research (Harpenden, Hertfordshire). We took samples at Rothamsted from areas of manured and unmanured arable land, and manured and unmanured grassland, in order to ascertain whether the method was replicable, before trying it out on the Céide Fields. The results were encouraging but mixed, and will be discussed after further analysis in a later publication. We had planned to compare the stable isotope/amino acid results with the results from insect analysis, but the lack of surviving insects made this impossible. This unsuccessful aspect of the project is introduced here in order to report on the negative evidence, as well as the positive.

Sampling strategy

Excavations were undertaken at the Céide Fields (Fig. 1c), Belderrig (Fig. 1b), and Rathlackan (Fig. 1d). We sampled buried soils dating to the Mesolithic at Belderrig (Test Pit F). In order to identify potential fertilizing materials, we also sampled a midden at Belderrig (Test Pit A). The field method involved digging 1 m x 1 m test pits through the peat and underlying Neolithic soils and sampling both the buried soil and the humified peat that overlay it. The more fibrous peat above the humified layer was not sampled because it was disturbed or redeposited during modern peat cutting. We sampled the humified peat overlying the buried soil for comparison, to ensure that any geochemical signatures in the soil were not derived from material leaching down from above. The buried soils were sampled for soil micromorphology, with bulk samples taken for geochemical, fecal biomarker, insect, and macrobotanical analyses.

Soil micromorphology

We conducted thin-section micromorphology to investigate the nature of the buried mineral soil, including the amount of biological activity, the soil structure, and the types and quantities of added cultural material such as charcoal, charred peat, and bone fragments. Thin sections of undisturbed soil were prepared at the Royal Holloway, University of London, and at the University of Reading, School of Human and Environmental Sciences. Both labs used oven drying and epoxy resin, rather than the standard technique of acetone and crystic resin; otherwise the techniques followed the standard practice (MacLeod 2008). The thin sections were examined at magnifications of 40x to 400x using a polarizing microscope, and were described using the International System for soil thin-section description (Bullock et al. 1985). Light sources included plane polarized (PPL), cross polarized (XPL) and oblique incident (OIL). Interpretations were aided by FitzPatrick (1993) and Courty et al. (1989), and by comparison to reference materials (including peat, hearth ash, and animal manures) collected in Shetland and manufactured as thin sections (Guttmann 2001).

The charcoal abundance in thin section was quantified in 5 size-classes: <150 µm, 150–250 µm, 250–500 µm, 500 µm–1 mm and >1 mm. We examined a total of 100 fields of view for each context using a Leica DMLP trinocular microscope at 200x magnification. Laterally contiguous fields of view were examined in transects across the slide until 100 fields of view had been recorded.

Phosphate

We conducted organic/inorganic phosphate analysis to identify and quantify added animal manures and domestic waste. Soil samples were air dried and sieved at 2 mm, and we took two 1-mg subsamples from each sample. One subsample was heated in a furnace at 550 °C for an hour in order to transform the organic P fraction into inorganic P, after which both samples were subject to sulphuric acid extraction following Mikkelsen (1997). The heated subsample thus provided an estimate of the total phosphate content of the sample (organic and inorganic), excluding the phosphorus bound in silicate structures (ibid.). The unheated subsample provided an estimate of the inorganic fraction. We subtracted the value of each unheated subsample from the heated, total P subsample, the difference being the value for the organic P content. Colourimetry was carried out using an ammonium molybdate reagent (ibid.)

Fecal biomarker lipids

Feces-derived lipids provide another suite of indicators for manuring. The 5b-stanols are acknowledged biomarkers of fecal input, and have been used in both archaeological and pedological research (Bethell et al. 1994; Bull et al. 1999a, 1999b, 2002; Leeming et al. 1996; Simpson et al. 1998, 1999b).

We extracted and analyzed the lipid biomarkers 5b-stanols using the method described by Bull et al. (1999b). Samples from all sites were processed, but not from all test pits. We made a selection based on the likelihood that the sample would be free from contamination, and ensured that each assumed land use was represented (pasture, arable, and control). Following the discovery of high phosphate in the peat overlying the buried soils, we processed additional samples from the peat.

Loss on ignition

We used loss on ignition (LOI) to distinguish soils with added organic matter from soils without such amendment, based on comparison with unamended local buried control soils dating to the Mesolithic. LOI was determined as percentage mass loss following ignition of oven-dried soil (105 °C) at 425 °C for 8 hours. We conducted LOI in the first season only because later peat infiltration into the samples rendered the analysis meaningless.

Macrobotany

We took 10-litre soil samples for charred macrobotanical remains from the buried soils in each test pit. The density of rootlets made sieving and analysis rather difficult. We scanned the 1-mm sieving fraction of all the samples using an illuminated magnifying glass, and selected 8 samples for further investigation under the microscope.

Soil magnetism

We analyzed soil magnetism (mass susceptibility, Xfd, ARM, IRM) in order to identify fuel ash residues in the soil (e.g., Peters et al. 2001). This method was not successful in distinguishing the different areas, probably because of the high degree of iron translocation in the soil, and the results will therefore not be discussed here. We examined soil magnetism in the first season only, and not in the second.

Results

Dating

The field walls have been firmly dated to the Neolithic (Caulfield et al. 1998), but 2 phases of activity were identified at Belderrig Beg (Fig. 1b), where a roundhouse and lazy beds were found (Caulfield 1978). Radiocarbon dates placed the later phase in the Bronze Age and the earlier in the Neolithic (ibid.). For the current research, we placed test pits in a Neolithic/Bronze Age midden (Test pit A) and in an area where the Bronze Age lazy beds were discovered (Test pit B). The aim of Test pit A was to identify the potential fertilizing material within the midden, and Test Pit B was placed to sample and compare the soil from the Bronze Age lazy beds and the underlying Neolithic soil. The lazy beds were not found, but a radiocarbon date from a charcoal fragment in the buried soil in Test Pit B confirmed a Bronze Age Date (Table 1).

Field observations and background

The peat in County Mayo reaches depths of over 4 m, so samples were taken predominantly from areas where some of the peat had been extracted. During peat extraction, the more fibrous and poorly humified upper “topsod” is removed and set aside

Table 1. Radiocarbon dates (calibrated at 95.4% probability).

Lab code	Test pit	Material	Date uncal. BP (BP = 1950)	Date (cal. BC)
OxA-15270	A	*Calluna vulgaris*	3563 ± 30	1920 ± 60
OxA-15271	A	*Salix*	3649 ± 30	2035 ± 105
OxA-15272	B	*Ilex aquifolium*	3091 ± 29	1360 + 70

(S. Caulfield, University College Dublin, Dublin, Ireland, pers. comm.), and the black, humified peat below is removed in long, thin blocks, to be then dried and used for fuel. As peat cutting progresses, the topsod is thrown back onto the truncated humified peat layer, creating what is often a sharp boundary between redeposited brown topsod and the truncated black peat that seals the buried soils (Fig. 2a). The sequence is not always simple; in places the buried soil was sealed by bands of brown and black peat, which may represent burning or peat cutting on more than one occasion (Fig. 2c). The layer of humified peat overlying the buried soils was between 1.10 m and just 10 mm thick, and in one instance (Test Pit C) the peat appeared to have been extracted right down to the level of the mineral soil (Fig. 2b).

The buried soils in the field were variable in color and texture (Appendix 1), ranging from 10YR2/1 (black) to 5/4 (yellowish brown), and the stone walls of the Neolithic fields often rested on buried soil horizons that were pale and leached (e.g., 10YR 5/4). The buried soils were 40–190 mm thick, and in a few instances there was evidence of soil profile development, with slightly paler, leached eluvial horizons below the buried topsoil. The thin depth of the buried soils suggests that they have been either truncated or eroded. Test Pit J (Fig. 3a) shows the development of soil horizons, consisting of a layer of black peat (126) over a thin, pale brown horizon with an indeterminate boundary onto a grey horizon. The brown/grey horizon (127) had characteristics of a buried soil, e.g., dense and very dense excremental fabric and a moderate porosity. Below this was a distinctly leached eluvial horizon that overlay gleyed till.

We had hoped to find traces of the lazy beds described by Caulfield et al. (2009) at Belderg Beg, but Test Pit B did not contain any obvious cultivation ridges or furrows. Possible cultivation ridges were found in Test Pit 3 in the Céide Fields, however, where there was a 4-cm-high ridge adjoining a 4-cm-deep furrow at the interface between the base of the buried soil and the surface of the till below. The buried soils in Test Pit 10 at Rathlackan were contained entirely within a furrow, reaching a depth of 10 cm and tapering to 0 cm over a length of 50 cm. Shallower and less convincing wavy interfaces occurred in Test Pit J (Céide Fields) and Test Pits 7 and 8 at Rathlackan (Fig. 4a).

On slopes, the field walls act as sub-peat drains, with water-lain silts and sands accumulating in lenses between and around the stones; this was a phenomenon that was also noted in excavation at Belderrig by Warren (2004). The passage of rainwater down through the soil profile has also affected the soil; iron panning was evident in some of the buried B horizons and also in the stony, compacted, and often gleyed glacial till below.

Micromorphology, LOI, and macrobotanical evidence

There was a vast amount of variation in the soil organic matter of the samples, and many of the horizons identified as mineral soils in the field were actually higher in organic matter than the layers identified as well-humified peat, based on loss-on-ignition results (Table 2; see also Supplementary Table 1, available online at http://www.eaglehill.us/JONAonline/supl-files/J091812-Guttman-Bond-s1, and for BioOne subscribers, at http://dx.doi.org/10.1656/J091812.s1). The thin-section analysis (Appendix 2) provides an explanation for these unexpected findings: the buried soils contain frequent rootlets in a state of partial decay, making them more organic-rich (Fig. 3b, c), and the black peat layers often contained charcoal, suggesting that some of the organic matter within them had already been burned. Regular burning of moorland prevents heather from growing too large and woody; it is possible that the fires were intentional, but natural fires in this region date back to the Mesolithic (Molloy and O'Connell 1995).

Many of the buried soil samples contained 15–20% organic material, as estimated in thin section. Conversely, the peat horizons contained up to 20–30% mineral material (silt and sand size), which suggests that either the peat was redeposited, or that sediment washed over or blew into these horizons and accumulated within them during their formation. It is also possible that the peat and soil were mixed due to cultivation; the soils in Test Pits 5 and 6 at Rathlackan—both within the same enclosure—contained peat fragments similar to those found in plaggen soils (cf. Guttmann et al. 2006). These

Table 2. Phosphate and loss on ignition (LOI) ranges given in mg per 100 g.

Location	Total P	Organic P	% LOI
Buried soils, Rathlackan	9.03–44.80	8.59–33.81	-
Buried soils, Céide Fields	6.45–76.12	8.20–74.58	5.48–90.54
Peat (Céide Fields)	28.25–88.24	24.05–86.62	7.24–11.45
Buried soils, Belderrig	10.60–33.88	10.46–29.29	9.09–31.70
Peat (Belderrig)	16.08	16.03	95.56
Buried soil, control Mesolithic	11.14–13.46	7.14–9.43	13.79–81.96
Till	13.68–34.06	9.43–33.48	12.68–89.08

Figure 2. (a) Soil profile, Test Pit B (Belderrig) photo and section drawing; (b) Test pit C (Belderrig) photo; (c) Test pit G (Belderrig) photo.

layers (contexts 202 and 200) included porous to dense excremental fabric, and 202 also contained organic material with intact sheets of phytoliths. Rathlackan's Test Pits 7 and 12 also contained peat fragments in the buried soils (205) and (217). Field observations support the notion that the peat layer was disturbed and possibly ploughed: Test Pit 7 had a wavy interface between the buried soil (205) and

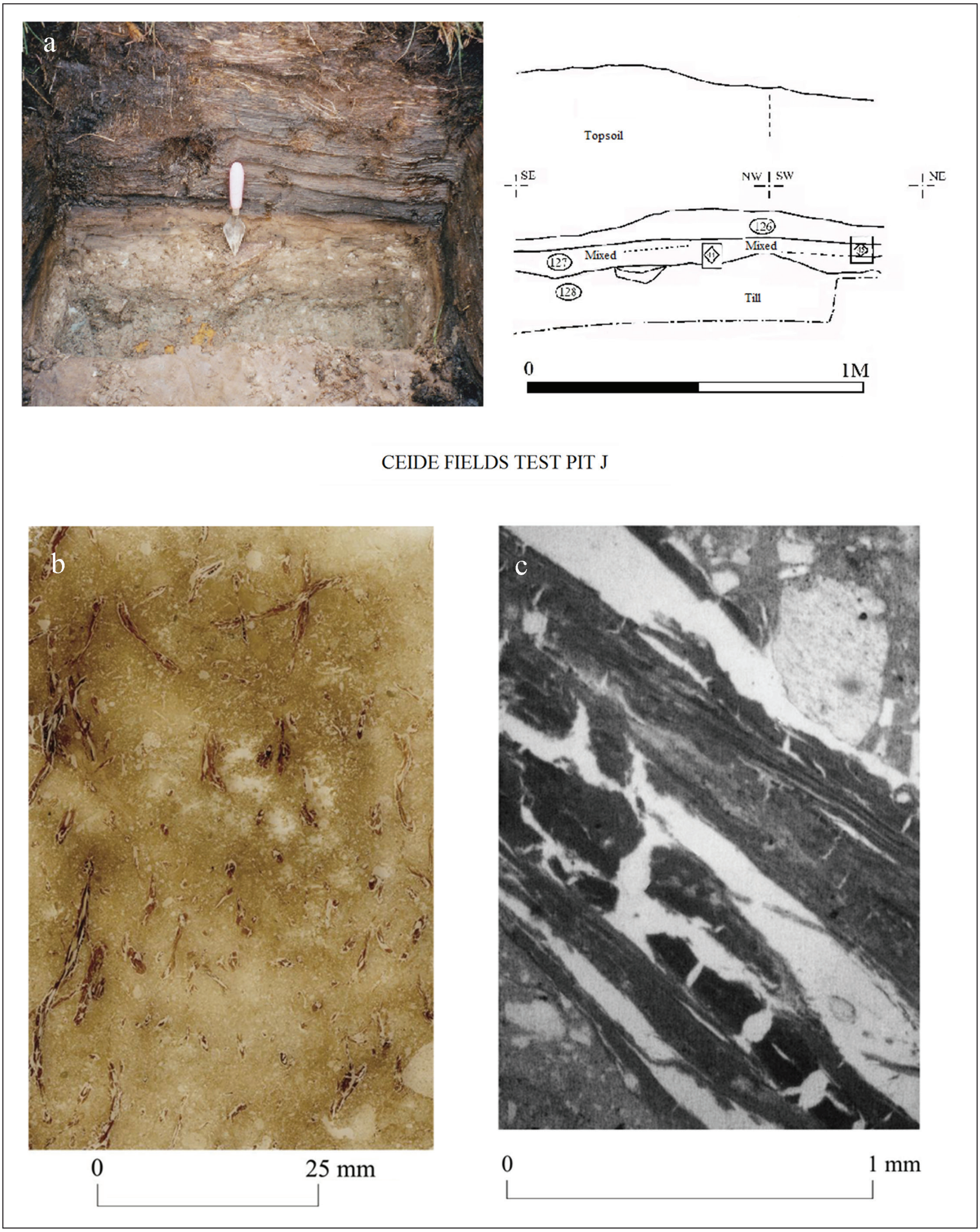

Figure 3. (a) Test pit J (Céide Fields) photo and section drawing; (b) Rootlets in the buried soil, macro (Céide Fields Test Pit I, layer 119); (c) Rootlets in the buried soil, micro (Céide Fields Test Pit I, layer 119).

the subsoil below (206), as well as at the base of the subsoil (Fig. 4a). Test Pit 12 showed an irregularity in the interface between the humic black peat (216) and the buried soil below (217); this finding could be due to either prehistoric arable activity or modern peat cutting (Fig. 4b).

Phytoliths occurred in both the peats and soils; phytoliths are concentrated in animal dung, but they also occur naturally in soil and peat. A more unusual occurrence was the occasional cluster of spherulites, which are an indicator of animal manure (Canti 1997), but it is difficult to believe that these calcitic structures could survive in such an acidic environment, and it is possible that they are an artifact of thin-section processing. A more convincing indicator for manuring was found in the form of a bright blue mineral (PPL and XPL) interpreted as vivianite in the buried soil (226) in the Céide Field Test Pit 3. Vivianite is a phosphatic mineral which occurs naturally in wet, peaty soils (Bullock et al. 1985:72) but it is also associated with human and animal excrement (Mcgowan and Prangell 2006).

The structure of the soils in thin section was characterized by cracks (due to wetting and drying) and channels, derived from either earthworm activity followed by root penetration or from root penetration alone. The channels were typically around 1 mm wide and have a vertical to 45° orientation. The remains of roots were evident within the channels, which carry on down into the till (hence the high LOI of many of the till samples). The organic root material within the channels was often well preserved or only slightly decayed. The porosity of the samples was typically 20–30%, with much of the void space occurring as channels in which rootlets were partially decayed.

A number of the samples were characterized by a platy structure of planar voids and flattened organic aggregates, a sign of compaction that is frequently interpreted as an indication of ploughing (Macphail et al. 1990). However, this was more often a characteristic of peat layers, occurring in a soil only in test pit 18 in the Céide Fields, in which soil (243) contained horizontal lenses of peat. In several layers, we noted that the channels cut through the horizontal peat layers, indicating that the rootlet penetration occurred at a later date. Test Pit 4 in the Céide Fields contained horizontal laminations in the peat and clay domains occurring in the soil fabric; the clay domains might be interpreted as fragmented plough pan.

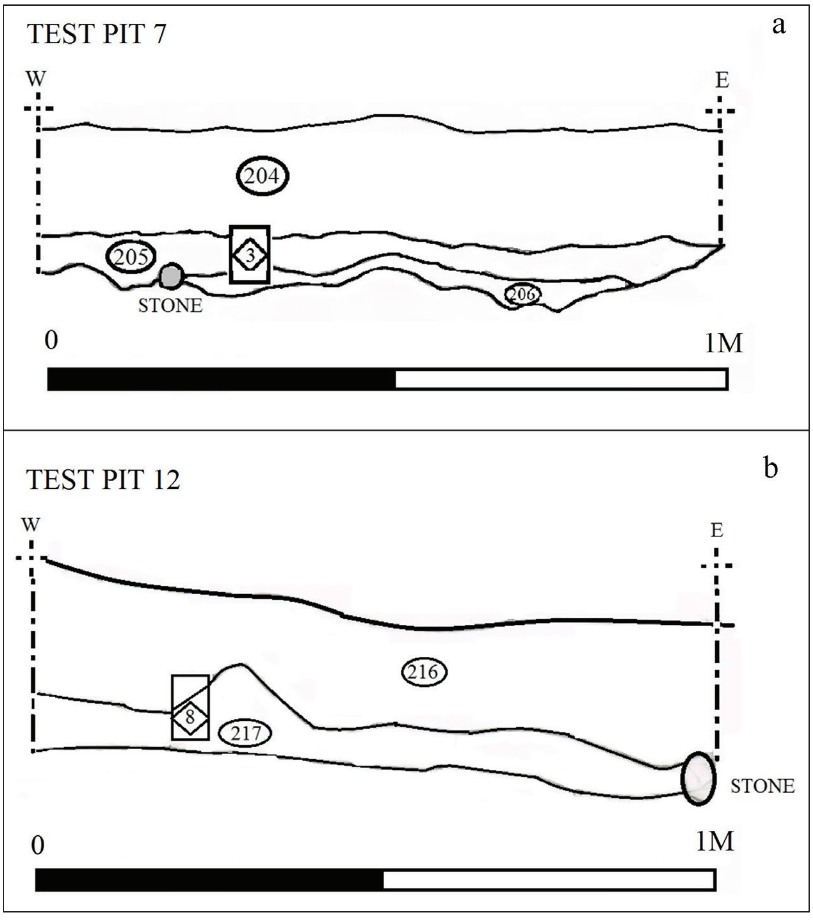

Figure 4. (a) Test pit 7 (Rathlackan) section drawing; (b) Test pit 12 (Rathlackan) section drawing.

Soils develop through processes of chemical and physical weathering, and are generally distinguished from sediments by the presence of soil horizons (French 2003:35). On a microscopic scale, soil formation can be identified by the presence of "pedofeatures", or soil-forming features (French 2003:40). Pedofeatures are characteristics that derive from physical and chemical weathering processes such as leaching and oxidation, and also from the biological activities of soil biota such as earthworms and mites. There was abundant evidence for oxidation and reduction in the samples, in the form of iron accumulation around the rootlets and the channels in which they occurred. This evidence for redox processes is indicative of wetting and drying, which is hardly surprising in a temperate landscape covered in blanket bog. Evidence for translocation of clays and silt was very rare; there were very rare mineral grains with birefringent coatings, but (apart from in Test Pit 1 in the Céide Fields) the soil voids did not have either the limpid clay coatings that might be expected from a woodland soil, or the dusty clay coatings which would indicate disturbance such as that brought about by cultivation (Jongerius 1983, Macphail et al. 1987).

Another important pedofeature that is useful in this context is excremental fabric, which is an indicator for the presence of soil biota. This fabric includes rounded aggregates of excrement in differing states of decay. When the aggregates are still distinct and rounded, the fabric is described as porous and very porous, and is an indication of recent biological activity (Bullock et al. 1985:137). Over time, the aggregates coalesce into dense and very dense excremental fabric. Nineteen soils (including soils from all 3 sites) contained rare to very rare porous excremental fabric, indicating potentially recent earthworm or mesofaunal activity (e.g., collembola, mites). The porous excremental fabric was confined almost entirely to the channels, in which organic material was partially decayed. Twenty-seven soils (from all 3 sites) contained dense and very dense excremental fabric, indicating both age and compaction of the soils (ibid.) and that the soils were once biologically active.

Potentially anthropogenic material visible in the soil thin sections was limited to charcoal and charred peat fragments. Soil charcoal is traditionally interpreted as the result of burning of the vegetation for land clearance prior to agriculture, but hearth ash is also applied as fertilizer in regions where the soil is naturally acidic (Guttmann et al. 2005). Ash is calcareous and helps to raise the soil pH, improving soil quality, attracting earthworms, and increasing agricultural yields.

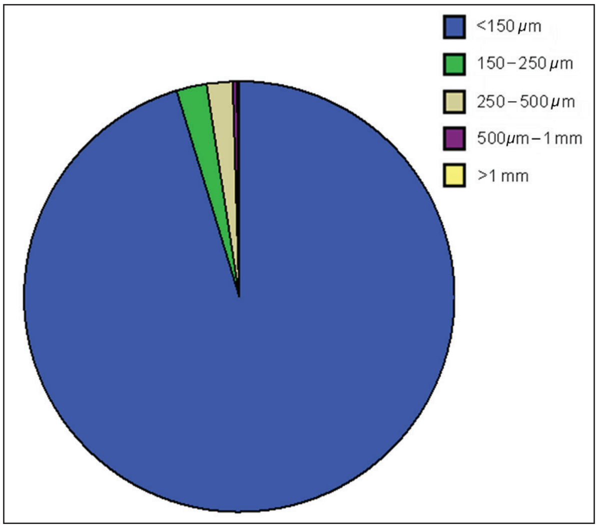

Figure 5. Charcoal distribution by fragment size range, based on contiguous transects of the thin section slides.

A size analysis on the charcoal fragments in thin sections from all sites indicated that 96.3% of the fragments were in the size class of <150 µm (Fig. 5; see also Supplementary Table 2, available online at http://www.eaglehill.us/JONAonline/supl-files/J091812-Guttman-Bond-s1, and for BioOne subscribers, at http://dx.doi.org/10.1656/J091812.s2). Since this is the size class most likely to be carried by the wind (Clark 1988), it cannot be conclusively stated that the land was intentionally fertilized with hearth ash. Larger fragments were found in small quantities in other contexts, particularly the Belderrig midden, but only 21 fragments over 500 µm were recorded in thin section. Some of the charcoal noted in thin section was from burned peat, identified by its structure and the inclusions of mineral grains (Davidson and Carter 1998).

Molloy and O'Connell (1995) noted that the black, humified peat layer in the Céide Fields area contained frequent charcoal, which was interpreted as a consequence of burning on the peat surface. The charcoal dates predominantly to before the Neolithic land clearance, with the latest major deposition occurring 200 years before the clearance phase (ibid.). Burning as part of the clearance phase is suggested by Caulfield (1978), who noted that charcoal occurs in all the exposures of the buried mineral soil within the field systems. Given the ubiquity of charcoal in the landscape before and possibly during the use of the field system, it is impossible to ascribe either natural or human causes to the burning, apart from the evidence within the clearly archaeological midden deposits at Belderrig.

All macrobotanical samples contained small- to moderate-sized charcoal measuring less than 6 mm. Most contained un-diagnostic spores, many of which seemed to have been charred. There were no charred seed remains in any of the samples investigated, but small lumps of humified peat were found in the bulk sieving from the buried soil in Test Pit G, and burnt peat was recovered from the Belderrig midden (Table 3). We identified charcoal from the Belderrig midden as *Calluna vulgaris*, another indicator that peat was burnt on this site.

Table 3. Macrobotanical remains.

Sample	Test pit	Site	Results
1	C	Belderrig	
4	D	Belderrig	2 fragments possible charred pine bracts
9	1050/990	Belderrig	
10	A (midden)	Belderrig	
13	B	Belderrig	Burnt peat
14	A (midden)	Belderrig	
15	A (midden)	Belderrig	
27	G	Ceide	Small lumps of humified peat

Phosphate

The phosphate results indicated raised levels of P in the buried soils as compared to the controls, which suggests low levels of anthropogenic inputs in the buried soils (Table 2; see also Supplementary Table 1, available online at http://www.eaglehill.us/JONAonline/supl-files/J091812-Guttman-Bond-s1, and for BioOne subscribers, at http://dx.doi.org/10.1656/J091812.s1, and Supplementary Table 3, available online at http://www.eaglehill.us/JONAonline/supl-files/J091812-Guttman-Bond-s3, and for BioOne subscribers, at http://dx.doi.org/10.1656/J091812.s3). The peat from the 3 sites was also significantly richer in phosphate than the control samples ($P = 0.000$), based on an ANOVA in SPSS using replicate samples from each site. Figure 6a shows that the highest levels of organic phosphate were actually derived from the peat, which is probably the result of several processes, to be discussed below. The outliers shown in Figure 6a indicate particularly high organic phosphate in contexts 121 (the buried soil in Test Pit G) and 226 (the buried soil in Test Pit 3; note that vivianite also occurred in this context). Test Pit G was in the field in which the ard marks and ard share were found in the 1991 excavation (Byrne et al. 2009b), and Test Pit 3 was in the field immediately to the south.

The main taphonomic problem with organic/inorganic phosphate analysis is that soil microbes convert organic P into inorganic P in aerobic conditions, but (as predicted) the waterlogging and acidity has prevented this from taking place. The samples contained predominantly organic P and very little mineralized P, which suggests that the inputs were organic material such as manures. The total P plot shows a similar distribution to the organic P (Fig. 6b). The outlier in Figure 6b showing higher total P levels is from the Céide Fields Test Pit 3, in the field to the south of the field containing ard marks.

If the sites are presented individually, the P distribution from the Céide Fields appears similar to the overall distribution (Fig. 7a), but a slightly different pattern is apparent at Belderrig, where P seems to have leached down into the till to a greater degree (Fig. 7b). The P levels in the Belderrig peat are lower than on the other sites.

Samples were taken from 2 fields and 2 enclosures at Rathlackan (Test Pits 5–12, 29, and 30; Fig. 1d). The total P distribution showed a high level of P in Test Pits 7 and 8 compared to the controls, with slightly raised levels also occurring in the field immediately to the south (Fig. 8). The 2 enclosures, by contrast, contained P at about the same levels as the controls.

Fecal biomarker lipids

The stanol index ([5β-stanol + epi-5β-stanol]:[5α-stanol + 5β-stanol + epi-5β-stanol]) (Simpson et al. 1998; Bull et al. 1999b, 2002), summarized as [5β:5α + 5β], was used to detect the ancient deposition of

Table 4. Concentrations (μg g^{-1} soil) of bile acids extracted from buried soils. LC = lithocholic acid, DOC = deoxycholic acid, CDOC = chenodeoxycholic acid, HDOC = hyodeoxychoilic acid, UDOC = ursodeoxycholic acid, and X = 3a-hydroxy-12-oxo-5b-cholanic acid. All acids given in μg g^{-1} soil.

Sample/ context	Site	Test pit	Type	LC	DOC	CDOC	HDOC	UDOC	X
10/108	Belderrig	A	Buried soil	0.00	0.41	0.00	0.27	0.00	0.00
07/104	Belderrig	D	Buried soil	0.00	0.36	0.00	0.00	0.00	0.00
13/110	Belderrig	B	Buried soil	0.00	0.94	0.00	0.00	0.00	0.00
47/129	Ceide	H	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
43/127	Ceide	J	Buried soil	0.47	0.95	0.05	0.06	0.00	0.19
27/121	Ceide	G	Buried soil	0.00	2.06	0.00	0.00	0.00	0.00
42/125	Ceide	G	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
30/119	Ceide	I	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
49/238	Ceide	27	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
24/222	Ceide	1	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
73/243	Ceide	18	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
33/117	Ceide	I	Peat	0.00	0.37	0.00	0.00	0.00	0.00
13/211	Rathlacken	9	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
09/208	Rathlacken	8	Buried soil	0.00	0.09	0.00	0.00	0.00	0.00
15/213	Rathlacken	11	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
05/205	Rathlacken	7	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
03/203	Rathlacken	5	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
07/206	Rathlacken	7	Buried sub-soil	0.00	0.00	0.00	0.00	0.00	0.00
11/209	Rathlacken	8	Buried sub-soil	0.00	0.00	0.00	0.00	0.00	0.00
44/234	Area E	24	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
60/136	Control	F	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
61/136	Control	F	Buried soil	0.00	0.00	0.00	0.00	0.00	0.00
63/136	Control	F	Buried soil	0.00	0.5	0.00	0.00	0.00	0.00

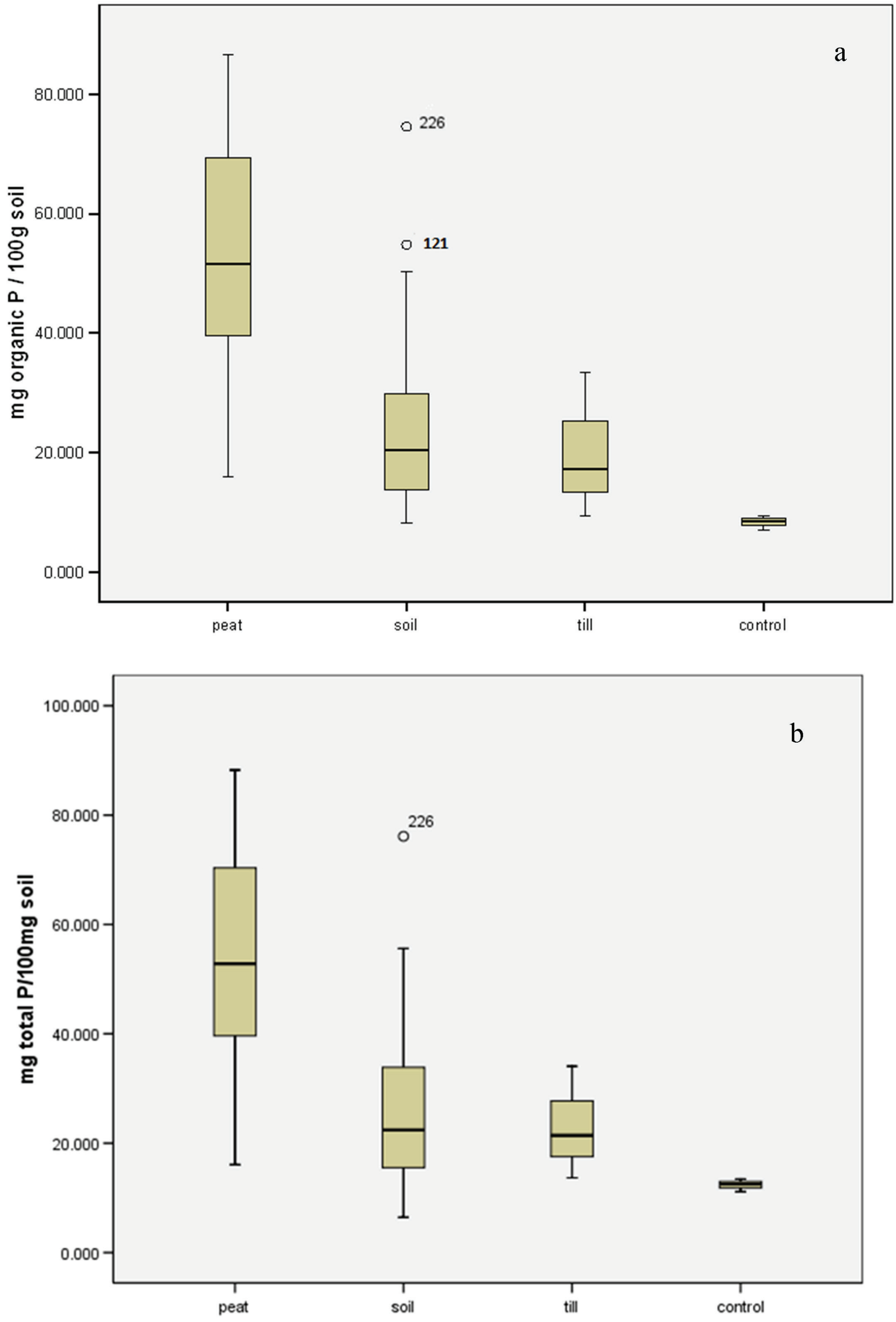

Figure 6. (a) Distribution of organic P in the Céide Fields, Belderrig, Rathlackan, Area E and the controls; (b) Distribution of total P in all sites. The boxplots show the maximum and minimum values for each sample set, with the median line in the center.

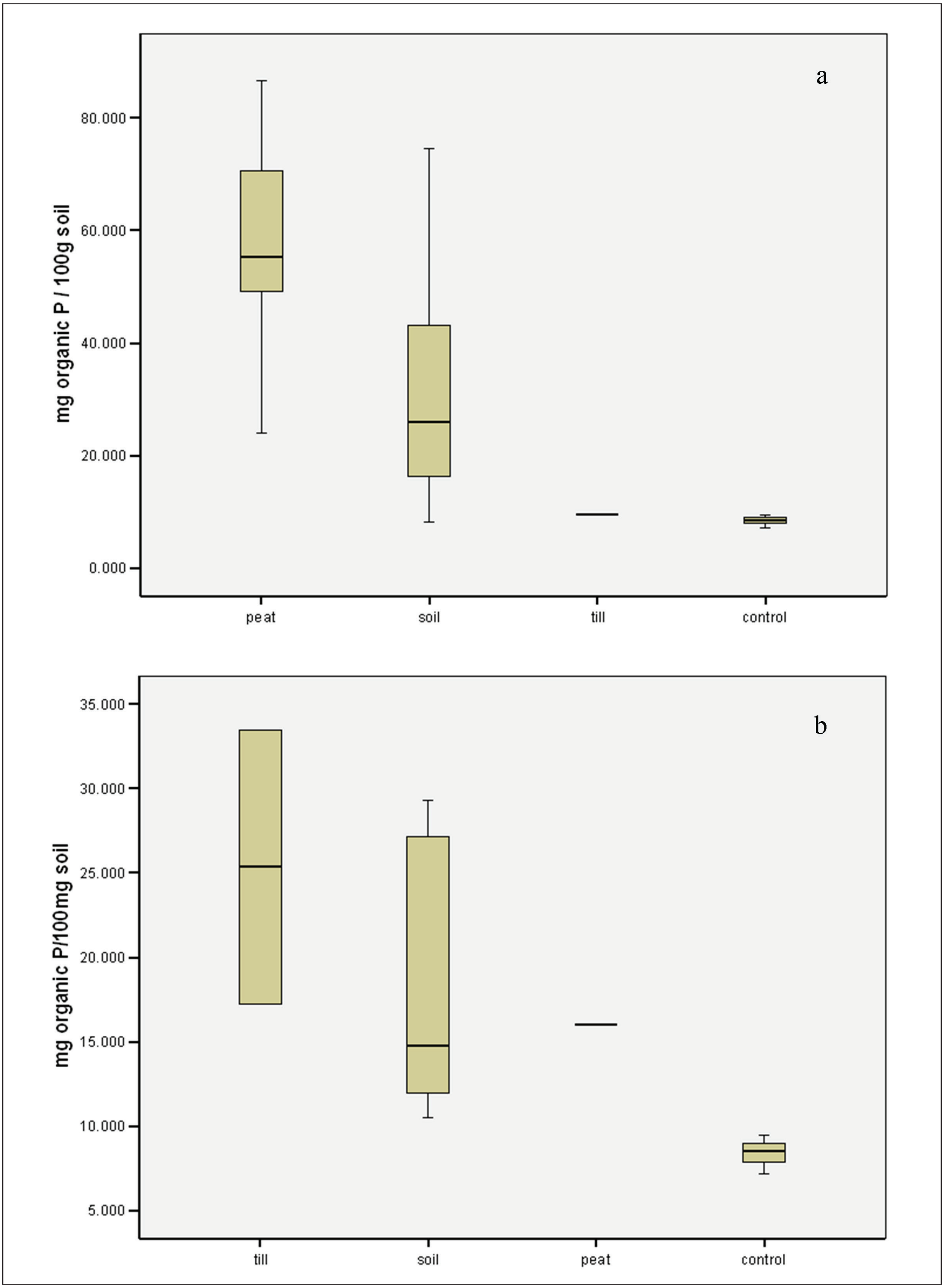

Figure 7. Organic P in (a) Céide Fields and control soils, and (b) in Belderrig and control soils. The boxplots show the maximum and minimum values for each sample set, with the median line in the center.

manures in archaeological soils at Céide, Rathlackan, and Belderrig (Table 4). All of the buried soils analyzed contained 5b-stanols, which suggests the presence of herbivore feces, but which could also be natural background levels. The undisturbed Mesolithic control soils contained a significantly higher stanols index [5β:5α + 5β] compared with Rathlackan, Belderrig, and Céide (Fig. 9), which indicates that the 5b-stanols are probably natural and do not suggest manuring. The single samples analyzed from the overlying peat at Céide and the buried soil from Area E provided ratios of (5β:5α + 5β) = 0.11 and 0.07, respectively, and (5β:5α + 5β) = 0.25 ± 0.11 for the buried sub-soil from Rathlackan, but these were less than or similar to the control soils ([5β:5α + 5β] = 0.29 ± 0.01). The 5b-stanols and total phosphate were correlated to test whether enhanced levels of organic phosphate were reflecting added organic manures (Linderholm 1997), but the results showed no statistically significant relationship (*P* = -0.24).

The analysis of bile acids produced some interesting but widely variable results. Overall, deoxycholic acid was the most common bile acid (Table 4). In isolation, deoxycholic acid provides evidence of bovine dung, and in combination with lithocholic acid it is evidence for human feces (Simpson et al 1999b). All of the soils that contained deoxycholic acid also contained 5b-stanols (but not vice versa). Deoxycholic acid occurred in 1 of the 3 control soils at 0.50 mg g^{-1} soil; it was 0.00 mg g^{-1} soil in the other two. Deoxycholic acid was identified in all Belderrig buried soil samples (Test Pit A: 0.41mg g^{-1} soil, Test Pit B: 0.94 mg g^{-1} soil, and Test Pit D: 0.36 mg g^{-1} soil). Test Pit B, with the slightly raised level, was the buried soil sample taken from a buried Bronze Age soil. Deoxycholic acid also occurred in 1 of 5 Rathlackan samples (0.19 mg g^{-1} soil), and also in a peat sample from Céide Test Pit I (0.37 mg g^{-1} soil). The buried sub-soil samples from Rathlackan and the buried soil from Area E contained no evidence of deoxycholic acid. Two of the 8 buried soil samples from Céide contained deoxycholic acid, but in significantly different concentrations: 0.95 mg g^{-1} (Test Pit J) and 2.06 mg g^{-1} in Test Pit G. Hyodeoxycholic acid

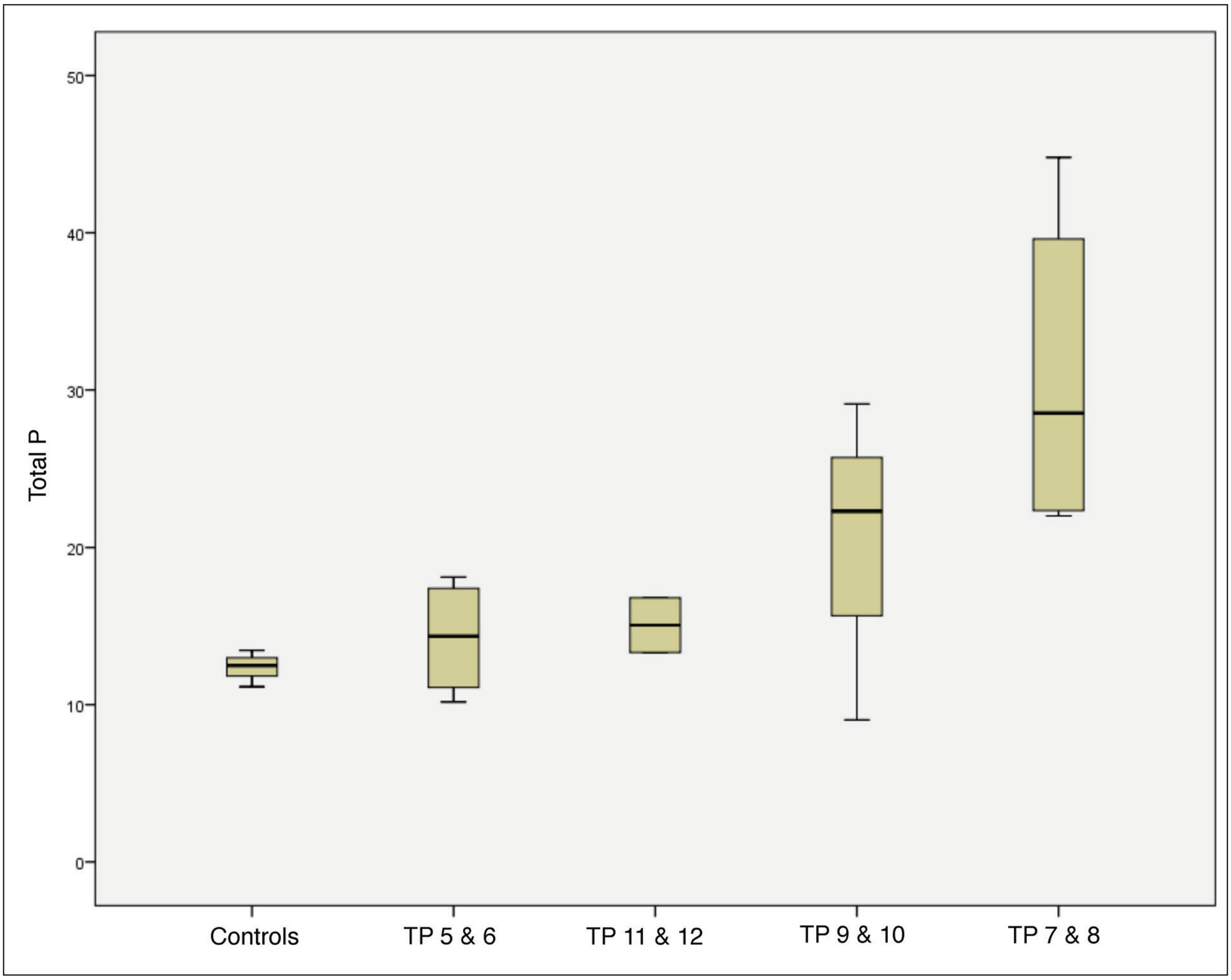

Figure 8. Total P in Rathlackan fields and enclosures. The boxplots show the maximum and minimum values for each sample set, with the median line in the center

was also identified in 1 of the Belderrig buried soils and in 1 of the Céide soils. In the latter sample, deoxycholic acid and hyodeoxycholic acid were identified along with lithocholic acid, chenodexoycholic acid, and 3a-hydroxy-12-oxo-5b-cholanic acid.

Discussion

In 1991, a cluster of ard marks and a stone ard share were uncovered in the Céide Fields in an area that is now beneath the Visitor Center (Byrne et al. 2009b). In 2004–2005, we placed 4 test pits to the east of the Visitor Center, in the same Neolithic field as the ard marks and ard share, and a further 3 test pits in the field immediately to the south. The evidence from these test pits suggests that the arable area extended to the south and east of the Visitor Center. The soil in Test pit 18 (ard mark field) contained planar voids with horizontal lenses of peat. The soil in Test Pits 3 (to the south of the ard mark field) and Test Pit G (the ard mark field) had organic phosphate levels that were significantly higher than the other soil samples, such that they appear as outliers in the organic P plot for all 3 sites. The highest level of deoxycholic acid on the site (2.06 µg g^{-1}) was found in Test Pit G. Test Pit G also had small lumps of humified peat in the buried soil, which may indicate mechanical mixing such as would take place in an arable ploughsoil. Taken together, these indicators suggest that the entire field may have been used as arable land, and that it is likely to have been manured with bovine dung.

The Neolithic field to the south of the ard mark field also contained potential arable indicators. The buried soil in Test Pit 1, located within a round enclosure to the south of the 1989 excavation trenches, contained the only dusty clay coatings noted in the excavation; these coatings are an indicator of disturbance usually associated with ploughing (Macphail et al. 1987), although they can also arise from other types of disturbance (Wilson 2000). Test Pit 2 was abandoned due to the truncation of the shallow soil, but the buried soil in Test Pit 3 contained an outlier with the highest total P found on all 3 sites. The buried soil in Test Pit 3 had a distinctively wavy interface with the till below, suggesting cultivation; this soils also had the highest organic P concentration found on the 3 sites, as well as vivianite, a phosphatic mineral associated with manuring. Test Pit 4 contained a possible re-worked plough pan in the form of disturbed clay domains (cf. Gebhardt 1992, Lewis 1998).

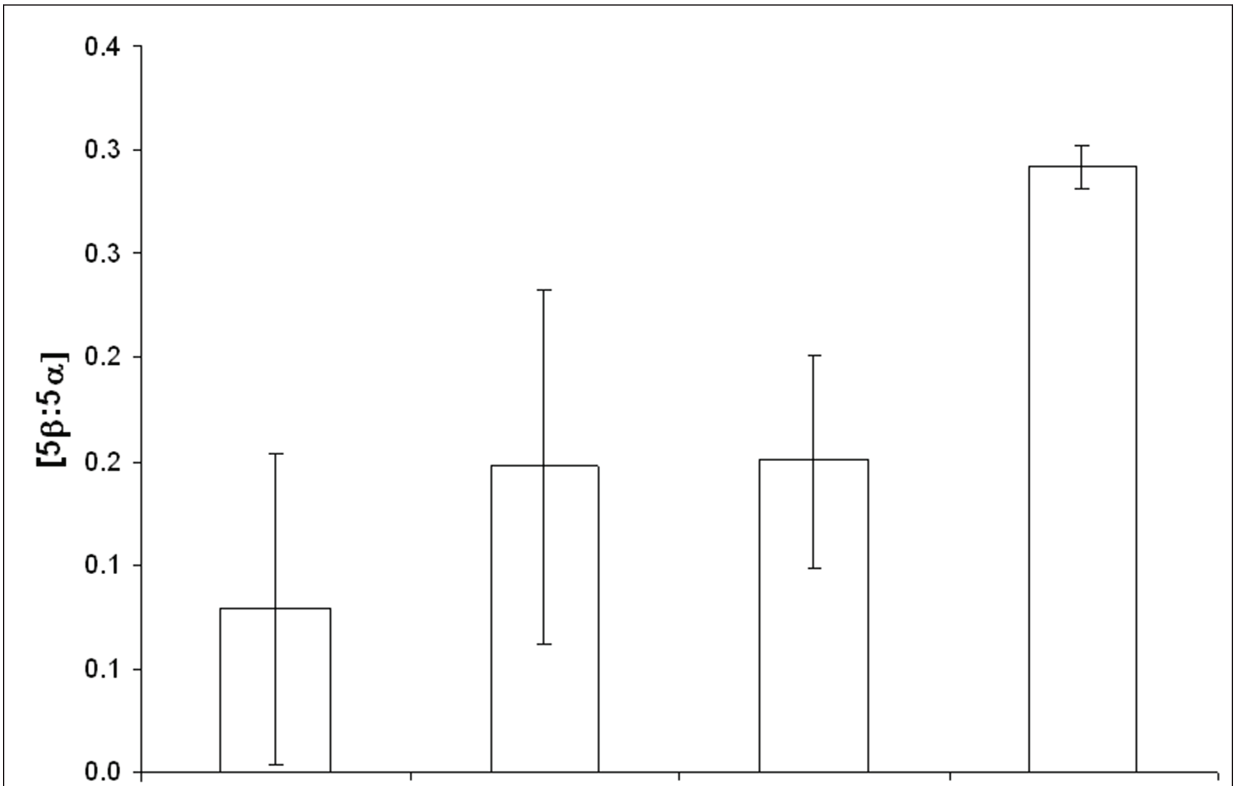

Figure 9. Mean (5β:5α + 5β) for buried soils from Belderrig (*n* = 3), Rathlackan (*n* = 5), Céide Fields (*n* = 8), and control areas (*n* = 3). The boxplots show the maximum and minimum values for each sample set, with the median line in the center.

Rathlackan had one field that was distinctly higher in P than the controls. Test Pits 7 and 8, within this field, not only had higher total P but also had evidence for possible ploughing or cultivation ridge and furrow. Test Pit 11, within the southern enclosure, also had a slightly wavy boundary between the base of the buried soil and the top of the natural till. Test Pits 10 and 11 had raised P compared to the enclosures, but it was not as pronounced as the distinctly higher levels in the northern field.

The phosphate sampling showed generally higher levels of P in the peat than in the buried mineral soils, although natural blanket peat is not naturally high in P (Grime and Guttmann-Bond 2011, Renou and Farrell 2005). Phosphorus gains derive from P that is sorbed on wind-blown dust particles, but this usually contributes very low levels of P to the developing peat (Brady and Weil 1999:551). The P enrichment of the peat in the Neolithic field systems is likely to derive partly from such aeolian deposits, but the high levels have most likely been brought up from the Neolithic mineral soils via plant roots. As plants decay on the peat surface, the P returns to the developing peat, and probably continued to be drawn up to the upper peat levels as the peat accreted. Water throughput in blanket peat is extremely slow, with movement of less than 1 cm per day (Renou and Farrell 2005); this water may have brought low levels of P from upslope, which in all cases consists of blanket bog. Erosion from the P-enriched Neolithic arable soils may also be a factor; the soils contained mineral grains which might have eroded into the peat via wind or sheetwash.

The thin-section analysis identified high quantities of sand and silt within the peat, interpreted as a result of erosion of the local soils via wind or sheetwash. Molloy and O'Connell (1995) also observed large quantities of mineral material in the peat when they undertook pollen analyses in the region, and they also concluded that the material represents erosion of local soils. This is a hilly region, and colluviation could have been accelerated by either arable agriculture or overgrazing. Occasional bog bursts also occur in this area during heavy rainfall.

Peat fragments also indicate mechanical mixing, possibly due to recent peat cutting but possibly also due to prehistoric cultivation. Both interpretations would explain the shallow depth of the buried soils identified in the field, but the evidence for mineral grains in thin section ties in with the work of Molloy and O'Connell (1995), who noted the presence of sediment in the peat and also frequent charcoal, indicative of burning on the peat surface. The charcoal deposition and erosion events that they identified took place before the Neolithic clearance for the Céide Fields (ibid.). The evidence from the current study suggests that soil erosion—possibly accelerated by ploughing or grazing animals—continued to take place while the Céide Fields were in use and may have continued after the fields were abandoned.

The burnt peat and *Calluna vulgaris* charcoal from the Neolithic/Bronze Age midden deposit at Belderrig, together with the occasional charred peat seen in thin section, suggests that peat was used as a fuel and may also have been used as fertilizer on the fields. Charred peat was identified in Test Pits A and B at Belderrig; Area E; Céide Fields Test Pits G, I, 1, 18, 19, 21, and 26; and Rathlackan Test Pit 8. Charred peat was also seen in thin section in the peat layer of Test Pits E, G, I, J, 19, 20, 21, and 26. The occurrence of charred peat fragments in the peat could be due to natural fires or to mixing—which suggests that the charred peat in the buried soils could also be natural. It is difficult to draw conclusive evidence from this indicator alone, but it may be significant that the one sample containing charred peat at Rathlackan was from a test pit with raised levels of phosphate in the field thought to be arable land.

The phosphate within the peat is likely to derive from the soil of the fields, and the low levels of P in the buried soils suggests that they have been depleted, either through truncation, removal of P by plants, or both. The enhanced organic P, together with the bile acid data, suggests that there was some amendment with animal manures. The presence of charcoal in the buried mineral soils suggests that fires continued to occur in the landscape, but there is no evidence to conclusively argue that charcoal was intentionally spread onto the land as fertilizer, or to distinguish whether the burning episodes were natural or intentional.

The lipid results were mixed. Although 5b-stanols were observed in most of the buried soil samples from Belderrig, Céide, and Rathlackan, these alone did not provide sufficient evidence to support the managed application of animal manures in the Neolithic. There is a natural background of 5b-stanols in the environment (Bethel et al. 1994), and, since the chemical precursors of the fecal biomarker sterols and 5a-stanols occur naturally in the environment, there exists the possibility for the diagnostic ratio of ($5\beta:5\alpha + 5\beta$) proxy to be obscured by the latter addition of the 5a component, be it directly or as a reduction product of its precursor. Downward transport of these components from overlying peat may explain why there was no definitive signal of fecal input using these biomarkers.

Bile acids are more specific indicators for fecal material as they derive from mammalian metabolism rather than as a reductive product of a dietary compound, i.e., stanols, and have been shown to be more stable in the environment than stanols (Elhmmali et al. 1997). The results of the analysis of the 2 compound classes described support this specificity; although all but 1 of the samples analyzed contained 5β-stigmastanol and/or its epimer, only 8 contained bile acids. Therefore, instances where deoxycholic acid was the dominant bile acid, and coincident with 5b-stanols, can be tentatively ascribed to cattle dung. The presence of cattle dung suggests that herbivore dung was added to the soil—although it may have simply been the unstructured deposition of fecal material by grazing animals. The highest level of deoxycholic acid on the site (2.06 $\mu g\ g^{-1}$) was found in Test Pit G, which was on or near the area of ard marks. Possible manuring also occurred in the buried Bronze Age soil at Belderrig, in the area where cultivation ridges were recorded in the excavation of 1971–1982 (Byrne et al. 2009). However, because most of the samples produced levels comparable to the control soils (0 to 0.5 $\mu g\ g^{-1}$), the results of this analysis did not strongly support the hypothesis of manuring of the Céide Fields, apart from in Test Pit G.

One buried soil sample from the Céide Fields contained a wider range of bile acids than the other samples. Test Pit J, placed in a field thought to be for pasture, contained a significant quantity of lithocholic acid. Although no coprostanol was observed, this indicator suggests the input of human fecal material. Human excrement has certainly been used as fertilizer in many parts of the world, and if composted can be quite safe (De Bertoldi et al. 1983, Poincelot 1972), but without more replicate samples it cannot be demonstrated that this “fertilization” was intentional.

Agricultural fields play a prominent part in landscape development in the Early Neolithic in Ireland, but for reasons we cannot explain, they apparently fell out of use in the Late Neolithic. This agricultural decline is supported by pollen analysis (O’Connell and Molloy 2001, Verrill and Tipping 2010) and by a radiocarbon dating program of charred Neolithic cereal grains, the majority of which date from ca. 3800–3000 (Brown 2007). It may be that large field systems were replaced by small plots of land which were more like gardens than fields—a form of agriculture that we see in the Neolithic in Scotland and on the Continent (Bogaard 2005, Guttmann 2005). This study has demonstrated that animal manures were probably used as fertilizer in early Neolithic agriculture in Ireland. This ties in with evidence from the Continent, and also with the new findings produced by Bogaard et al. (2013) indicating the use of animal manure fertilizer in the UK. This is very different to the rather slower development of agriculture in England, where animal manure fertilizer does not seem to have been used until the Iron Age (Guttmann et al. 2005).

Conclusions

The hypothesis for this project was that the land within the enclosed Neolithic fields may have been manured or fertilized, given that 1) ard marks and cereal pollen indicate that some of the land was cultivated, 2) fertilizing material would have been available, and 3) the land was enclosed, which suggests an intensity of land use. The actual site of the ard marks now sits underneath a building, so we could not obtain a set of samples from a soil that was unambiguously arable, but buried soils from the test pits within the same Neolithic field produced high phosphates and the highest levels of deoxycholic acid found on all 3 sites, which suggests the presence of animal manure in the soil in this area. Micromorphology also suggested possible ploughing in this field, as did the presence of small lumps of peat mixed into the buried soil. The field to the south of this one also had evidence for soil amendment and ploughing, including dusty clay coatings, a possible plough pan, and the highest P from any of the test pits.

The conclusion is that the early Neolithic Céide Fields, Belderrig, and Rathlackan were used for both arable and pastoral farming, and that herbivore dung was added to the soil of 2 fields at Céide and possibly also 1 at Rathlackan. We also have tentative evidence for the presence of bovine manure in the Bronze Age soil at Belderrig, together with burning of peat for fuel. Caulfield (1978) suggested that land use at Belderrig may have actually prevented the peat from spreading into the fields, and the evidence from this study supports this idea.

Acknowledgments

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Literature Cited

Bakels, C.C. 1997. The beginnings of manuring in western Europe. Antiquity 71:442–445.

Barclay, G.J. 1997. The Neolithic. Pp.127–149, *In* K.J. Edwards and I.B.M. Ralston (Eds.). Scotland: Environment and Archaeology, 8000 BC– AD 1000. John Wiley and Sons, Chichester, UK.

Barker, G. 1985. Prehistoric Farming in Europe. Cambridge University Press, Cambridge, UK.

Bethell, P.H., L.J. Goad, R.P. Evershed, and J. Ottaway. 1994. The study of molecular markers of human activity: The use of coprostanol as an indicator of human faecal material. Journal of Archaeological Science 21:619–632.

Bogaard, A. 2004. Neolithic Farming in Central Europe: An Archaeobotanical Study of Crop Husbandry Practices. Routledge, London, UK.

Bogaard, A. 2005. "Garden agriculture" and the nature of early farming in Europe and the Near East. World Archaeology 37(2):177–196.

Bogaard, A., R.A. Fraser, T.H.E. Heaton, M. Wallace, P., Vaiglova, M. Charles, G. Jones, R.P. Evershed, A.K. Styring, N.H. Andersen, R.-M. Arbogast, L. Bartosiewicz, A. Gardeisen, M. Kanstrup, U. Maier, E. Marinova, L. Ninov, M. Schäfer, and E. Stephan. 2013. Crop manuring and intensive land management by Europe's first farmers. Proceedings of the National Academy of Sciences 110(31):12,589–12,594.

Bradley, R. 2003. Neolithic expectations. Pp.218–222, *In* I. Armit, E. Murphy, E. Nelis, and D. Simpson (Eds.). Neolithic Settlement in Ireland and Western Britain. Oxbow Books, Oxford, UK.

Brady, N.C., and R.R. Weil. 1999. The Nature and Properties of Soils. Prentice-Hall International, London, UK.

Brown, A. 2007. Dating the onset of cereal cultivation in Britain and Ireland: The evidence from charred cereal grains. Antiquity 81:1042–1052.

Bull, I.D., I.A. Simpson, P.F. van Bergen, and R.P. Evershed. 1999a. Muck n' molecules: Organic geochemical methods for detecting ancient manuring. Antiquity 73:86–96.

Bull, I.D., I.A. Simpson, S.J. Dockrill, and R.P. Evershed. 1999b. Organic geochemical evidence for the origin of ancient anthropogenic soil deposits at Tofts Ness, Sanday, Orkney. Organic Geochemistry 30:535–556.

Bull, I.D., M.J. Lockheart, M.M. Elhmmali, D.J. Roberts, and R.P. Evershed. 2002. The origin of faeces by means of biomarker detection. Environment International 27:647–654.

Bullock, P., N. Federoff, A. Jongerius, G. Stoops, and T. Tursina. 1985. Handbook for Soil Thin Section Description. Waine Research Publications, Wolverhampton, UK.

Byrne, G. 1990. Rathlackan: Court tomb with associated pre-bog settlement. Available online at http://www.excavations.ie/report/1990/Mayo/0001024/. Accessed 3 March 2016.

Byrne, G. 1991. Céide Fields, Glenulra and Behy, Neolithic Field System. Available online at http://www.excavations.ie /report/1991/Mayo/0001157/. Accessed 3 March 2016.

Byrne, G., Downes, M., N. Dunne, G. Warren, S. Rathbone, D. McIlreavy, and P. Walsh. 2009a. Archaeological excavations at Belderg Beg (E109): Stratigraphic report. Unpublished Report. University College Dublin School of Archaeology, Dublin, Republic of Ireland.

Byrne, G., N. Dunne, S. Caulfield, G. Warren, P. Walsh, D. McIlreavy, and S. Rathbone. 2009b. Archaeological excavations in association with the construction of the Céide Visitor Centre (E494). Stratigraphic Report. Unpublished Report. University College Dublin School of Archaeology, Dublin, Republic of Ireland.

Canti, M. 1997. An investigation of microscopic calcareous spherulites from herbivore dungs. Journal of Archaeological Science 24:219–231.

Canti, M. 2003. Aspects of the chemical and microscopic characteristics of plant ashes found in archaeological soils. Catena 54:339–361.

Case, H. 1969. Neolithic explanations. Antiquity 43:176–186.

Caulfield, S. 1978. Neolithic fields: The Irish evidence. Pp.137–143, *In* H.C. Bowen, and P.J. Fowler (Eds.). Early Land Allotment in the British Isles: A Survey of Recent Work. British Archaeological Reports (British Series 48), Oxford, UK.

Caulfield, S. 1983. The Neolithic settlement of north Connaught. Pp.195–215, *In* T. Reeves-Smith and F. Hammond (Eds.). Landscape Archaeology in Ireland. British Archaeological Reports (British Series 116), Oxford, UK.

Caulfield, S., R.G. O'Donnell, and P.I. Mitchell. 1998. ^{14}C dating of a Neolithic field system at Céide Fields, County Mayo, Ireland. Radiocarbon 40(1–2):629–640.

Caulfield, S., G. Byrne, M. Downes, N. Dunne, G. Warren, S. Rathbone, D. McIlreavy, and P. Walsh. 2009. Archaeological excavations at Belderg Beg (E109). Unpublished Report. University College Dublin School of Archaeology, Dublin, UK.

Clark, J.S. 1988. Particle motion and the theory of charcoal analysis: Source area, transport, deposition, and sampling. Quaternary Research 30:67–80.

Cooney, G. 2003. Rooted or routed? Landscapes of Neolithic settlement in Ireland. Pp.47–55, *In* I. Armit, E. Murphy, E. Nelis, and D. Simpson (Eds.). Neolithic Settlement in Ireland and Western Britain. Oxbow Books, Oxford, UK.

Courty, M.A., P. Goldberg, and R. Macphail. 1989. Soils and Micromorphology in Archaeology. Cambridge University Press, Cambridge, UK.

Davidson, A., and P. Carter. 1998. Micromorphological evidence of past agricultural practices in cultivated soils: The impact of a traditional agricultural system on soils in Papa Stour, Shetland. Journal of Archaeological Science 25:827–838.

De Bertoldi, M., G. Vallini, and A. Pera. 1983. The biology of composting: A review. Waste Management and Research 1(2):157–176.

Dungait, J.A.J., R. Bol, M.J.I. Briones, and R.P. Evershed. 2008. Bulk tissue and fatty acid stable isotope investigation of the trophic exploitation of cow pats by epigeic and endogeic earthworms. Rapid Communications in Mass Spectrometry 22:1643–1652.

Dungait, J.A.J., L. Cardenas, M. Blackwell, L. Wu, A. Whitmore, P. Murray, D. Chadwick, R. Bol, A. Macdonald, and K. Goulding. 2012. Future-proofing macronutrient cycling in UK agricultural systems. Science of the Total Environment 434:29–50.

Elhmmali, M.M., D.J. Roberts, and R.P. Evershed. 1997. Bile acids as a new class of sewage pollution indicator. Environmental Science and Technology 31:3663–3668.

FitzPatrick, E.A. 1993. Soil Microscopy and Micromorphology. Wiley, Chichester, UK.

French, C. 2003. Geoarchaeology in Action: Studies in Soil Micromorphology and Landscape Evolution. Routledge. London, UK.

Gebhardt, A. 1992. Micromorphological analysis of soil structure modifications caused by different cultivation implements. Pp. 373–381, *In* P.C. Anderson (Ed.). Préhistoire de L'agriculture: Nouvelles Approches Expérimentales et Ethnographiques. Monographie du CRA no. 6, éd. CNRS. Paris, France.

Gibson, A. 2003. What do we mean by Neolithic settlement? Some approaches, 10 years on. Pp.136–145, *In* I. Armit, E. Murphy, E. Nelis, and D. Simpson (Eds.). Neolithic Settlement in Ireland and Western Britain. Oxbow Books, Oxford, UK.

Grime, G., and E. Guttmann-Bond. 2011. The use of PIXE for the identification of plaggen soils. X-Ray Spectrometry 40:210–214.

Guttmann, E.B. 2001. Continuity and change in arable land management in the Northern Isles: Evidence from anthropogenic soils. Ph.D. Dissertation. University of Stirling, Stirling, UK.

Guttmann, E.B.A. 2005. Midden cultivation in prehistoric Britain: Arable crops in gardens. World Archaeology 37(2):224–239.

Guttmann, E.B.A., S.J. Dockrill, and I.A. Simpson. 2004. Arable agriculture in prehistory: New evidence from soils in the Northern Isles. Proceedings of the Society of Antiquaries of Scotland 134:53–64.

Guttmann, E.B., I.A. Simpson, and D.A. Davidson. 2005. Manuring practices in antiquity: A review of the evidence. Pp. 68–76, *In* M. Brickley and D. Smith (Eds.). Fertile Ground: Papers in Honour of Susan Limbrey. Oxbow Books, Oxford, UK.

Guttmann, E.B., I.A. Simpson, D.A. Davidson, and S.J. Dockrill. 2006. The management of arable land in prehistory: Case studies from the Northern Isles of Scotland. Geoarchaeology 21(1):61–92.

Herity, M., and G. Eogan. 1977. Ireland in Prehistory. Routledge and Kegan Paul, London, UK.

Jongerius, A. 1983. The role of micromorphology in agricultural research. Pp 111–138, *In* P. Bullock, and C.P. Murphy (Eds.). Soil Micromorphology Vol. 1: Techniques and Applications. AB Academic Publishers, Berkhamsted, UK.

Leeming, R., A. Ball, N. Ashbolt, and P. Nichols.1996. Using faecal sterols from humans and animals to distinguish faecal pollution in receiving waters. Water Resources 30(12):2893–2900.

Lewis, H. 1998. The characterisation and interpretation of ancient tillage practices through soil micromorphology: A methodological study. Ph.D. Dissertation. University of Cambridge, Cambridge, UK.

Linderholm, J. 1997. Prehistoric land management and cultivation. A soil chemical study. Bulletin 1 of the Archaeological Soil Micromorphology Working Group, University College London, London, UK. Pp. 9–16.

Long, C.B, C.V. MacDermot, J.H. Morris, A.G. Sleeman, D. Tietzsch-Tyler, C.R. Aldwell, D. Daly, A.M. Flegg, P.M. McArdle, and W.P. Warren. 1992. Geology of North Mayo: A geological description to accompany the bedrock geology 1:100,000 map series; Sheet 6, North Mayo. Geological Survey of Ireland, Dublin, Ireland.

MacLeod, G. 2008. Thin section and micromorphology at the University of Stirling—Methods: Impregnation. Available online at http://www.thin.stir.ac.uk/2008/06/03/methods-impregnation/.

Macphail, R., J.C.C. Romans, and L. Robertson. 1987. The application of micromorphology to the understanding of Holocene soil development in the British Isles with special reference to early cultivation. Pp. 647–656, *In* N. Fedoroff, L.M. Bresson, and M.A. Courty (Eds.). Micromorphologie des sols. Association Française pour l'Étude du Sol (AFES), Paris, France.

Macphail, R.I., M.A. Courty, and A. Gebhardt 1990. Soil micromorphological evidence of early agriculture in northwest Europe. World Archaeology 22(1):53–69.

McGowan, G., and J. Prangnell. 2006. The significance of vivianite in archaeological settings. Geoarchaeology 21(1):93–111

Mikkelsen, J.H. 1997. Laboratory method for determination of organic, inorganic, and total phosphate. Bulletin 1 of the Archaeological Soil Micromorphology Working Group. University College London, London, UK. Pp. 5–8.

Molloy, K., and M. O'Connell. 1995. Palaeoecological investigations towards the reconstruction of environment and land-use changes during prehistory at Céide Fields, western Ireland. Probleme der Küstenforschung im südlichen Nordseegebiet 23:187–225.

Nielsen, B.O., V. Mahler, and P. Rasmussen. 2000. An arthropod assemblage and the ecological conditions in a byre at the Neolithic settlement at Weier, Switzerland. Journal of Archaeological Science, 27:209–218.

O'Connell, K., and M. Molloy. 2001. Farming and woodland dynamics in Ireland during the Neolithic. Biology and Environment: Proceedings of the Royal Irish Academy 101B(1–2):99–128.

Ottaway, J.H. 1984. Persistence of organic phosphates in buried soils. Nature 307:257–259.

Peters, C., M.J. Church, and C. Mitchell. 2001. Investigation of domestic fuel sources on Lewis using mineral magnetism. Archaeological Prospection 8:227–237.

Poincelot, R.P. 1972. The biochemistry and methodology of composting. Bulletin 727.The Connecticut Agricultural Experiment Station, New Haven, CT, USA.

Renou, F., and E.P. Farrell. 2005. Reclaiming peatlands for forestry: The Irish experience. Pp. 541–557, *In* J.A. Stanturf and P.A. Madsen (Eds.). Restoration of Boreal and Temperate Forests, CRC Press, Boca Raton, FL, USA.

Simpson, I.A., R. Bol, S.J. Dockrill, K.-J. Petzke, and R.P. Evershed. 1997. Compound-specific δ15N amino acid signals in palaeosols as indicators of early land use: A preliminary study. Archaeological Prospection 4(3):147–152.

Simpson, I.A., S.J. Dockrill, I.D. Bull, and R.P. Evershed. 1998. Early anthropogenic soil formation at Tofts Ness, Sanday, Orkney. Journal of Archaeological Science 25:729–746.

Simpson, I.A., R. Bol, I.D. Bull, E.P. Evershed, and K. Petzke, K. 1999a. Interpreting early land management through compound specific stable isotope analyses of archaeological soils. Rapid Communications in Mass Spectrometry 13(13):1315–1319.

Simpson, A.A., P.F. van Bergen, V. Perret, M. Elhmmali, D.J. Roberts, and R.P. Evershed. 1999b. Lipid biomarkers of manuring practice in relict anthropogenic soils. The Holocene 9:223–229.

Thomas, J. 1991. Rethinking the Neolithic. Cambridge University Press, Cambridge, UK.

Thomas, J. 1999. Understanding the Neolithic. Routledge, London, UK.

Verrill, L., and R. Tipping. 2010. Use and abandonment of a Neolithic field system at Belderrig, Co. Mayo, Ireland: Evidence for economic marginality. The Holocene 20(7):1011–1021.

Warren, G. 2004. Belderrig quartz scatter. Unpublished report, Department of Archaeology, University College Dublin, Republic of Ireland.

Whittle, A. 1996. When did Neolithic farmers settle down? British Archaeology 16:7.

Wild, A. 1993. Soils and the Environment: An Introduction. Cambridge University Press, Cambridge, UK.

Wilson, C. 2000. Processes of post-burial change in archaeologically buried soils. Unpublished Ph.D. Dissertation. University of Stirling, Stirling, UK.

Appendix 1. Field descriptions, showing area, test pit, and contexts (in brackets).

Area	TP	Top sod	Humified peat	Buried soil	Sub-soil	Till
Belderg Beg	A		-109	(108) humic silt. (112) sandy loam 10YR 3/2. Midden layers (130, 131, 132)		
Belderg Beg	B		(135) Black	-110		(134) 10YR 4/4 sandy silt
Belderg More	C	(100) 5YR 4/6	7.5YR 2.5/2	(101) 10YR5/4 soft clayey silt, v. frequent large stones, peat mottles		10YR5/4 large stones, poorly sorted
Belderg More	D	(102) 5YR5/6		(104) 10YR5/3 clayey silt with gleying		(105) 10YR5/4 frequent large stones, poorly sorted
Area E	E		(113) Black, humified	(115) 10YR2/2 brown peaty silt	(115) 10YR3/2 silt loam	10YR5/3
Belderg Beg	F			(136) 10YR2/2 sandy silt		10YR 4/6 compact, 50–60% large stones
Céide Fields	G		(124) Black humified peat	(121) 10YR2/2 organic clayey silt	(125) 10YR4/3 brown, compact, frequent large stones	
Céide Fields	H		(122) Black	(123) 10YR4/2 dark greyish brown soft clayey silt	(129) 10YR3/2 and 10YR4/3 very compact silty clay, 10–20% poorly sorted stones	Gley 1 4/10Y dark greenish grey
Céide Fields	I		(117) Black	(118) 10YR3/2 silty clay	(119) 10YR2/2 silty clay	(120) 10YR4/2 compact clayey silt
Céide Fields	J		(126) Black, moderately humified, freq rootlets	(127) 10YR3/2 very dark greyish brown organic rich clay-silt		(128) Mottled 10YR3/2 and 5Y4/2 olive grey. Gleyed, decayed sandstone.
Belderrig, (analyzed for UCD)	K		-133	(107) 10YR 4/3 soft clayey silt. 20–30% poorly sorted stones, 2–5% charcoal flecks		

Area	TP	Top sod	Humified peat	Buried soil	Sub-soil	Till
Céide Fields	1		(221) Black, humified	(222) 10YR2/2 very soft clayey silt	(223) 10YR3/1silty clay	Gleyed till
Céide Fields	3	(224) Black, fairly well humified	(225) Black, humified peat, clayey	(226)		Compact stony till
Céide Fields	4	(218) Black, fairly well humified	(219) Black, Well humified, clayey	(220) 10YR3/2 silty clay, frequent sandstone, occassional charcoal		
Rathlackan	5	Fibrous	(202) Black, well humified	(203) 10YR2/2 v dark brown clayey silt, frequent rootlets		Stony till
Rathlackan	6		(200) Black, well humified, frequent rootlets	(201) 10YR2/2 silty clay loam		
Rathlackan	7		(204) Black and orange	(205) 10YR2/1	(206) 10YR3/2	
Rathlackan	8		(208) Black, humified	(209) Dark brown humic clay	Yellow brown silty clay, sandy inclusions	
Rathlackan	9		(210) Black, humified, frequent roots and rootlets	(211)10YR2/2 to 10YR 4/4, clayey silty, mottled very dark brown, paler with depth.		
Rathlackan	10	Fibrous peat	(214) Black, fairly well humified, moderate rootlets	(215) 10YR2/2 clayey silt		10YR5/3
Rathlackan	11		(212) Black peat. Darker, denser band at base.	(213) 10YR2/2 dark brown, frequent sandstone		
Rathlackan	12		(216) Black	(217) 10YR2/2 dark brown clayey silt, occassional small stones		
Céide Fields	18	Reddish, fibrous peat	(242) Black, v humified	(243) 10YR2/2 silty clay, occassional small stones		Compact, with large stones

Area	TP	Top sod	Humified peat	Buried soil	Sub-soil	Till
Céide Fields	19		(227) Black	(228) 10YR 2/2 very dark brown, m paler mottles (10YR 3/2) occassional small stones		
Céide Fields	20	(244) Band of charcoal within peat	(245) 10YR2/1 Black, well humified, freq roots and rootlets	(246) 10YR2/1, occ stones, occ charcoal flecks. Near field wall at base of slope; possible lynchet?	(247) 10YR3/2, distinct from till below, paler than horizon above	Compact
Céide Fields	21		(248) 10YR2/1 Very dark brown humified peat	(249) 10YR very dark brown clayey silt, occassional charcoal, occassional stones	(250) 10YR3/3 dark brown silty clay, moderate stones, occassional charcoal	Very stony compact till
Area E	22	Dark brown	(229) Black, well humified, freq rootlets	(230) 10YR3/2 dark brown clayey soil, sandstone inclusions		Stony till
Area E	23		(231) Black, well humified, frequent rootlets	(232) 10YR3/2 clayey silt, very soft		10YR4/3 and 4/4 Sandy clay loam, ~30% stones up to 28 cm
Area E	24		(233) Black, humified	(234) 10YR3/2 silty clay, very soft, frequent rootlets		10YR4/3 frequent blackened rootlet holes
Area E	25		(235) Very dark black, humified, occassional rootlets	(236) 10YR3/3 light brown, clayey, occassional large sandstone fragments up to 15 cm		
Céide Fields	26		(251) 10YR 2/1 black, humified	(252) 10YR3/2 very dark brown, as thin as 1cm in places. Roots, rootlets		Stony—large stones

Area	TP	Top sod	Humified peat	Buried soil	Sub-soil	Till
Céide Fields	27		(237) Black, well humified. Overlies possible wall.	(238) 10YR2/2 organic clayey soil with occassional charcoal. Buried soil? Overlies stones of possible wall.	(239) One large stone directly over this layer; light yellow brown sandy silt, friable, 20–25% small stones. Buried soil? Part of wall construction?	
Céide Fields	28		(240) Banded horizons; disturbed?	(241) 10YR3/1 very organic horizon. Roots, no stones.	(253) 10YR4/2 silty clay, 10–20% small stones under 10 mm.	Stony till. Gley 4/10Y dark greenish grey.

Appendix 2. Micromorphology Ceide, Belderrig and Rathlackan, 2004 and 2005. Key: + Very Rare (<0.5%), ++ Rare (0.5-2%), +++Very Few (2-5%), · Few (5-15%), ·· Frequent (15-30%), ··· Common (30-50%), ···· Dominant/Very Dominant.

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
A Belderrig midden	17, 18	108	Soil	Complex. Spongy with channels filled by organics. Porphyric.	●●	●●	●●●	●●	●●	23 16 15 21 26	2–5% charred material up to 2mm. LOI average 20
A Belderrig midden	18	109	Peat	Complex. Spongy, with channels, chambers and cracks. Open porphyric.	+++	●	-	●●●●	-	-	Peat shrinkage has altered structure. Possible charcoal in peat. Very pronounced horizontal laminations. Channels contain decaying organic material and porous excremental fabric.
A Belderrig midden	17	112	Layer	Spongy, with channels. Very compressed granular fine fabric (dense and very dense excremental fabric). Porphyric.	●●●	●●	●●	●●	●	5	2–5% charred peat and charcoal. Very rare phytoliths. Porous, dense and very dense excremental fabric.
B Belderrig	56	110	Soil	Spongy structure with channels, chambers and vughs. Porphyric.	●●	●●	●●●	●	●●	22 17	Channels filled by decaying rootlets. Wholly excremental fabric, porous to dense. 2–5% charred peat and charcoal. Very rare diatoms, very rare phytoliths. Very rare spherulites.
C Belderrig	3	100	Redeposited peat	Crack structure; less than 2% channels and chambers.	++	+++	-	●●●●	●●●●	96	Less than 2% fine sand and silt. Rare phytoliths, v. rare pollen grains, rare fungal sclerotia, v. rare porous excremental pedofeatures.
C Belderrig	3	101	Soil	Channel structure with vughs. Porphyric.	●●	●●	●●●	+++	●●	32 27	
D Beldering	6	103	Redeposited peat	Channel and chamber with cracks. Open porphyric.	+	●●	-	●●●●	-	-	Multiple fabrics. Context is disturbed. Field observations suggest the disturbance was probably by peat cutting.

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
D Beldering	6	104	Soil	Spongy structure with channels. Open porphyric.	●●	●●	●●●	+++	●●	18 19	2–5% charred material.
E control	37	229	Peat	Channel, chamber and crack. Open porphyric.	++	●	●●●●	●●	–	–	5-10% charred peat. Excremental fabric. Yellow-brown B-fabric looks more like soil than peat. Organic material fills c. 95% of voids.
E control	37	230	Soil	Massive, with organic-filled channels and vughs. Close porphyric.	●●●●	++	●●●	●●●	-	-	0.5–2% charred peat. Rare phytoliths, including distinct dumbbell shaped. Very rare pollen. Rare porous excremental fill in voids. Dense and very dense excremental fine fabric.
E Control (TP23)	38	232	Soil	Massive, with organic material filling channels, which are mainly vertical. Close porphyric.	●	●	●●●●	●●	-	-	5–10% charred peat. Rare phytoliths. Rare very dense excremental fabric.
G Céide arable?	36	124	Peat	Channels and cracks. Open porphyric.	+++	●●	-	●●●●	-	-	Typical red, fibrous peat. Contains charred peat and charcoal.
G Céide arable?	36	121	Soil	Crack and channel structure, channels predominantly vertical and contain organics (rootlets). Open porphyric.	●	●●	●	●●●●	●●●	48	Very rare fungal sclerotia, very rare phytoliths and pollen. Rare charred woody material. Dense and very dense excremental fabric; very rare porous excremental fabric.
G Céide arable?	48	125	Till?	Complex; crack and channel but mainly massive structure with fairly well sorted silt, very fine sand and fine sand. Close porphyric.	●●●●	●●	●●	●●	●●	15	
H Céide	37	122	Peat/soil	Horizontal cracks and vertical channels. Open and close porphyric structure	●●	●●	+++	●●●●	●	39	Very mineral-rich for a peat deposit.

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
H Céide	37	123	Soil	Crack and channel structure; close porphyric.	●●●	●●	●	●●	●	11	Very rare diatoms. Dense excremental fabric.
H Céide	46	129	Sub-soil or till	Channel and chamber. Fine fabric shows angular blocky structure. Porphyric.	●●	●●	●●	●●	●	9	Channels filled by decaying rootlets. Rare dense and v. dense excremental fabric.
I Céide enclosure	49	117	Peat	Complex: channels, chambers and cracks. Porphyric.	●●	●●	-	●●●●	●	19	Decayed organics in some channels. 2–5% charred peat. Interface with soil below (118) is gradual; channels penetrate into 118. Cracks are horizontal and channels are vertical.
I Céide enclosure	49	118	Silty clay	Spongy, with channels. Close porphyric.	●●●●	●●	●●	●	●	7	Very rare charred peat, very rare charcoal. Very rare phytoliths, very rare pollen. Peat in channels comminuted by soil biota/ microbes. Fine fabric porous to very dense excremental, esp. near top of layer. Several microfabrics present.
I Céide enclosure	26	119	Silty clay	Channels, filled by iron-enriched rootlets with mainly vertical orientation. Close porphyric.	●●●	●●	●●●	●	●	11	Rare phytoliths, very rare pollen. Dense and very dense excremental. fabric. Occasional channels contain dense and very dense excremental fabric. Very rare porous excremental fabric.
I Céide enclosure	26	120	Till	Channel structure, predominantly vertical and filled by organic material (decayed roots). Open porphyric.	●●●	●●●	●●●●	●●	●	5	Dense excremental fabric and decaying peat in channels.
J Céide Pasture?	45	126	Peat	Structure includes channels, chambers and cracks.	++	●●	-	●●●●	●●●●	91	5–15% charred peat and charcoal. Organic-filled channels cut through thin horizontal laminated peat.

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
J Céide Pasture?	44, 45	127	Soil	Channel structure. Root channels contain decaying organic material. Porphyric.	●●●●	●●	●●	●	●●	27	Dense and very dense excremental fabric, including infilled worm channels which are filled by compact, darker and more humic fine fabric.
K Céide Pasture?	8	133	Peat	Channel, chamber and crack. Open porphyric.	+	●	-	●●●●	-	-	2–5% charcoal. Dense, fibrous dark red peat.
K Céide Pasture?	8	107	Soil	Channel structure, vertical orientation to channels. Very close porphyric.	●●●●	●●	●●	●	●	9	2–5% charcoal, up to 60µm. Fabric predominantly dense and vry dense exc. fabric. Very rare porous excremental fabric.
1 Céide	9	221	Peat	Complex: channel and crack, but also platy near surface.	+++	++	-	●●●●	-	-	Peat is coalescing and becoming comminuted into excremental fine fabric with a granular structure
1 Céide	9	222	Soil	Channels up to 2 mm wide. Close porphyric.	●●	●	●●●●	●	-	-	Rare charcoal, rare charred peat. Charcoal lens in peat above buried soil. Very rare phytoliths. Moderate birefringence; reticulate striations (clay domains). Very rare porous and rare dense exc. fabric. Pendant, crescent and typic hypocoatings of dusty clay (inner) and limpid clay (outer).
3 Céide	12	225	Peat	Channels and planar voids. Open porphyric- mineral grains rare.	++	●●●●	-	●●●●	-	-	Excremental fabric
4 Céide	10	219	Peat	Channels and cracks. Open porphyric.	+++	+++	●●●	●●●	-	-	Horizontal laminations made up of compressed organic material. Rare charcoal.

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
4 Céide	10	220	Soil	Channel and chamber. Close porphyric.	●●	●	●●●	●●	-	-	Very rare charcoal, probably wood. Very rare phytoliths. Areas of concentrated clay domains; possibly fragmented plough pan? Chambers filled by organics. Dense and very dense exc. fabric occurring very rarely in channels.
18 Céide	13	242	Peat	Complex: platy, with channels and cracks. Open porphyric, with rare mineral grains.	++	●	●●●	●●●●	-	-	5–10% charred material.
18 Céide	13	243	Soil	Channel structure; roots infilling channels. Porphyric.	●	●●	●●●●	●●	-	-	Horizon is sealed by a birefringent clay and silt horizon, which itself is sealed by an organic peat layer. 5–10% charred peat. Contains horizontal lenses of peat. Rare dense and very dense excremental fabric; very rare porous.
19 Céide	14	227	Peat	Channel structure. Open porphyric.	++	●	●●●●	●●	-	-	Large channels, charred peat. Fine fabric includes excremental fabric.
19 Céide	14	228	Soil	Close porphyric. Crack and channel structure. Two fabrics: a more organic-rich one appears in occasional channels and chambers, indicating worm activity.	●●	●●	●●●●	●●	-	-	2–5% charred peat. Decaying organic material in channels (roots). Very rare phytoliths and diatoms. Rare porous excremental fabric; very rare dense.
20 Céide	16	245	Peat	Platy structure, with channels, chambers and cracks.	+	●	●●●	●●●●	-	-	2–5% charred peat containing mineral grains. Organic material in horizontal cracks. Channels mostly vertical.
20 Céide	16	246	Soil	Very open porphyric. ~10% silt to very fine sand. Fabric looks like decayed peat (very red fabric) with channels, cracks and chambers.	++	+++	+++	●●●●	-	-	Very rare fungal sclerotia. Rare phytoliths; areas of surviving plant remains with sheets of intact phytoliths. Very rare diatoms. Common dense and very dense excremental fabric; very rare porous.

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
21 Céide	17	248	Peat	Complex: platy with channels and cracks; also acrumb structure.	+	●	●●●●	●●	-	-	2–5% charred peat. Organic material in horizontal cracks. Fine fabric made up of porous to dense excremental fabric, coalescing into flat, platy aggregates.
21 Céide	17, 18	249	Soil	Channel and chamber. Open porphyric. Mineral material predominantly silt and fine sand.	●	●	●●●●	●●	-	-	0.5–2% charred peat. Excremental fabric. Reticulate striations of clay domains. Very rare fungal sclerotia. Rare charcoal. Common dense and very dense excremental fabric; very rare porous.
21 Céide	18	250	Sub-soil	Cracks and organic-filled channels. Very close porphyric.	●●●●	●	●●	+++	-	-	Buried sub-soil
26 Céide	19	251	Peat	Cracks and root channels.	++	+++	●●●●	●	-	-	5–10% charred peat. Rare phytoliths. Very rare diatoms. Fine fabric all decayed peat?
26 Céide	19	252	Soil	Channel and chamber. Porphyric.	●●	++	●●●●	●●●●	-	-	5–10% charred peat. Rare phytoliths. Very rare diatoms. Fine fabric may derive from decayed peat. Peat above grades into this soil; B-fabric increases with depth. Organic-filled channels and chamber. Cracks and root channels. Very dense excremental fabric.
5 Rathlackan	2	202	Peat/soil	Channel and chamber. Porphyric.	●	●●	●	●●●	-	-	Identified as peat in the field, but has fragments of peat within fabric; 5–15% peat fragments up to 5 mm. Excremental fabric, porous to dense. 5–10% organic material with intact sheets of phytoliths.
5 Rathlackan	2	203	Soil	Channels and chambers. Porphyric.	●●●●	●	●●	●●	-	-	Channels and chambers filled by organic and decayed organic. Occasional dense and very dense excremental fabric; very rare porous in channels. Interpreted as subsoil.

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
6 Rathlackan	1	200	Peat/soil	Complex: channel and chamber, crack, and crumb. Open and close porphyric.	●	●●●	●●	●●●●	-	-	Peat is disturbed; peat fragments occur in a matrix of fine fabric and peat.Large (up to 1 cm, mostly under 5 mm), frequent peat fragments, similar to 202. Channels filled by decaying organics and porous excremental fabric. Fine fabric also includes very porous to dense excremental fabric. Very heterogeneous fabric.
6 Rathlackan	1	201	Soil	Open porphyric.	●●●●	●●●	●	●	-	-	Very rare charcoal, wood. Very rare phytoliths. Very rare porous and very porous excremental fabric in channels and chambers. Very rare dense excremental fabric.
7 Rathlackan	3	205	Soil	Channel and chamber. Open porphyric.	●	●●●	●●	●●	-	-	Some channels infilled by organic material. Rare porous to dense excremental fabric in channels with very decayed organics. Channels cut decayed peat fragments.
8 Rathlackan	4	208	Soil	Channel and chamber. Porphyric.	●	●●	●	●●●●	-	-	Very rare phytoliths and fungal sclerotia. Rare charcoal up to 1mm and rare charred peat. Very rare dense excremental fabric; very rare porous excremental in channels.
9 Rathlackan	5	211	Soil	Channel, slightly spongy. Close porphyric.	●●●	●●	●●	●●	-	-	2–5% charred material. Rare phytoliths and pollen. Very Rare fungal sclerotia. Very rare, very dense excremental fabric; low porositiy, deriving mainly from channels left where roots have decayed.
10 Rathlackan	7	214	Peat	Channels, chambers and planar voids.	+++	●●	+++	●●●●	-	-	Excremental fabric within channels. Interleaved fine fabric and organic material. Rare charred material, fungal sclerotia.
10 Rathlackan	7	215	Soil	Channel and chamber. Open porphyric	●	●●	●●	●●●	-	-	2–5% phytoliths, very well preserved. Very rare charcoal. Organic material in chambers. Excremental fabric, porous to dense. Rare calcitic spherulites?

Test pit (for location see Figs. 3, 4 and 5)	Sample	Context	Substrate	Microstructure and related distribution	% Mineral	% Porosity	% Fine fabric	% organic / peat	Loss on ignition	% loss on Ignition	Notes
11 Rathlackan	6	212	Peat	Channels and chambers. Very open porphyric.	+++	●	+++	●●●●	-	-	Excremental fabric in channels and chambers. Also decayed organic material in channels. Very rare charcoal. Horizontal compacted organic remains and planar voids.
11 Rathlackan	6	213	Soil	Channel and chamber. Open and close porphyric.	●●	●●	●	●●●	-	-	Organic material (rootlets) in channels. Very rare phytoliths. Very rare charcoal. Porous to dense excremental fabric.
12 Rathlackan	8	216	Redeposited peat	Complex: channel, chamber, crack and crumb. Open porphyric	+++	●●	●●	●●●	-	-	20–30% peat fragments up to 3 mm. Fine fabric almost completely porous to dense excremental fabric. Very mixed and heterogeneous. Organic material with intact sheets of phytoliths.
12 Rathlackan	8	217	Soil	Channel and chamber. Close porphyric.	●●	●●	●	●●	-	-	Organic material in channels. Very rare charcoal, 2–5% phytoliths, including within intact plant remains. Very rare diatoms. Rare dense and very dense excremental fabric.