Ancient manuring practices pollute arable soils at the St Kilda World Heritage Site, Scottish North Atlantic

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Received 18 August 2005; received in revised form 30 January 2006; accepted 30 January 2006

Abstract

The impact of ancient fertilization practices on the biogeochemistry of arable soils on the remote Scottish island of Hirta, St Kilda was investigated. The island was relatively unusual in that the inhabitants exploited seabird colonies for food, enabling high population densities to be sustained on a limited, and naturally poor, soil resource. A few other Scottish islands, the Faeroes and some Icelandic Islands, had similar cultural dependence on seabirds. Fertilization with human and animal waste streams (mainly peat ash and bird carcases) on Hirta over millennia has led to over-deepened, nutrient-rich soils (plaggen). This project set out to examine if this high rate of fertilization had adversely impacted the soil, and if so, to determine which waste streams were responsible. Arable soils were considerably elevated in Pb and Zn compared to non-arable soils. Using Pb isotope signatures and analysis of the waste streams, it was determined that this pollution came from peat and turf ash (Pb and Zn) and from bird carcases (Zn). This was also confirmed by 13C and 15N analysis of the profiles which showed that soil organic matter was highly enriched in marine-derived C and N compared to non-arable soils. The pollution of such a remote island may be typical of other ‘bird culture’ islands, and peat ash contamination of marginal arable soils at high latitudes may be widespread in terms of geographical area, but less intense at specific locations due to lower population densities than on Hirta.

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Keywords: As; Cu; Pb; Zn; Peat ash; Plaggen soils; Seabirds

1. Introduction

Isolated island communities of the North Atlantic Ocean contend with poor soil resources, low temperatures and high precipitation (Amorosi et al., 1998). Colonization of these islands depends upon alternative protein sources to substitute for unavailable or inadequate vegetables and grain production, or agricultural soils have to be improved with locally devised manures (Simpson, 1997; Davidson and Carter, 1998; Simpson et al., 1999). Fishing is an obvious food source, but seabirds can also be procured (Baldwin, 1974) as, for instance, in the Westmanns, Iceland, the Faroe Islands, and the Scottish islands of Mingulay, North Rona and Hirta (Fig. 1). Perhaps the most famed of these ‘bird culture’ islands is Hirta in the St Kilda archipelago (Harman, 1997), which has been occupied since at least the Iron Age and arguably much longer (Fleming...
A long record of ethnographic description, starting with Martin in 1698 (Martin, 1999; Fleming, 2005), has provided remarkably detailed accounts of island life, including soil management. St Kilda was famously evacuated in 1930 as the population fell below sustainable levels due to a legacy of emigration accelerating from the latter half of the 19th century (Harman, 1997).

The St Kilda archipelago is the remains of a collapsed volcanic rim, 160 km from the northwest Scottish mainland. The island group has been granted UNESCO World Heritage status. The largest island, Hirta, is the only one to have extended periods of occupation. It has the largest sea cliffs and is home to the largest seabird colony in the British Isles. Hirta has only one beach and this is often inaccessible due to heavy North Atlantic swells which keep the island isolated and provide a deterrence to fishing.

The total arable cultivated area of St Kilda was 15–30 ha and this supported a population of around 200

Fig. 1. Locations mentioned in the text: (A) the eastern north Atlantic; (B) the Outer Hebrides; (C) sample sites on Hirta.
people (0.15 ha per person) (Harman, 1997). In 1951 the average comparable figure for the available cultivated land in the Outer Hebrides as a whole was 0.64 ha per person (O’Dell and Walton, 1962). St Kilda was able to support a population density considerably above the regional norm because the principle livelihood of St Kildans was seabird hunting, taking large quantities of puffin (Fratercula arctica), fulmar (Fulmarus glacialis) and gannet (Morus bassanus) and their eggs. The eggs, flesh and oil (the latter from fulmar) were stored for winter food, while the excess, including feathers, provided rent for the landlord of the island (Harman, 1997).

The small area of arable land was well tended. Martin (1999) states “Their grain is only some bear [barley] and some oats: the barley is the largest produced in all the western isles...”. As the soils of northern Scotland are typically acidic and skeletal, plant husbandry was achieved through extensive manuring. Martin (1999) comments that “The chief ingredient in their composts is ashes of turf mixed with straw; with these they mix their urine... they join also the bones, wings, and entrails of their sea-fowls to the straw...”. The addition of large quantities of seabird waste to the composting stream meant that the manuring practice of the St Kildans differed from other coastal and island areas of Scotland. Elsewhere, seaweed was available and used as a manure (Noble, 1975), whereas the St Kildans had only limited access to this resource. Another major factor was the quantity of manure applied to the land. On St Kilda, around 200 people were contributing to the fertilization of only 15–30 ha. Over the millennia this has led to the formation of over-deepened soils (plaggen), with such augmentation reaching 1.5 m in depth (Hornung, 1974).

The research presented here was aimed at determining whether the intensive and unusual manuring of St Kilda led to elemental enrichment, and to ascertain if geochemical profiling of the soils could confirm or otherwise establish manuring sources. Stable isotopes (13C, 15N, Pb isotopes), 14C dating, soil micromorphology (combined with microprobe analysis) and elemental profiling of archaeological samples of house floors and of soil profiles are presented to show that the plaggen soils of Hirta became contaminated by intensive application of waste materials, namely peat ash and bird remains. Pollen analysis provides environmental and land-use contexts for the study. The comparative study of fertilized plots on the neighbouring island of South Uist, which did not have a seabird culture, was also investigated to determine if the addition of peat ash had an impact on arable soils.

2. Materials and methods

2.1. Soil and environmental samples

These were collected from Hirta during the period 2002–2004 (Fig. 1). For mineral soil profiles, overlapping Kubi-ena tins were used to sample from shovel pits. Additional samples, collected in the same manner, were also obtained from the neighbouring island of South Uist. For ombrotrophic peat on the plateau (altitude 320 m a.s.l.) between the hills of Conachair and Mullach Mór, a Russian corer (Jowsey, 1966) was used to obtain deposits. Soil pit samples were procured from areas of known archaeological significance, viz. the arable field systems of the settlement known as Village Bay, including samples in a datable context from beneath a consumption dyke (a wide wall made from rocks cleared from a field) constructed in AD 1830; pits from ‘lazy beds’ (cultivation ridges) around the enclosures of An Lag, where cultivation ceased before AD 1695 (according to Martin, 1999); and samples from lazy beds in a valley (Gleann Mór) on the North of the island where human occupation and cultivation also ceased before 1695. Bird bones taken from a dwelling floor sealed in the 1850s, were obtained during earlier archaeological excavations (Emery, 1996). For modern analogue purposes, environmental materials were collected on Hirta, including fresh seabird tissues from puffin and fulmar that had died naturally.

2.2. Analyses

All chemical samples were oven-dried at 80 °C for 24 h before processing. Pb, Pb isotope and Zn analyses were performed by an ICP-MS (Agilent 7500c) calibrated with appropriate standards. Certified Reference Materials (CRMs) were run with each analytical batch, with soil (National Research Centre for CRMs, GBW07406) and cattle bone meal (National Institute of Standards and Technology, 1486) used throughout. All soil samples were sieved (2 mm mesh) and, following dilution in distilled water, digested with concentrated nitric acid (Aristar grade) at 160 °C in a block digester. Spiked samples and blanks were used as part of the quality control. Whole bird femurs were digested using identical procedures. P levels were determined using flow injection colorimetric analysis after reaction with molybdenum blue. On ball-milled samples, 13C/12C ratios (δ13C) and 15N/14N ratios (δ15N) were obtained by continuous flow isotope ratio mass spectrometry using a Europa Scientific ANCA-NT 20-20 Stable Isotope Analyser with ANCA-NT Solid/Liquid Preparation Module (Europa Scientific Ltd., Crewe, UK). Sample size was adjusted to give ~100 µg N or ~300 µg C, using single isotope mode for all samples except animal tissue. δ13C values are expressed in parts per thousand (‰) relative to the V-PDB standard and δ15N values are expressed in ‰ relative to atmospheric dinitrogen. 14C AMS dates were obtained on samples with pre-treatment and analysis performed by Beta Analytic Inc. (Miami, Florida). Dendrochronological calibrations to calendar years were performed using the program CALIB v. 5.01 (Stuiver and Reimer, 2005). Age estimates are based on straight-line extrapolation between the mid-point of
age measurement ranges (2σ), using maximum probabilities and rounding to the nearest 10 years.

Soil thin sections were produced according to standard procedures (Murphy, 1986). Soil micromorphological analysis involved the quantification of features attributable to anthropogenic input and then determining the distribution of particular elements using a Cameca SX100 electron probe microanalyser (EDX). Thin sections were prepared from 5 pits in Village Bay, and representative slides are shown here (Fig. 6).

Pollen preparation followed standard HCl, NaOH, HF and acetylsalicylic treatment (Faegri and Iversen, 1989) with palynomorphs mounted unstained in silicone fluid of 12500 cSt viscosity. Counting sums varied between 300 and 450 total land pollen (TLP). Plant names and pollen type nomenclature follow Stace (1997) and the catalogue of Bennett (2005). Pollen statistics, diagram zonation and construction were performed using TILIA and TILIA GRAPH computer programs (Grimm, 1991).

2.3. Experimentation

In order to investigate further the potential role of peat burning and bird composting in concentrating metals, upland turfs, representing different geological substrata, and peat sampled to a depth of 10 cm, were ashed at 350 °C in a furnace for 24 h and then Pb and Zn determinations conducted on the ash.

3. Results and discussion

3.1. Pb pollution

In contrast to cultivation ridges at An Lag and Gleann Mór, the Conachair peat core and the peat and soil samples from non-cultivated areas of the island, the soils of Village Bay are heavily polluted with Pb and Zn compared to background soils on Hirta (Fig. 2). In all samples from Village Bay, Pb declines down-profile, including beneath the

![Fig. 2. Pb and Zn levels (open circles) and Pb 206/207 ratios (solid line) in soil and peat profiles. The Peat core was 14C-dated (uncalibrated dates shown on the right-hand Y axis).](image-url)
1830s consumption dyke. At least part of the Pb elevation in surface horizons is due to atmospheric deposition since the Industrial Revolution, from approximately AD 1800 in the British Isles (Farmer et al., 1996; Mackenzie et al., 1997; Bacon, 2002). This near-surface peak can be attributed to the rapid build-up of organic C in surface horizons since abandonment of the island in 1930 (Fig. 3), leading to Pb retention as indicated in the Conachair peat core (Fig. 2) and alteration of the Pb isotope signature from one that is atmospherically-derived to one that reflects the signature of mineral substrates. For An Lag (profile 12) in particular, the shift in isotopic signature follows total Pb in the soil. The site is relatively uncontaminated and shows a very high build-up of organic matter in surface profiles. The Pb content of the mineral subsoil of An Lag contrasts strongly with the records from the Conachair core and the organic lazy bed (pit 15) in Gleann Mór, with the organic subsoils having very low Pb contents. For the last two sites, Pb deposition has a distinctive modern pattern (i.e., last 200 year), which declines markedly in two steps. These phases are marked by shifts in Pb isotopes. 206/207 rises with depth in a pattern well known since the decline in use of Pb in petrol, with leaded petrol in the UK manufactured with Australian Pb being light in

![Graphs showing depth vs. Phosphorus (mg/kg), Delta PDB, C, and N](image-url)
the 206/207 ratio (Farmer et al., 1996; Mackenzie et al., 1997; Bacon, 2002). The pattern observed in the Conachair core is very similar to those from an ombrotrophic peat core from the neighbouring island of North Uist (Mackenzie et al., 1997) and from the more northerly island grouping of the Faroes (Shotyk et al., 2005). The second earlier decline is related to a further shift in isotopic ratio and could derive from the Roman exploitation of Spanish Pb mines (Rosman et al., 1997; Shotyk et al., 2005). There is a hiatus in the age-depth profile for the Conachair profile, evident also in the pollen record (Fig. 4), and this means that no long core evidence for chemical or environmental change exists for the period between approximately 3380 and 1740 cal BP. The hiatus is probably due to peat extraction prior to 1740 cal BP, and peat-winning at the site could extend back to the late Iron Age/early Historic period or even earlier.

It is far from straightforward to establish age-depth models for soil profiles, especially as historical records show that these have been highly cultivated and therefore lack precise stratigraphic integrity as a result of soil mixing. However, the stratigraphies show strong trends with respect to total Pb concentrations and Pb isotopes, particularly in pit 8 below the consumption dyke. A profiling of Pb isotopes in a peat core on the neighbouring island of North Uist shows a sharp decline in atmospheric Pb deposition by AD 1800, concurrent with expansion of the Industrial Revolution. Thus, the 10-fold decline in total Pb observed down the profile in pit 8, with an 1830 surface, cannot be attributed to atmospheric inputs from declining industrial sources. Also, the strong and steady shift in 206/207 ratio from 1.15 to 1.02 cannot be attributed to shifting atmospheric inputs, as the Conachair core signature does not drop below 1.10 over the last 1740 years, and stays above 1.15 for most of this period with only more recent inputs of industrially-derived Pb causing the drop. It would seem that land management caused the very strong shift in total Pb and in 206/207 ratios. Similar shifts are shown in pit 6. Pit 2 contrasts with pits 6 and 8. Although similar Pb shifts are observed in total Pb for pit 2, the isotope ratio remains relatively constant around 1.15. These differences between pit 2 and pits 6 and 8 may be related to different manuring practices—potentially pits 6 and 8 already had a deeper natural soil to which surface manures were applied, maintaining the stratigraphy of the unpolluted natural soil, with perhaps pit 2 manured to, or built artificially from the regolith upwards. Pits 6 and 8 are also located on different geologies, the former being located on mixed basic rocks and pit 8 on granite. Analysis of nitric acid extracts of rock fragments from natural soils from the island showed that mixed basic and granite rocks do differ in their isotope ratios, although the granite ratios average around 1.09 and the mixed basic around 1.14 (data not shown), opposite to what was found at the base of the three pits, i.e., the granite pit has a soil around 1.15 206/207 ratio (Fig. 2). The peat (95% organic) has an isotope ratio around 1.17. This is potentially responsible for the enriched isotope ratio in the soil profiles.

Bird bones are also another major waste stream. Pb isotope ratios of the three economically important species on the island (puffin, fulmar and gannet) are around 1.14 for the 206/207 ratio (Table 1), consistent with the polluted

![Fig. 4. Selected palynological data from the Conachair core. Pollen taxa are percentages of TLP. The 14C dates (uncalibrated) were used for dendrochronological correction to calendar years (see text for details).](image-url)
part of the soil profiles as well as with the Pb isotope signatures of North Atlantic waters (Veron et al., 1994, 1999) where the birds feed. However, total Pb in bones is below 2 mg/kg (Fig. 5), and is unlikely to account for the elevated levels found in the soils. Archaeological samples excavated from the floor of an AD 1850s house are about 10× higher in lead, with Zn concentrations also higher in archaeological bones. Washing of modern and archaeological bones in distilled water and oxalic acid show this additional contamination to be readily desorbed (data not shown) and to result from diagenic concentration of Zn and Pb from floor peat ash. Even the concentrations in the archaeological bird bones cannot explain the soil contamination. Microprobe analysis of a soil thin section taken from pit 8 clearly shows slight Pb elevation in bone shards compared to background soil, or at least diagenic concentration of Pb in the bone (Fig. 6). Zn levels shown by microprobe contrast very strongly with Pb, as Zn shows considerable elevation in bone shards compared to bulk soil (Fig. 6). The soil micromorphology and microprobe analysis confirm that bird bones are not a major source of Pb.

The historic records state that turf and peat were collected from the upland slopes of Hirta for use as fuel (Harman, 1997). The results of experiments on modern samples (Fig. 7) showed that the minimum Pb content of any ash was 120 mg/kg, the maximum 340 mg/kg. There is enough Pb present in ash to explain the contamination observed in the arable soil profiles of Village Bay (Fig. 5), and the Pb isotopic signature of the soils from which the ash is derived is also enriched in 206/207, explaining the elevation in this ratio in the soils at depths below those indicating Industrial Revolution atmospherically-deposited lead. Although none of the arable soil levels reach the very high ratios observed in blanket peat and basic turf, they do match the granite turf signature. In any case, the turf and peat ash signature would be diluted by native soil and other waste streams. So turf and peat ash look likely candidates for the Pb pollution.

3.2. Zn pollution

All profiles from within Village Bay show elevated Zn concentrations (by an order of magnitude) compared to

Table 1

<table>
<thead>
<tr>
<th>Bird</th>
<th>Zn (µg/g)</th>
<th>Pb (µg/g)</th>
<th>%N</th>
<th>%C</th>
<th>δN</th>
<th>δPDB</th>
<th>Pb 206/207</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puffin</td>
<td>193.138</td>
<td>0.661</td>
<td>5.490</td>
<td>19.120</td>
<td>14.650</td>
<td>−15.620</td>
<td>1.1732</td>
</tr>
<tr>
<td>Puffin</td>
<td>175.951</td>
<td>2.266</td>
<td>4.300</td>
<td>15.180</td>
<td>14.860</td>
<td>−14.790</td>
<td>1.1125</td>
</tr>
<tr>
<td>Fulmar</td>
<td>185.064</td>
<td>0.614</td>
<td>4.320</td>
<td>15.150</td>
<td>15.440</td>
<td>−14.800</td>
<td>1.1934</td>
</tr>
</tbody>
</table>

Fig. 5. The effect of ashing (at 350 °C in a muffle furnace for 24 h) on Pb and Zn concentrations in soil from Hirta. Diagonal hatch, peat; cross hatch, ultra basic; horizontal hatch, basic and no hatch, granite underlying geologies. The ratio graph is ash/soil concentration, the circle is the weight of soil/weight of ash. Samples were collected from non-arable areas on the island (N = 3, bars are ±standard error).

Fig. 6. Examples of elemental distributions from a thin section sample collected from 15 to 23 cm from the base of the consumption dyke (site 8). In the centre of each image is a bone fragment approximately 1.7 mm in length. Note that the elemental measures are on a relative scale. The bone fragment is obvious in the Ca map where it shows up red. (For interpretation of colour in this figure legend, the reader is referred to the web version of this article.)
profiles outwith Village Bay and in the Conachair core (Fig. 2). However, the Zn pollution contrasts strongly with Pb as there is relatively uniform down-profile Zn contamination in the Village Bay soils. There are at least two potential explanations for this. The first is that Zn is more mobile than Pb in soil (Alloway, 1993) and has therefore leached down-profile, homogenizing the Zn content. The second explanation is that Zn has additional sources of contamination to Pb, as the latter for Hirta has been shown to derive primarily from peat/turf ash. Unlike for Pb, bird bones have naturally high levels of Zn, at around 200 mg/kg dw for modern fulmar and puffin femurs collected from Hirta, increasing considerably upon burial in peat ash, ranging from 450 to 2000 mg/kg in excavated fulmar, gannet, guillemot, puffin and razorbill bones from the ash floor of the 1850s house (Fig. 7). As Zn levels are around 100 mg/kg in the soil profiles from Village Bay, fresh bird bones have a Zn content that could have contributed to this pollution. This is illustrated in Fig. 5, which shows high levels of Zn in bone shards from pit 8, the most contaminated pit with Zn levels reaching 600 mg/kg. As this pit has a datable surface of AD 1830, atmospheric deposition of Zn derived from Industrial Revolution sources cannot be responsible and lateral translocation of Zn from adjacent unburied soils is unlikely because Pb isotope signatures show no intrusion of Industrial Revolution Pb signatures into this pit. It is conceivable that pit 8 is sited on a midden or composting heap rich in bird bone and peat ash.

3.3. C, N and P

Most pit profiles were elevated in P, excluding pit 12 on An Lag (Fig. 3). Pit 15 in Gleann Mór showed elevation, especially towards the base of the pit, though the reasons for elevation in this profile and its distinctive shape (i.e., enhanced in the basal section) are not known. Highest P concentrations were observed in pit 8 from Village Bay and this is consistent with high levels of bone incorporation. Any human faeces and urine in this manuring stream would also have contributed to P elevation. P concentrations are fairly uniform down the profile of pit 8, consistent with the Zn, but not the Pb profile, suggesting that the P and Zn are of related biogenic origin.

Total C profiles show that pit 15 in Gleann Mór is highly organic and typical of natural soils of this area, especially on North-facing slopes. The rest of the soil pits analysed for C are minerogenic at depth, but are reverting to peat close to the surface and this is particularly obvious in pit 12. This suggests that the soils were managed in such a way during occupation, including at An Lag, so as to inhibit the build-up of organic matter. The cessation of turf-stripping may explain why An Lag’s soils have only recently returned to being highly organic. A number of commentators noted how the villagers stripped turf for fuel from close to the village (Harman, 1997). In cultivated soils, high levels of peat ash inputs and oxidation of C may explain the relatively low C content compared to natural soils in this area. It is notable that pit 8, the one sealed beneath the 1830s dyke, does not show this reversion to peat. Total N follows similar trends to C in Village Bay profiles, though reversion to peat is more marked, perhaps due to the recycling of N pools in surface horizons by plants, or greater down-profile mobility of N in ammonium and nitrate forms.

Both δ13C and δ15N showed similar patterns, with the δ15N being more discriminatory (Fig. 3). In arable pits from Village Bay, δ15N is, in the main, over 8%o, while An Lag and Gleann Mór pits have δ15N ratios of 8%o or below. There is a very noticeable trend in all pits, excluding pit 8 under the consumption dyke, with δ15N decreasing strongly, concurrent with the reversion of surface soils to peat. δ15N values of upland soils from ‘natural’ control areas show low ratios, with blanket peat having δ15N values of less than 4%o, and the soil turf from basic and granite geological substrates having less than 7.5%o. This contrasts strongly with puffin and fulmar bones which all had δ15N values above 11%o (Table 1).
Although there is a similar enhancement of $\delta^{13}$C in seabird tissue (Table 1) compared to background soils (Fig. 3), this is more weakly reflected in Village Bay soil profiles, with an enrichment of about 2%o (as opposed to around 8%o for $\delta^{15}$N). All soil profiles, excluding the truncated pit 8, revert to the terrestrial ratio at the surface of the profile, concurrent with reversion to peat.

### 3.4. Palynology

The palynomorph assemblages of the peat core from below Conachair (Fig. 1) are dominated by the pollen of Poaceae (grasses), Cyperaceae (sedges) and Potentilla-type (cf. tormentil) with Rumex acetosa (common sorrel) especially common before approximately 4610 cal BP and Calluna vulgaris (heather) after that date. These are typical constituents of sedge-heathland (Gwynne et al., 1974) and reflect the damp boggy environment with some drying of the peat surface after peat cutting ceased at the site from approximately 1740 cal BP. The negative relationship between R. acetosa and charcoal to pollen ratios throughout the core may be reflecting the presence of humans, with burning in both pre-historic (Neolithic and Bronze Age) and historical times (since 1740 BP). The burning may have been domestic in nature, or, given the later increased representation of Calluna pollen, there might also have been efforts to promote browse through heather burning (Edwards et al., 1995).

Apart from the strong suggestion of peat cutting, the profile further reveals glimpses of human activity from as early as 5110 cal BP when cereal-type pollen is first seen within the Neolithic, a period when stone implements may also have been produced (Fleming and Edmonds, 1999). Continued activity, especially evident after the hiatused section of the profile post-1740 cal BP, is characterised by enhanced values for Hordeum-type (cf. barley) pollen, for weeds such as Lactuceae (thistle/dandelion family), and Plantago lanceolata (ribwort plantain), and increased charcoal to pollen ratios.

The relatively high total values (frequently exceeding 52% TLP) for woodland and shrub taxa at this site for the period approximately 4950–3380 cal BP (the upper date is for the hiatused part of the profile) are assumed to derive from off-island locations (Walker, 1984; Brayshaw et al., 2000). These would be primarily from the Outer and Inner Hebrides (Edwards et al., 2000) and mainland Scotland (Edwards and Whittington, 1997)—areas that are known to have been at least partially wooded during the latter half of the Holocene. The woodland signal—especially for Betula (birch), Quercus (oak), Alnus glutinosa (alder) and Corylus avellana-type (cf. hazel)—is strongest when pollen concentrations are low. This is particularly noticeable in mid-profile, when values are below 50000 grains cm$^{-3}$ of wet sediment. Low concentration values may be related to low local pollen productivity at this exposed and high altitude site. An unknown factor, of course, is the proportion of non-tree pollen and microscopic charcoal that could also be of off-island origin. These palynomorphs, however, unlike woodland types, are well represented in the other sites from Hirta, providing confidence in the value of anthropogenic microfossil indicators.

### 3.5. Implications

To the best of our knowledge, the results presented in this study are thus far unique, showing the accumulation of high levels of Pb and Zn contamination in soils due to traditional manuring practices. Surveys of arable environments in similar marginal Scottish and Irish contexts have shown no particular enhancement in potentially toxic elements (Entwistle et al., 1998; Conry and MacNaeidhe, 1999), although Castlehouse et al. (2003) showed that As was elevated above background levels on peat soils manured with seaweed. Elevation of Pb and Zn is often observed around hearths of excavated buildings, but such hearth contamination is generally highly localised (Middleton and Price, 1996). Toxic metal-based pigments used in wall decoration and artefact manufacture (Wells et al., 2000) are another source of contamination in settlement contexts, but again the resulting elevation in pigment-derived contaminants is spatially restricted.

The fact that the contamination of the arable soils of Village Bay, Hirta is thus far unique, suggests that the nature and intensity of agricultural activity was distinctive. The high levels of Zn in seabird bones may have contributed to the pollution of the soils, but it is peat/turf ash that seems to be the primary source of contamination. The bird economy of the island, allowing a high human population density, was responsible ultimately for the greatly elevated levels of toxic metals in the soils. Waste products were carefully collected by Scottish island communities for use as manures, and the inhabitants of Hirta were not particularly unusual in using such fertilization practices. It is the scale and intensity of the activity that marks out Hirta. Once the peat ash hypothesis had been identified, further survey of another Outer Hebridean island, South Uist, which does not have access to large seabird colonies, was able to determine specific areas (the vegetable gardens—roughly $20 \times 20$ m in area) within the croft complex which showed the same contamination pattern as arable soils on Hirta (Fig. 8). The difference between South Uist and Hirta is that the peat ash of the former was so precious that it was set aside specifically for vegetable cultivation. On Hirta, peat ash production was so high, and available arable soil so limited, that the soils of Village Bay all received additions of ash. The use of stable isotopes ($^{13}$C, $^{15}$N, $^{206}$Pb, $^{207}$Pb, $^{208}$Pb) has shown that the plaggen soils of Village Bay are constructed of ash and seabird waste. This extensive enrichment in seabird tissues is also thus far unique, and sets apart the cultural land management practices on Hirta compared to other investigated islands.

In addition, the results show that the lazy beds in Gleann Mór are probably a relict feature of a limited period of agricultural activity as there is no obvious manuring.
shown is the representative of 14 garden plots sampled from South Uist. The data points represent the mean of these three sites ± standard error. The garden shown is the representative of 14 garden plots sampled from South Uist.

signature. Martin (1999) records that a past landlord forced the inhabitants of Hirta to increase the arable area by farming land in the North of the island. The villagers reported that this activity was unsuccessful and rapidly abandoned. The enclosures on An Lag have also been a mystery as to their function and use. Our findings show that the soils in An Lag were not improved beyond the construction of lazy beds. It is suggested that turf-stripping was practised here, as the surfaces of the soil profiles have only recently reverted to organic soil accumulation.

Did the build-up of Pb and Zn in the arable soils of Hirta matter? We have grown traditional crops (oats, rye, barley and cabbage) on this arable soil and there is no particular elevation in Pb and Zn in edible parts (data not shown). Plants grew much better compared to ones planted in unimproved soils from the west coast of Scotland. Historical evidence suggests that crop yields started to fail in Village Bay during the 19th century (Harman, 1997) whereas 17th and 18th century commentators said that crop production at Village Bay was the best seen in the west coast of Scotland— and this in spite of the climatic constraints associated with the Little Ice Age (Grove, 2001). The 19th century decline may have been due to a failure to rotate crops and to renew seed stock, as well as the enhancement of Pb and Zn in the soils.

These results must also be viewed in the wider context. St Kilda differs from most Scottish islands in the high amounts of bird carcases in the waste stream, and also in that it did not have substantial access to seaweed, widely used as a fertilizer by Scottish coastal communities (Castlehouse et al., 2003). These other communities also generated peat ash, and this was used as a fertilizer as well (Davidson and Carter, 1998). What differed with respect to peat ash application to the soil was that crofts reserved peat ash for vegetable production, but used seaweed to fertilize grain production and cattle grazing pasture (Castlehouse et al., 2003). Our findings suggest that considerably elevated metal concentrations should be found at many Scottish coastal crofts.

Acknowledgements

The Leverhulme Trust are thanked for funding this study. Robin Turner, Jill Harden and Susan Bain of the National Trust Scotland kindly supported this project and arranged transportation and sampling. Sally Foster of Historic Scotland is thanked for sampling permissions. Thin sections were investigated at the NERC National Facility for Electron Probe Microanalysis at the University of Manchester, and the assistance of David Plant is acknowledged. SCRI is supported by the Scottish Executive Environment and Rural Affairs Department. Alison Sandison is thanked for preparing the maps.

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