Historic landscape management: a validation of quantitative soil thin-section analyses

W. Paul Adderley, Ian A. Simpson, Donald A. Davidson

Journal of Archaeological Science 33 (2006) pages: 320-334

http://dx.doi.org/10.1016/j.jas.2005.07.016

Historic landscape management: a validation of quantitative soil thin-section analyses

W. Paul Adderley*, Ian A. Simpson, Donald A. Davidson

School of Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, UK

*Corresponding author. Tel.: C44 1786 467861; fax: C44 1786 467843. E-mail address: w.p.adderley@stirling.ac.uk (W.P. Adderley).

Abstract

The archaeological interpretation of past land management practices can be greatly enhanced through examination of soil thin sections. Features relating to manuring practice are among those key to interpreting agricultural practices. The sources and the processes leading to the distribution of these manure materials may further improve knowledge of the past landscape utilisation. The use of quantitative analyses to examine soil thin sections opens the possibility of considering these relationships between manured areas in greater detail and to extract more subtle spatial and temporal changes in past management. In this study the validation of this methodology has been tested with quantitative image analysis methods used to examine manure inputs to a well-documented historical landscape of Papa Stour, Shetland, where intensive manuring has been practised until the 1960s. By using both historic and ethnographic evidence to validate the image analysis protocol, differences in spatial and temporal distribution are examined for the practices of manuring with both fuel residues and with turf. The validation of the hypotheses expected from ethnographic and historical data that quantitative soils-based evidence allows the definition of variations in manuring strategies and provides a more secure basis from which to interpret manuring management strategies in archaeological landscapes.

Keywords: Shetland; North Atlantic; Manuring; Plaggen soil; Micromorphology; Image analysis; Landscape history; Ethnography

1. Introduction

The study of thin-section micromorphology, the microscopic investigation of undisturbed soils and sediments, is a distinctive and well-established approach for addressing a wide range of questions in archaeology and environmental history [7,10]. Kemp [24], in reviewing the role of micromorphology in palaeopedology studies, identifies a range of outstanding micromorphological issues that are equally applicable to archaeological or environmental history contexts. In particular, he highlights the problem of equifinality where different combinations of pedogenic processes and/or environments can result in similar micromorphological characteristics. From such studies, it is clear that there is a need to better understand the relationships between environmental processes and features as evident in soil thin sections. In essence ways need to be found in order to place micromorphological interpretation on a more secure basis through rigorous validation procedures. Laboratory and field-experimen-tation on ecofacts and artefacts seen in soil thin sections provides one approach for achieving this [5,33]. An alternative and complementary methodology is to analyse soil thin-section micromorphology from well-known contexts, the approach adopted in this study.

Central to validation must be quantification of micromorphological features in order to permit statistical analysis. Overall, in micromorphology as applied to archaeology, there has been limited quantification of features with systematic description being the most common approach; the consequence is that comparisons between thin sections are difficult. One approach to quantifying features in soil and sediment thin sections is through image analyses, permitting quantification and characterisation of objects of interest by image segmentation based on optical and/or morphological characteristics. Recently, imaging methods applied to thin-section micromorphology have undergone significant advance, with the parallel developments of multispectral thresholding and improved image acquisition. Imaging techniques have now been developed which allows the detection of large sets of discrete features within large, statistically representative, areas of the thin section, and provided there is suitable control over the optical properties of the thin section during production, inter-slide comparisons can be made [2]. The combination of these large-area analyses with multi-spectral thresholding has already allowed a quantitative analysis of features and fabrics associated with fuel residue materials in micro-stratigraphic waste-midden contexts [36] and these imaging methods now require validation in other archaeological contexts.

Identifying former land management practices in agrarian settlements remains a key archaeological question and an essential pre-requisite to discussions on past crop yields and the enhancement of yields, on variations in the relationships between arable and livestock husbandry and on the economic and social organisation of earlier rural landscapes [37,38]. In this paper we aim to assess the validity of soil thin-section image analyses techniques in quantifying micromorphological indicators of turf-based arable land manuring practices associated with relict anthropogenic raised soils on the island of Papa Stour, Shetland. Previous studies on this site by Davidson and Carter, using conventional microscopy, considered the extent to which spatial variations in manuring practice were reflected in micromorphological attributes [9]. This work revealed the potential benefits in developing and validating the application of image analysis techniques, the focus of this paper.

Papa Stour is an ideal location to study historical landscape management. The traditional agrarian system was abandoned on the island in the early 1960s in place of extensive sheep production. As a result there is little disturbance to the soil through tillage. In addition there are detailed historical accounts relating to agriculture on the island together with extensive ethnographic evidence on agrarian practices during the 1960s at the time of the demise of traditional agricultural practices [16,17]. Present-day ethnographic evidence is also available from long-resident occupants. This means that there is detailed information on how the land was managed in the different areas of Papa Stour, thereby creating an ideal situation for validating the use of micromorphological measures considered to be indicative of past land management practices. From such analyses a more secure basis can be developed using quantified soil thin-section image analyses from which to interpret land management strategies from cultural soils in archaeological landscapes.

2. Development of hypotheses from ethnographic and historical sources

2.1. Papa Stour

Papa Stour is a small (c. 2000 ha) island located off the western coast of Shetland (Fig. 1). The island is composed of acid igneous rocks of Devonian Age (rhyolite and tuff) with basalt and sandstone at its eastern edge [27,28]. There is a shallow, stony, glacial till over most of the island and in the east this is covered to a variable depth by wind blown sand. These two superficial deposits are the parent materials for the two Soil Associations mapped on the island [42]. Gleys, peaty gleys, peaty podsols and rankers of the Walls Association are formed on the till; calcareous regosols, brown calcareous soils and calcareous gleys of the Fraserburgh Association are formed on the sands. Present agricultural activity is limited to extensive sheep grazing, but until the 1960s, traditional agrarian activities were practised including tillage by either delling (delving) spade or plough and intensive turf-based manuring of selected field areas. The latter practice is considered by Davidson and Carter [9] to have been undertaken since the late Norse period. As a consequence of this management, in particular the manuring strategy, anthropogenic raised soils of up to c. 75 cm in thickness have formed in arable locations, similar in nature to the extensive plaggen soils of the north European plain [11,32,44]. Such soils are classified as plaggic anthrosols in the FAO/World Reference Base system [51] or plaggepts in the USDA system [43]. Three distinct farm areas on Papa Stour (Fig. 1), each with anthropogenic raised soils, were considered by this study; The Biggins (Grid reference HU 177603), a central farm associated with a toun complex of several small settlements and ongoing excavation of a Norse farm [8], Braga-setter (HU 173595), a smaller discrete peripheral farm, and Hamna Voe (HU 164602), an isolated, now abandoned, farm [40]. These farm study areas were also selected on the basis of the availability of ethnographic and historical data and because of their lack of disturbance following the abandonment of traditional farming practices. Traditional farming practices were abandoned across the island in the early 1960s [16].

2.2. Ethnographic and historical information of traditional land management

Farmers on Papa Stour at Bragasetter and The Big-gins detailed different land areas in the enclosed, infield, toun that were subject to different traditional land management, including differences in cropping practice, till-age, animal numbers and the type, source and timing of manure applications. Four distinct areas of land management are found within the infield area; these received different tillage and various inputs of manure materials. These areas are (i) the kailyarddan enclosed area adjacent to the farmstead in which field vegetables, mainly cabbage (kail) was grown, this was tilled by delling spade and regularly manured; (ii) the rig landdthe unen-closed arable area used to cultivate barley, oats and potatoes; (iii) the grazing landduncultivated areas used for hay production and grazing of animals, such as a tethered milk cow; and (iv) the plantiecrueda walled plant nursery, tilled by delling spade and used for raising Brassica seedlings (Fig. 1). Historic cartographic evidence including a commissioned 1846 survey [22] and post-division surveys by Ordnance Survey [30,31] together with place-name evidence from Peterson [34] (see also [1]) all confirm the positions of these land management areas.

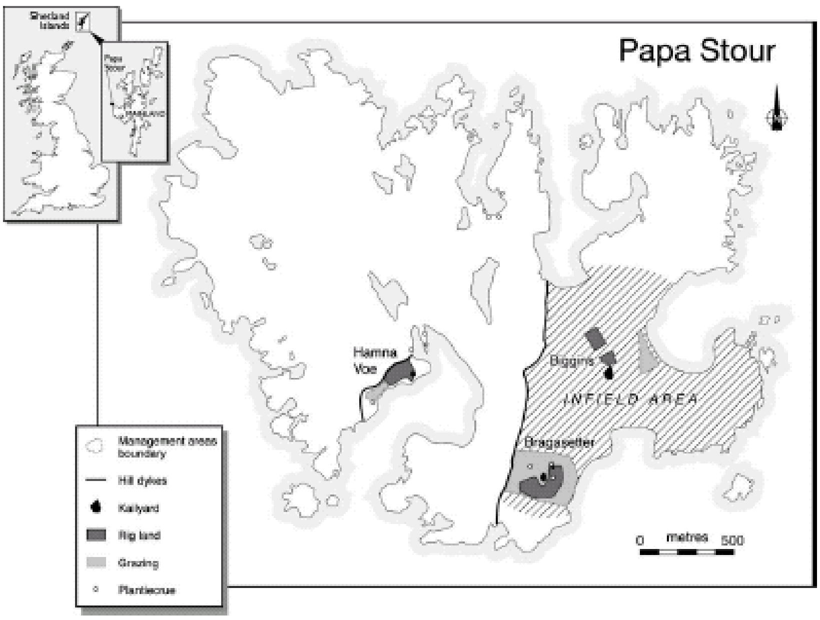

Fig. 1. Papa Stour, Shetland, showing location of farm study areas.

Traditional manuring practices are discussed in the Old Statistical Account [29] and other early records by Low [26], Skirving [39], Donaldson [13], Brand [3], Evershed [15] and Thomson [46], and complement the ethnographic evidence. The managed sources of manure on Papa Stour were turf materials collected from the hill-land beyond the enclosing head-dyke (the outfield), seaweed, and faecal material of stalled animals. In the Old Statistical Account [29], it is noted that seaweed is the best source of manure, possibly indicating exclusive use of seaweed, whereas later practices are recorded by Fenton with use of a mixture of seaweed, turf, ash and byre manures [16]. For Bragasetter farm, fifty kishies (baskets used to carry turves, seaweed and manure on the back) of turf were collected per year for animal bedding and one hundred were collected for fuel. Whilst turf and thatch would have also been used for roofing, this appears to have become less common from the late19th century with an increase in the availability of slate and tin-sheeting. The ash from the spent fuel was also used to soak up urine and faeces in the byre. Turves were selected on the basis of texture and organic content, with sand-rich turves being reserved for bedding. In the period post-1945 coal was an additional fuel used, with three (long imperial) tons (3048 kg) of coal consumed annually at Bragasetter. Coal ash residues were also used in the byre. From 1946 until 1960 the animals kept inside over winter (November to March) at Bragasetter comprised one milk cow, one ox, three cattle and fifteen sheep. Through this period, no pigs were kept at Bragasetter but may have been kept at the Big-gins. The manure from animals in the byre was mucked out weekly and allowed to stand over winter. To this material human latrine waste was also added.

Composting middens, or muck-roogs [16], were constructed for the kailyard and each rig land area receiving manure. These middens comprised of 10-12 wheel-barrow loads (=30 kishies) of byre manure forming one layer and 28 kishies of tang seaweed (Fucus nodosus) gathered from littoral seashore areas, to form a second layer. With this process repeated three to four times, the midden was left to stand for two to three weeks. The kailyard was manured annually in March, whilst rig land manuring was biennial. Depending on its availability after winter storms, sub-littoral ware seaweed (Fucus digitatus) was collected from specific shoreline areas, and was irregularly applied directly to rig land; interviews with the farmers suggest that there may have been a greater quantity of ware used at The Biggins in comparison with Bragasetter. Grazing land received manure from tethered livestock. Fenton's 1960s ethnographic studies [16e18] confirm these pat-terns, but differ in respect of the manure type used in one type of land management area, the plantiecrue. Fenton [16] suggesting that only ashes were used and applied in March; farmer interview suggests that one kishie of tang was used on each plantiecrue and applied in late July or early August. Semi-quantitative calculations of the rate of manure application to Bragasetter farm take account of volumetric data on kishie sizes (c. 90 dm^{-3}) held in the Shetland Museum, Lerwick [1]. Extending this analysis across Papa Stour, volumes are expressed on a management area basis derived from the historic cartographic evidence (Table 1).

Discussion of the timing and intensity of land management practices for each of the four land management areas within the infield arose during the farmer interviews. Historical evidence for the type and nature of tillage practices employed is sparse. However archaeological finds suggest that both early ploughs and spades were used. However, a dominance of spade cultivation in Shetland emerged in the late 18th century and was noted by Kemp [23] in 1801. The Old Statistical Account [29] (1799) records a total of just three ploughs in the parish of Walls and Sandness, an area including Papa Stour. The increasing use of spade cultivation in Shetland during the 18th and early 19th centuries is considered a result of recurrent subdividing of land holdings creating smaller parcels of the rig land areas due to population growth. This period was followed by the reintroduction of ploughing to rig land areas in the late 19th century [16]. Observations made by Fenton in 1967 on spadework, suggest that there is an overall downhill movement of soil with each cultivation, and that the soil is tilled, or delled, to a maximum depth of 10-12 cm. If tilled by plough the use of a hand drawn set of harrows to break up the turned sod was commonly employed on rig land [16]. Of the four land management areas, it is clear that the kailyard areas and planticrues will have received the most frequent cultivation, whilst the rig land and kailyard areas will have received the most intense cultivation (Table 1). The effect of the frequency and of the intensity of tillage practices is therefore confounded across the kailyard, rigland and planticrue areas with the grazing area not tilled. Past studies on the effect of tillage on hortisol soils suggests that the effect of tillage is expected to be seen in the size and shape of the organic components of the added manure materials [6,12]. A diminution in the size of material fragments and more rounded shapes are expected with tillage.

2.3. Hypotheses - relationships between turf-manuring, cultivation practices and soil micromorphology features

Using these detailed historical and ethnographic data, hypothetical relationships between turf-manuring and cultivation practices and soil micromorphology features in raised soils can be constructed. Four hypotheses consider the relative amount of manuring materials. It is expected that:

Table 1
Distribution of traditional land management areas on farms studied on Papa Stour, Shetland and summary details of manuring and tillage practices for each land management area

Land area	Farming practice	Bragasetter arm (% farm area)	The Biggins (% farm area)	Hamna Voe (% farm area)	Tillage	Manure type	Frequency of manuring	Quantity of manure per application ($kg\ m^{-2}$)
Rig land	Cropping of barley and oats *Hordeum sativum*; *Avena strigosa*; *Avena sativa*	9	45	28	Plough and hand drawn harrow. (Spade in late 18th and early 19th century)	Compost from midden heaps	Biennial	~4.14
Kailyard	Brassica crops	4	10	4	Delling spade (and harrow?)	Compost from midden heaps	Annual	>4.14
Plantiecrue	Brassica plant nursery	~1	~1	~1	Delling spade	Tang seaweed (*Fucus nodosus*)	Annual	~5.75
Grazing	Managed grazing (i.e. tethered)	86	44	67	None	Grazing animal dung	N/A	Random

N/A, not available.

- Kailyard, rig land and plantiecrue soils will contain micromorphological features indicative of: fuel residue manuring (carbonised plant and rubified mineral); and turf-manures (non-carbonised plant materials);
- Grazing management area soils will not contain micromorphological features indicative of turf-manuring;
- Micromorphological features indicative of turf-manuring will vary in amount across management areas with kailyard Orig land Oplantiecrue;
- Micromorphological features of both fuel residue and turf-manuring, within management areas, will vary in amount across the three farm locations with central (The Biggins) Operipheral (Bragasetter) Oisolated (Hamna Voe).

A further two hypotheses consider the individual shape and size of each object of these materials. It is expected that:

- Individual micromorphological objects will vary in shape and size, with more rounded shapes and smaller size objects reflecting the confounded effects of the frequency and intensity of cultivation disturbance in different farm locations with central (the Biggins) ≥ peripheral (Bragasetter) > isolated (Hamna Voe);
- Individual micromorphological objects in soils will vary in shape and size, reflecting cultivation disturbance across different management areas with kailyard = plantiecrue = rig land > grazing land.

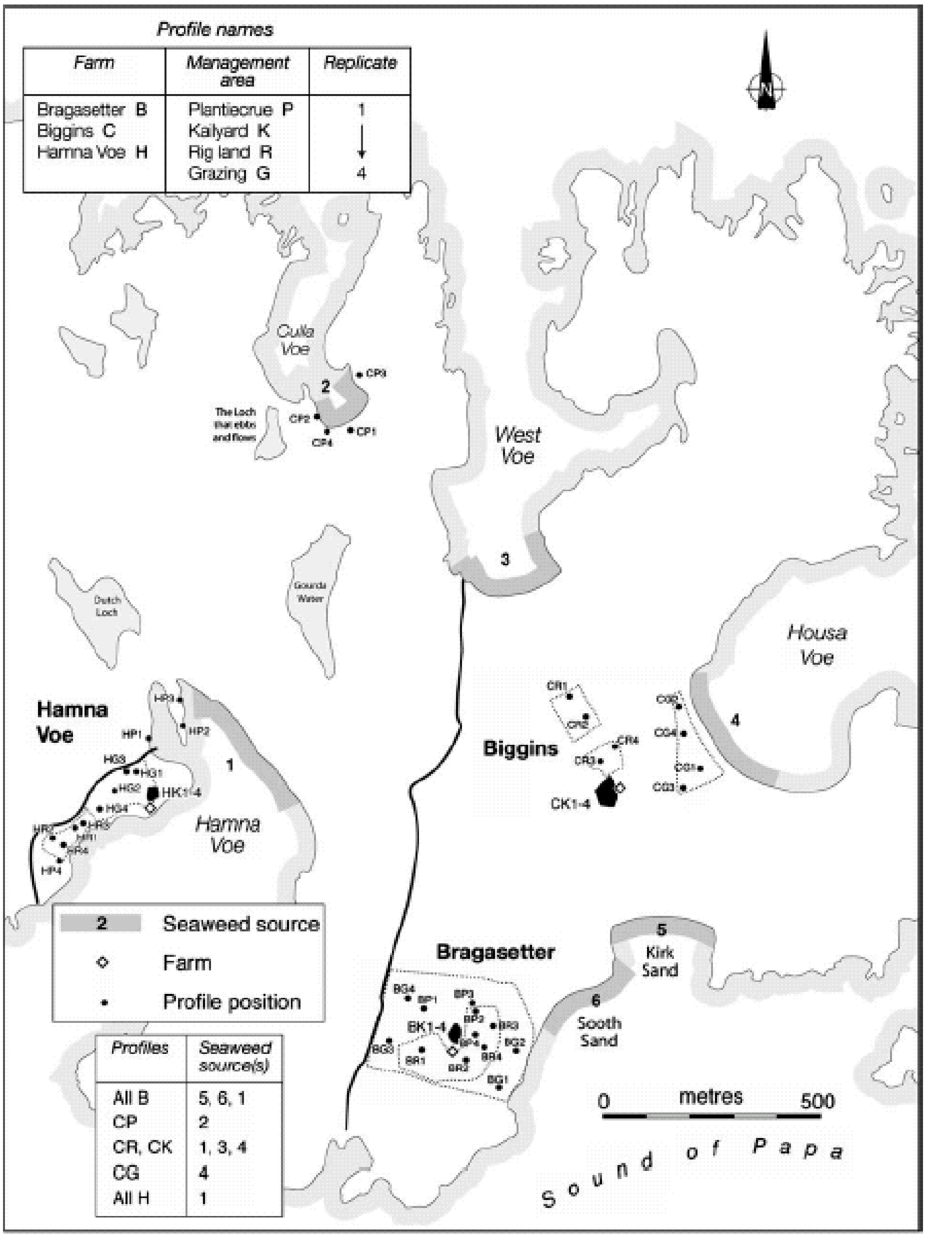

Fig. 2. Map of profile locations on Papa Stour, with sources for seaweed collection identified relative to each land management area within each farm study area.

3. Methods and materials

3.1. Sampling

Sampling focussed on the three farm site study locations of Bragasetter, The Biggins and Hamna Voe. The boundaries of the four management areas were defined by the ethnographic and historical data (Fig. 1). For each farm site four profiles were dug within each of the four management areas (kailyard, rig land, plantiecrue, grazing land; Fig. 2). In the case of The Biggins, the farm's plantiecrues are located at Culla Voe. For each farm site/management area combination, profile locations were randomly allocated to ensure valid unbiased statistical comparisons between sites, management areas and profiles. The profiles were described following the terminology of Hodgson [19]. Soil sampling was undertaken at fixed depth intervals (15 cm) in each of the 48 profiles and the total depth of each profile recorded.

3.2. Production and description of soil thin sections

Soil thin sections were produced after drying through acetone replacement and impregnation with polyester resin with standardised University of Stirling procedures used throughout (http://www.thin.stir.ac.uk). Uniform 30 μm slide-thickness was monitored through optical and micrometer measurements [2]. Sections were described following the accepted International System terminology [4,45] with the coarse/fine limit taken at 10 μm.

3.3. Quantitative image-analysis of thin sections

In order to identify small objects occurring with an infrequent periodicity, the analysis procedure was of a high-resolution over a large image area. Large-scale image acquisition and colour-based image thresholding [2,35] were used to segment and quantitatively analyse the thin sections using proprietary software [41]. A 16 X 16 mm slide area was analysed since this is considered statistically a representative elementary area for the carbonised materials using criteria defined by VandenBygaart and Protz [47] of ≤10% variation in total area measurement of features between three successive equal-area images from a single thin-section slide.

The image analysis of the thin sections was linked to conventional micromorphology procedures in order to segment and quantitatively characterise discrete classes of objects rather than produce a mathematical or spectral description of the whole image. Segmentation used both multi-spectral thresholds and shape parameter thresholds and followed the procedures of Adderley et al. [2] latterly used by Simpson et al. [36] on experimental materials. Four classes of objects were selected to reflect manuring practices: rubified mineral material, carbonised organic material and uncarbonised organic material subdivided according to size and mineral inclusions. The colour, shape and minimum-size criteria used to segment these objects in the captured images are detailed in Table 2.

The size and shape characteristics of each feature object were recorded for each thin-section image. Size was considered by measuring the area (μm^2) and perimeter (mm) of each object. Shape of each object was considered by Feret measurement - distance between parallel tangents to outside of the object, 360 positions at 1° intervals around the centre of each object [14] (Duda and Hart, 1973) - and by the ‘‘compactness’’ factor, defined as Compactness =4Π·Area/(Perimeter^{2}) [20,49]. The Feret measurements give an indication of both the absolute size and the shape of the objects, whereas the compactness measure considers how close to a circle the shape of the object seen in thin section is. A circle has a compactness factor of 1, and every other shape has a compactness factor less than 1 with the more convoluted the shape, the smaller the compactness factor.

Table 2
Image analysis threshold criteria for segmentation of micromorphological features

Feature	Colour and illumination characteristics (HLS colour space; see Adderley et al., [2])	Minimum size (μm^2)
Carbonised organic material	Oblique incident illumination Hue (0–360): 355–0 Lightness (0–255): 35–60 Saturation (0–255): 30–90	25
Rubified mineral material	Oblique incident illumination Hue: 355–40 Lightness: 200–255 Saturation: 155–255	25
Uncarbonised organic material	Oblique incident illumination Hue: 350–10 Lightness: 15–100 Saturation: 80–160	25
Uncarbonised organic material, with coarse micro mineral material	Oblique incident illumination	Uncarbonised organic material: 40
	Hue: 350–10	Mineral inclusion: 20
	Lightness: 15–100 Saturation: 80–160	
	Mineral inclusions: Circular polarised illumination Hue: 95–325 Lightness: 240–255 Saturation: 10–100	

3.4. Data treatment

The image analysis data were comprehensive for all the thin-section images and from all the profiles examined on Papa Stour (Fig. 2). To allow comparison between contexts these data have been statistically summarised and examined using S-Plus software [21,48]. The measurements made for each variable for each sample were analysed using a residual maximum likelihood (REML) model analysis of variance technique with model design statements made after reference to Winer et al. [50] and Littell et al. [25]. This technique calculates predictions, or linear combinations of both fixed and random effects, such as the defined land management areas and replicate profiles respectively, in a mixed statistical model. This overcomes the limitations of standard methods of univariate analysis of variance (ANOVA). The REML analysis for each image analysis measurement variable allows consideration of the nested interactions between (i) the farm sites on Papa Stour, (ii) land management areas within each of these farm sites, and (iii) depth within profile.

Since many of the soils examined have developed through repeated cultural amendment by manure application, the constancy of such practice can be considered by examining differences between the fixed-depth samples taken from each profile. To consider this time-depth relationship in each profile more fully, another complete set of REML model analyses were examined considering the interactions of the farm site, land management area and profile factors as above but with an auto-correlation structure applied to the fixed-depth samples. This allows consideration of whether the measurement made on the 15-23 cm depth sample predicts the measurement on the 30-38 cm depth sample, then if the 30-38 cm sample measurement predicts the 45-53 cm sample measurement, et seq. In addition to the results of the image analyses, two other measurements were also considered. First the distance of the profile from the farm location; second, the distance of the profile from the seaweed source. Fig. 2 shows profile locations, farm locations and shoreline positions for each. These two variables were summarised independent of other data and also used as individual co-variates in two further sets of REML analyses. One covariate used was the distance of the profile from the seaweed source, and the other was the ratio of the distance of the profile from the farm location: the distance of the profile from the seaweed source.

4. Results and discussion

4.1. Field characterisation

The nature of the manured soils seen in exposed profiles for each of the four management areas was consistent across the farm study areas allowing a typical profile from each to be described (Table 3). The main differences, in particular for the intensely manured soils of the kailyard and rig land areas, relate to the depth of the resulting soil profile and variation in these depths between farm study areas is also summarised. Differences in depths of the rig land and kailyard soils significantly correlate ($P < 0.05$) with the frequency of manuring of activities, derived from the ethnographic evidence, and to the period of manuring activities, derived from the historical evidence. From the field evidence alone, it is not possible to determine between the different ethnographic accounts, ash vs. seaweed, in manuring strategy for the plantiecrues.

Table 3
Typical profile descriptions (SSEW notation; Hodgson, 1976) for land management areas on Papa Stour, Shetland; including variation in profile depth measurements

	Kailyard (The Biggins; profile CK1)	Rigland (The Biggins; profile CR1)	Plantiecrue (The Biggins; profile CP2)	Grazing (Bragasetter; profile BG1)
	0–3 cm; Lf; 3–43 cm; Ap1; 10 YR 3/1 very dark grey; sandy loam; weakly developed small subangular blocky; few small subangular stones; gradual wavy boundary;	0–2 cm; Lf; 2–57 cm; Ap; 5 YR 3/1 very dark grey; sandy loam; moderately developed medium subangular blocky; common small subangular stones; gradual wavy boundary;	0–4 cm; Lf; 4–24 cm; Ap; 5 YR 3/1 very dark grey—5 YR 2.5/1 black; sandy silt loam (organic); weak coarse granular; common small angular stones; wavy clear boundary;	0–2 cm; Lf; 2–29 cm; Ah; 7.5 YR 3/2—4/3 brown/dark brown; sand; very weak granular; few small rounded stones in lower part of horizon; gradual wavy boundary;
	43–78 cm; Ap2; 7.5 YR 3/2 dark brown; sandy loam; very weakly developed small subangular blocky; common medium angular stones; sharp wavy boundary; 78–86 cm; AC; 5 YR 3/2 dark reddish brown; sandy loam; massive; many small subangular stones	57–72 cm; B; 5 YR 3/3 dark reddish brown; sand; massive breaking to single grain; common; common medium rounded stones; till at base	24–30 cm; BC; 5 YR 3/3 dark reddish brown—5 YR 4/6 yellowish red; sandy; massive; very large subrounded stones at base	29–42 cm; Bx; 10 YR 4/3 brown; sandy loam; massive breaking to single grain; common medium/large angular stones; till at base
Depths of profiles ($n = 12$)				
Mean	63.3 cm	56.2 cm	28.0 cm	38.2 cm
Maximum	115.0 cm	85.0 cm	35.0 cm	63.0 cm
Minimum	27.0 cm	29.0 cm	24.0 cm	25.0 cm
SD	25.1 cm	19.2 cm	3.8 cm	13.8 cm

4.2. Micromorphology and features associated with turf-manuring practice

In thin section these soils have typical occurrences of frequent (15-30%) to dominant (50-70%) quartz together with few (5-15%) to frequent rhyolite coarse mineral material, with the rhyolites typically containing glassy phenocrysts. The very few (<5%) coarse mineral materials include feldspar, biotite, garnet and heated (rubified) minerals. With the exceptions of the grazing land areas and much of the Hamnavoe farm area, occurrences of very few bone fragments are also seen throughout these soils. Coarse mineral material is randomly arranged and poorly sorted except on sandier soils where it is well sorted. Fine material is typically brown to dark brown organo-mineral with stipple-speckled fabrics. Coarse organic material typically includes very few fungal spores, lignified tissue and parenchymatic

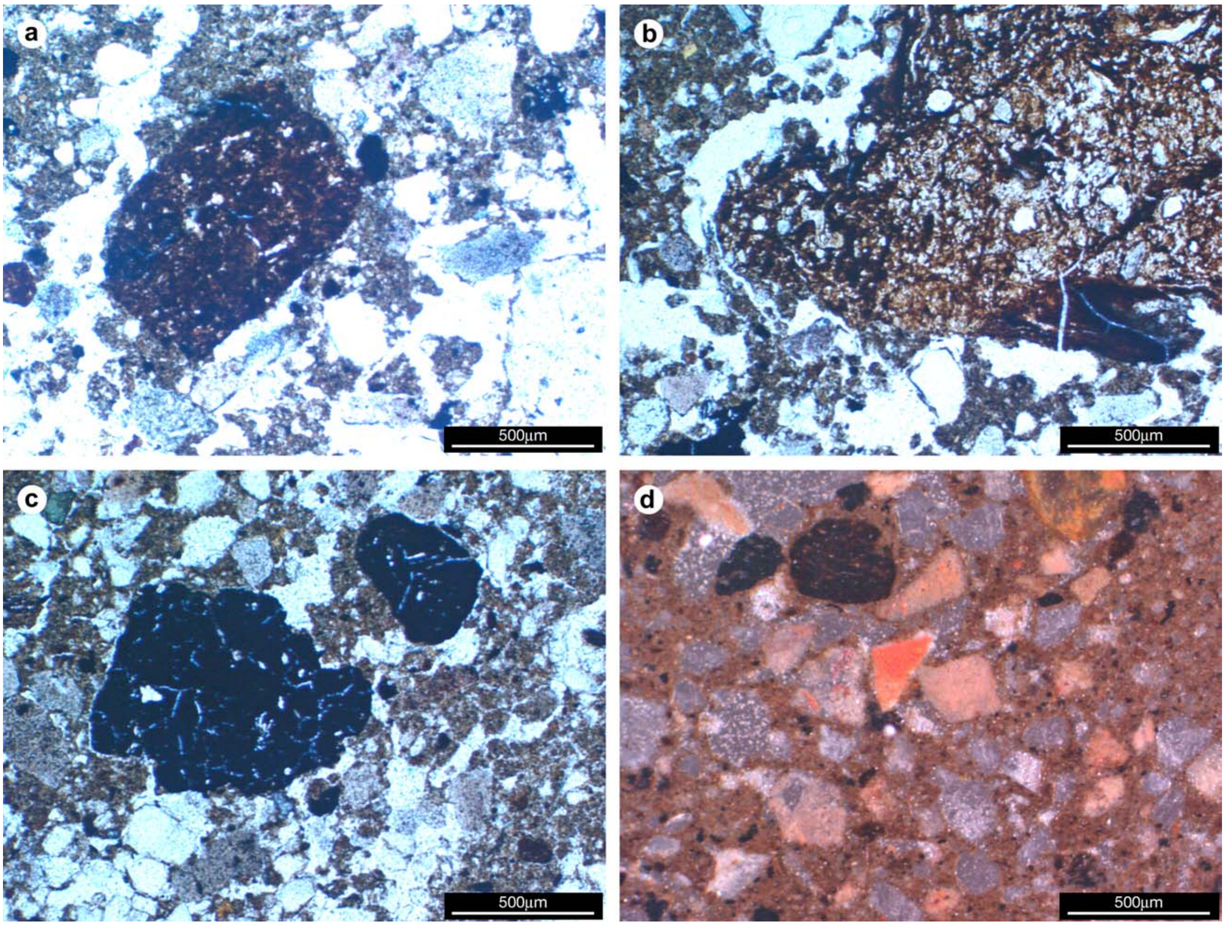

Fig. 3. Micromorphological features of turf-manuring observed in thin section, Papa Stour, Shetland. (a) Uncarbonised turf feature (plane polarised light); (b) uncarbonised organic material, with coarse micro mineral material (plane polarised light); (c) carbonised turf feature (plane polarised light); (d) rubified mineral material (oblique incident light). All samples are from The Biggins, kailyard profile 1, sample 30-38 cm.

tissue of variable frequency. Amorphous organic material includes very few to frequent brown and reddish brown colours together with black carbonised materials. Related distributions between coarse and fine materials are typically porphyric, except in sandier areas where enaulic related distributions can also occur. Very infrequently occurring and rare (0.5-2%) textural pedofeatures are evident in a number of the thin sections and include silty clay infills and clay coatings, while similarly rare calciumeironephosphate features are also evident in a small number of the thin sections. Very few iron based crypto-crystalline infills and coatings together with associated iron depletion pedofeatures are found infrequently in these thin sections, and rare spheroidal and rare to many mammillate excremental pedofeatures occur throughout these thin sections and are associated with predominantly channel and chamber, granular and intergrain micro-aggregate microstructures.

Within these thin sections and evident in varying frequencies, amorphous brown and reddish brown uncarbonised organic material fragments, with and without mineral inclusions (Fig. 3a,b), black carbonised organic material fragments (Fig. 3c) and rubified heated mineral features (Fig. 3d) occur; typical attributes of these features are summarised in Table 4. Amorphous brown organic material fragments reflect materials collected from the hill-land for animal bedding and subsequently composted and applied to the arable area. Coarse mineral inclusions or their absence within this material may reflect origins as mineral-based turf material or peaty turves respectively. Black carbonised organic material fragments and rubified heated mineral features reflect the fuel residues of combusted turf material, also collected from the hill-land. These three features are consistent with the interpretation of their association with the turf-manuring land management practices outlined above (Section 2.3), and therefore can be used to validate quantified soil thin-section image analyses techniques in relation to ethnographic and historical sources of turf-based manuring practices.

Table 4
Micromorphology description of turf-manuring features observed in thin section, Papa Stour, Shetland

Carbonised organic material	Amorphous; 350–1000 μm in diameter (coarse meso to fine macro); black in plane polarised light and under cross polars; very few to frequent; smooth and subrounded; low variability
Rubified mineral material	Coarse mineral; 100–250 μm in diameter (fine meso to mediuim meso); red in oblique incident light and black in plane polarised light; very few to few; smooth angular; low variability
Uncarbonised organic material	Amorphous; 350–1000 μm in diameter (coarse meso to fine macro); brown and reddish brown in plane polarised light and black under cross polars; very few to frequent; smooth and subrounded; low variability
Uncarbonised organic material, with coarse micro mineral material	Amorphous; 500–1500 μm in diameter (fine macro to medium macro); brown and reddish brown in plane polarised light and black under cross polars; very few to frequent; smooth and subrounded; medium variability with varying occurrence of quartz and rhyolite coarse micro mineral material

4.3. Image analysis quantification of manuring features

Following the segmentation of the image, the results of measuring the size and shape of each object in the thin-section image in the four classes of manuring feature (carbonised organic material, rubified mineral material, uncarbonised material with mineral inclusions, uncarbonised material without mineral inclusions) are recorded. For each of these four classes, the number of features examined varied from ~200 to ~17000 image^{-1}, with a total of in excess of 6.4 million measurements over all the images examined. To summarise the size data results, the total area of the image covered by each class of features was calculated and likewise the total perimeter of all the features in each image. These total per image data are summarised by calculating a mean and standard deviation for all images analysed for each farm study area/land management area combination (Table 5). The shape characteristics of each feature object are summarised by first calculating the compactness factor and the mean value of the Feret measurements for each object for each individual image. Second, these mean per slide values are summarised by calculating their mean and standard deviation for each farm study area/land management area combination (Table 6).

For the image analysis results from the Bragasetter and The Biggins samples, the total per image data (Table 5) show a clear differentiation between the manured kailyard, rig land and plantiecrue areas and the unmanured grazing areas for carbonised organic and rubified mineral manuring materials. The results of the REML statistical analysis of the total per image data (Table 7) also show significant ($P < 0.05$) differentiation between land management areas for all three sites for the carbonised and uncarbonised manuring materials. The data from the Hamna Voe samples is less distinct (Table 5) and whilst there is a clear difference between the Kailyard samples relative to the other land management areas, the rubified material shows a marked increase in the grazing area compared to both other areas at Hamna Voe and relative to the grazing areas at

Table 5
Summary of the quantity (mean of total per slide values) of manuring materials measured by image analysis in thin section, tabulated over three farm study areas and four land management areas, Papa Stour, Shetland

		Kailyard		Rig land		Plantiecrue		Grazing	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Bragasetter		$n = 11$		$n = 10$		$n = 4$		$n = 5$	
Carbonised organic	Area (10^5 μm^2)	39.3	48.3	20.6	25.0	6.2	2.2	1.6	2.1
	Perimeter (10^5 μm)	10.7	12.7	6.3	8.0	1.8	0.7	0.5	0.6
Rubified material	Area	77.6	81.5	36.9	42.6	14.9	4.1	9.3	9.8
	Perimeter	8.7	6.9	3.7	3.7	2.4	0.9	2.2	2.4
Uncarbonised material—turf	Area	87.2	69.0	42.9	42.0	32.6	19.7	38.1	45.1
	Perimeter	10.1	8.3	7.0	10.1	5.0	3.1	7.6	9.2
Uncarbonised material—polymorphic fine material	Area	36.2	32.9	35.4	53.7	24.2	18.2	14.3	13.8
	Perimeter	6.5	5.6	5.9	9.3	3.9	2.0	3.6	3.5
The Biggins		$n = 20$		$n = 15$		$n = 4$		$n = 10$	
Carbonised organic	Area (μm^2)	46.8	37.8	28.2	21.0	17.4	13.9	8.6	18.1
	Perimeter (μm)	13.7	11.8	8.2	6.3	5.3	4.6	2.9	6.8
Rubified material	Area	85.0	61.6	54.9	35.6	62.7	26.7	43.1	98.0
	Perimeter	7.9	4.8	6.1	3.0	13.0	8.9	7.9	16.4
Uncarbonised material—turf	Area	60.7	50.0	38.8	29.2	43.5	34.3	48.9	112.7
	Perimeter	5.6	2.9	4.43	3.65	9.5	8.6	15.7	37.0
Uncarbonised material—polymorphic fine material	Area	14.8	13.3	14.5	12.8	15.1	11.9	55.3	136.3
	Perimeter	1.9	1.0	2.4	2.0	5.5	5.1	16.0	39.0
Hamna Voe		$n = 8$		$n = 7$		$n = 4$		$n = 4$	
Carbonised organic	Area (μm^2)	148.4	90.5	28.9	19.0	26.8	20.9	51.9	15.4
	Perimeter (μm)	43.9	25.7	8.9	5.7	7.4	5.9	14.2	4.4
Rubified material	Area	32.1	15.9	75.1	48.2	57.5	45.1	122.4	42.1
	Perimeter	3.96	1.9	10.9	8.2	6.9	4.9	17.4	8.2
Uncarbonised material—turf	Area	251.3	137.2	98.0	146.3	139.9	117.4	162.9	130.0
	Perimeter	24.4	11.9	14.6	5.7	21.7	15.8	13.1	4.9
Uncarbonised material—polymorphic fine material	Area	70.4	35.2	40.2	18.0	40.1	27.6	44.4	28.9
	Perimeter	10.9	5.6	8.9	3.6	10.4	8.5	77.4	49.4

Results are mean of sum values (i.e. summary of totals per slide). n, number of thin-section images.

Bragasetter and at The Biggins. These data may explain the REML analyses for the rubified mineral materials (Table 7). These reveal no significant difference between land management areas, yet significant differences between farm study areas. This suggests that either the image analysis procedure confounds the rubified materials seen in thin section at Hamna Voe with another feature during the image segmentation, or that there has been burning, presumably managed, of the infield grazing areas. From the methodology adopted the first possibility is improbable, and furthermore the conventional micromorphology suggests that the Hamna Voe grazing areas are atypical compared to the other grazing areas, supporting the conclusion that these areas have been extensively burnt. The occurrence of fuel residue features in a grazing area is unexpected since there is no ethnographic evidence for this practice on Papa Stour. If this evidence of either direct burning of extensive amendment with fuel residues on the grazing land at Hamna Voe is seen as an exception, these results (Table 5) validate the hypotheses from the historical and ethnographic information (Section 2.2) relating to the nature of manure inputs and the contrast between manured and non-manured land-management areas. The types of turf manuring material on the rig-land and kailyard land management areas, therefore follow both the ethnographic evidence of this study and of that of Fenton [16].

More subtle differences can be seen in the data set when the land-management areas are considered across the three farm study areas. The Biggins and Bragasetter data sets relate to each other as hypothesised, and furthermore the differences between distinct land-manage-ment areas match those described by Davidson and Carter [9] for the Oligarth farm site on Papa Stour. However, the quantities of manuring materials found in these two sites in the present study are greater, particularly in the most heavily manured kailyard areas. This difference may be attributed to both the inclusion of smaller objects in the image analysis of the thin section than considered by eye, and also to inter-site variation. Inter-site variability is highlighted in these land-manage-ment area results, with Hamna Voe having larger concentrations of uncarbonised turf materials than at either The Biggins or Bragasetter (Table 5) which suggests that there is an anomaly in the hypotheses surrounding Hamna Voe.

Whilst direct turf amendment is expected in the kailyard and rig-land land management areas, the occurrence of quantities of turf manuring features in the soils found in the plantiecrues of The Biggins and at Hamna Voe is unexpected (cf. Section 2.3). This result in part contradicts Fenton’s evidence [16] where ash rather than seaweed and composted manures is reported used on the plantiecrue. These differences at Hamna Voe may in part be explained by the effect of the total profile depth, and consequent variation on the number of fixed-depth samples per profile, with the Hamna Voe profiles all much shallower that at the other sites. It is clear however, that the peripheral farm of Bragasetter and the isolated farm of Hamna Voe were putting greater emphasis on use of turf materials and less on fuel residue materials in both intensive areas of manuringdthe kailyard and rig land. Across all the sites, the total quantity of the all the uncarbonised organic materials is consistently greater than the carbonised features, reflecting the proportions of fuel residue materials and turf materials used as soil amendments.

Table 6
Summary of the shape of manuring materials measured by image analysis in thin section (mean of the mean per slide values), tabulated over three farm study areas and four land management areas, Papa Stour, Shetland

		Kailyard		Rig land		Plantiecrue		Grazing	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Bragasetter		$n = 11$		$n = 10$		$n = 4$		$n = 5$	
Carbonised organic	Compactness	0.20	0.03	0.20	0.03	0.22	0.02	0.21	0.05
	Mean Feret (μm)	49.7	6.8	50.4	6.8	52.0	10.5	47.2	4.7
Rubified material	Compactness	0.41	0.11	0.46	0.11	0.42	0.05	0.34	0.07
	Mean Feret (μm)	45.9	4.2	44.6	4.2	44.3	2.3	41.3	3.9
Uncarbonised material—turf	Compactness	0.28	0.11	0.28	0.12	0.25	0.05	0.19	0.06
	Mean Feret (μm)	76.6	9.9	79.0	10.4	78.9	7.0	78.0	8.3
Uncarbonised material—polymorphic fine material	Compactness	0.31	0.10	0.31	0.12	0.26	0.03	0.22	0.04
	Mean Feret (μm)	54.6	7.3	56.3	10.5	56.3	5.8	54.1	3.9
The Biggins		$n = 20$		$n = 15$		$n = 4$		$n = 10$	
Carbonised organic	Compactness	0.22	0.02	0.21	0.03	0.22	0.02	0.16	0.07
	Mean Feret (μm)	56.9	7.5	55.3	5.9	47.1	5.3	46.1	18.4
Rubified material	Compactness	0.43	0.08	0.42	0.08	0.38	0.12	0.29	0.07
	Mean Feret (μm)	47.4	5.2	47.0	5.1	46.7	3.15	45.7	10.6
Uncarbonised material—turf	Compactness	0.36	0.08	0.28	0.10	0.24	0.12	0.15	0.11
	Mean Feret (μm)	82.9	6.75	82.3	9.6	75.4	11.4	82.1	15.8
Uncarbonised material—polymorphic fine material	Compactness	0.35	0.06	0.29	0.08	0.24	0.11	0.14	0.05
	Mean Feret (μm)	52.9	4.2	56.0	8.5	50.5	5.7	65.4	19.8
Hamna Voe		$n = 8$		$n = 7$		$n = 4$		$n = 4$	
Carbonised organic	Compactness	0.21	0.01	0.18	0.03	0.19	0.02	0.22	0.01
	Mean Feret (μm)	48.3	4.3	51.5	4.62	56.5	9.0	47.9	1.9
Rubified material	Compactness	0.41	0.05	0.38	0.8	0.38	0.06	0.43	0.07
	Mean Feret (μm)	48.8	6.7	44.4	2.5	46.9	4.4	44.0	2.8
Uncarbonised material—turf	Compactness	0.29	0.07	0.22	0.05	0.17	0.09	0.32	0.06
	Mean Feret (μm)	81.4	12.7	77.0	4.6	83.4	9.0	76.8	10.4
Uncarbonised material—polymorphic fine material	Compactness	0.34	0.05	0.25	0.04	0.21	0.06	0.33	0.03
	Mean Feret (μm)	55.5	6.8	55.1	4.64	68.4	7.0	52.7	4.4

Results are mean of mean values (i.e. summary of means per slide). *n*, number of thin-section images.

This will have an effect in the mean totals from each farm area/land-management area combination (Table 5). The depth of the sample is considered as part of the REML statistical analyses with significant effects seen in the results of total amounts of carbonised organic materials, and uncarbonised material with mineral inclusions (Table 7a). The effect of the auto-correlation structure in the REML analyses is significant for the total carbonised organic material and rubified mineral material data (Table 7b). These results suggest that manuring practices involving fuel residues have been employed continuously and since any data show such auto-correlation, this further suggests that the manuring practices have been employed for a long period and without significant phases of, say, aeolian sand accumulation. The quantities of turf material are at greater concentrations than expected in plantiecrue and grazing-land samples, whereas the relative quantity of each of the manuring materials in the kailyard and rigland soils follows the hypothesised relationships.

Considering the size and shape of the individual objects seen in each thin section allows hypotheses relating the confounded effects of the frequency and intensity of cultivation to be considered. The results of the size and shape measurements of the individual features (Table 6) for the rubified or carbonised organic materials show no differentiation between either, the farm study areas or the land-management areas. The Feret and compactness factor measurements (Table 6) indicate that the characteristics of these fuel-residue manures are similar between all sites, suggesting a commonality of practice across the island. This is logical in that the farms would have drawn upon similar fuel resources, with the exception of Hamna Voe which was abandoned before the onset of coal use in the 20th Century, and also in agreement with the recorded and past [16,18] ethnographic survey data. In contrast, the uncarbonised material with mineral inclusions and uncarbonised material without mineral inclusions, both show a range of differences between study areas; the larger fragments, i.e. larger mean Feret, occurring at Hamna Voe and The Biggins. For these materials, and with the exception of the Hamna Voe grazing area again, the compactness values show a trend across the land management areas from more rounded materials in the intensively cultivated areas of the kailyard and rig-land to the planticrue and grazing land. This follows the hypothesised relationship (Section 2.3) between shape and the confounded effects of the frequency and intensity of cultivation. The size of the individual micromorphological features of uncarbonised manures shows a clear trend across the land-management areas, whilst the shape measurement varies significantly with depth. The fuel-residue materials show no such trend or relationship with the depth of the sample. Across the three farm-study areas, there are no significant relationships between the shape and size of individual materials. Where the results do not follow the hypothesised relationships, the three farm areas show less distinction between each other than anticipated, which is understandable considering the commonality of resources and of land-use practice over long-periods.

The REML analyses (Table 7) of these shape measurements show significant relationships for the depth of sampling for the uncarbonised materials and for carbonised fragments. Since the shape of particles in thin section is dependent on, either or, both the material origin and the processes operating in the soil the relationships with depth in this instance are important. Assuming that the nature of the turf or fuel-residue manures themselves has not altered when applied, then these depth relationships must be as a result of the intensity of cultivation disturbance.

Table 7

Results of multi-variate restricted maximum likelihood (REML) analyses (a) between farm-areas, land-management areas and depth of sampling, (b) effect of depth variable auto-correlation tested and (c) with relative distance to manure sources as co-variates (all values tested at 95% significance, i.e. $\alpha=0.05$)

Micromorphological feature	Carbonised organic material						Uncarbonised material - turf with mineral inclusions						Uncarbonised material - no mineral inclusions						Rubified mineral material					
	Totals		Means				Totals		Means				Totals		Means				Totals		Means			
Measure	Area sum	Perimeter sum	Area mean	Perimeter mean	Compactness	Feret mean	Area sum	Perimeter sum	Area mean	Perimeter mean	Compactness	Feret mean	Area sum	Perimeter sum	Area mean	Perimeter mean	Compactness	Feret mean	Area sum	Perimeter sum	Area mean	Perimeter mean	Compactness	Feret mean
a) REML Model with farm study area, land management areas and sampling depth as factors																								
Interaction																								
Between farm study areas	#	#	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	#	#	~	~	~	~
Between land management areas	#	#	~	~	~	~	#	#	~	~	~	~	~	#	~	~	~	~	~	~	~	~	~	~
Between soil sampling depths	#	#	~	~	#	~	#	#	~	#	~	#	~	~	~	~	#	#	~	~	~	~	~	~
b) REML Model as a) with depth autocorrelation structure rather than depth as factor																								
Effect																								
Depth autocorrelation	~	#	~	~	~	~	~	~	~	~	#	#	~	~	~	~	#	~	#	~	~	~	~	~
c) REML Model as a) with co-variate																								
Co-variate																								
Distance of profile from seaweed source	~	~	#	#	~	~	#	#	~	~	#	~	#	#	~	~	#	~	#	#	~	~	~	~
d) REML Model as a) with covariate																								
Co-variate																								
Ratio of distance from farm:distance from seaweed source	~	#	#	#	~	#	#	#	~	~	#	~	#	#	#	~	#	~	#	#	~	~	~	~

Key:
significant interaction/effect at p. <0.05
~ no significant interaction/effect at p. <0.05

The relationships between the measurements used as individual covariates in the REML analyses of the image analysis data are shown in Fig. 4. Across the three farm sites, there are clear differences between the plantiecrues and grazing areas compared to similarities for the rig-land and kailyard both in distance from the sources of seaweed manures and from the farmsdthe sources of fuel residues and byre material manuring materials. The effect of the covariates is considered in the REML analyses (Table 7c,d): these show significant effects in respect of the shape measurements of uncarbonised materials. These covariate analyses also clearly show that the distances from manure material sources are significant in respect of the quantities of materials seen in thin section. This suggests that the management of the manure resource in respect to its application in different land-management areas has led to discrete concentrations in accord with the ethnographic evidence.

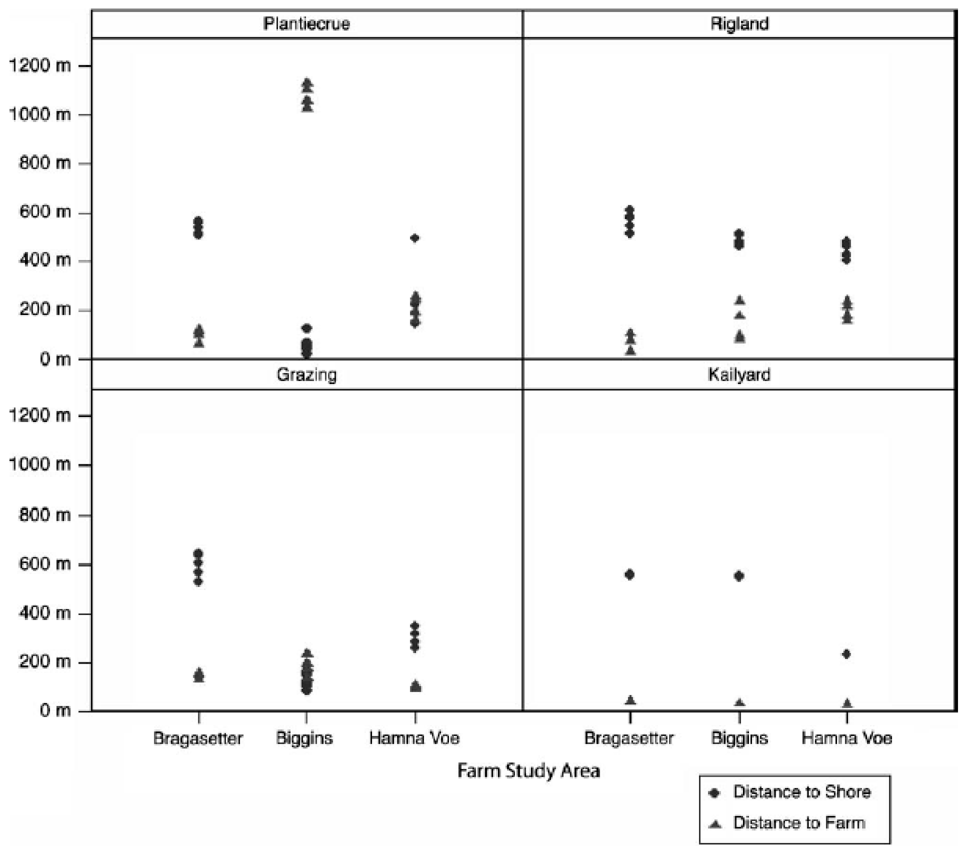

Fig. 4. Distances between land management areas and manure sources by each farm study area.

5. Conclusions

The management of traditional manuring practices is a key factor in understanding the management of early agricultural landscapes. In this paper the validation of one of the key methods employed in the study of such practices has been demonstrated through comparisons between a framework of ethnographic and historical evidence and image analysis measurements made on soil thin-section samples. It has been demonstrated that the micromorphological features relating to turf and fuel residue manures can be identified and quantified in thin section by image analysis. Developed to allow feature identification akin to conventional micromorphology, the analysis method used with standardised and precisely controlled thin-section production [2] allows quantification of features indicative of both turf-material and ash residue amendments to soils. This demonstrates that image measurements from many thin-section slides from different site contexts can be compared successfully. Since past studies have tended to be semi-quantitative within one site, the approach adopted of a fully quantitative study over several sites demonstrates clear advances in both methodology and in the value of this type of thin-section study. Constructing the comprehensive set of results from the image analysis of soil thin sections and their subsequent statistical analysis allows the method to be validated against other data sources.

The set of hypotheses constructed from synthesising the ethnographic and historical data relating the nature of the farm-study areadcore, isolated and peripheraldand to the manure inputs on four distinct land-man-agement areasdkailyard, rig land, plantiecrue and infield grazingdland have matched relative predictions, with a small number of exceptions. The comprehensive nature of the image analysis data also permits more subtle relationships to be explored, deepening the understanding gained from the broad historical and ethnographic data. Excepting the anomalies, the relative quantities of manure found at each location match the postulated hypotheses and this serves to validate the image analysis approach, allowing future analyses of manuring materials to be undertaken in relatively unknown contexts. It is also clear that incorporation of ethnographic evidence into studies of past management of soils and manuring resources allows a more secure understanding of early land management activities.

Acknowledgements

This study was supported by U.K. Natural Environment Research Council grant NERC GR3/11649. The authors kindly acknowledge the sincere support given by the people of Papa Stour whilst undertaking field work, in particular Mr and Mrs A. Holt-Brook, Mr and Mrs G. Peterson, and Mr and Mrs J. Scott. From the School of Biological and Environmental Sciences, University of Stirling, George MacLeod manufactured the thin sections and Bill Jamieson assisted in the production of maps and figures.

References

[1] W.P. Adderley, I.A. Simpson, M.J. Lockheart, R.P. Evershed, D.A. Davidson, Modeling traditional manuring practice: soil organic matter sustainability of an early Shetland community? Human Ecology 28 (2000) 415-431.
[2] W.P. Adderley, I.A. Simpson, D.A. Davidson, Colour description and quantification in mosaic images of soil thin sections, Geoderma 108 (2002) 181-195.
[3] J.A. Brand, A Brief Description of Orkney, Zetland, Pightland Firth and Caithness, 1701-1703.
[4] P. Bullock, N. Federoff, A. Jongerius, G. Stoops, T. Tursina, Handbook for soil thin section description, Waine Research Publications, Wolverhampton, 1985.
[5] M.G. Canti, N. Linford, The effects of fire on archaeological soils and sediments: temperature and colour relationships, Proceedings of the Prehistoric Society 66 (2001) 385-395.
[6] M.R. Carter, E.G. Gregorich, D.A. Angers, R.G. Donald, M.A. Bolinder, C. Organic, N storage, and organic C fractions, in adjacent cultivated and forested soils of eastern Canada, Soil and Tillage Research 47 (1998) 253-261.
[7] M.A. Courty, P. Goldberg, R.I. Macphail, Soil Micromorphology and Archaeology, Cambridge University Press, Cambridge.
[8] B.E. Crawford, B. Ballin-Smith, The Biggins, Papa Stour, Shetland: The history and excavation of a royal Norwegian farm, Society of Antiquaries of Scotland Monograph Series Number 15, Edinburgh, 1999.
[9] D.A. Davidson, S.P. Carter, 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 (1998) 827-838.
[10] D.A. Davidson, I.A. Simpson, Archaeology and soil micromorphology, in: D.R. Brothwell, A.M. Pollard (Eds.), Handbook of Archaeological Sciences, Wiley, Chichester, 2001, pp. 167-177.
[11] H. De Bakker, Anthropogenic soils in The Netherlands, Roczniki Gleboznawcze 31 (1980) 323-328.
[12] H. Domzl, J. Hodara, A. Slowińska-Jurkiewicz, R. Turski, The effects of agricultural use on the structure and physical properties of three soil types, Soil and Tillage Research 27 (1993) 365-382.
[13] G. Donaldson (Ed.), The Court Book of Shetland: 1602e1604, Scottish Record Society, Edinburgh, 1952.
[14] R.O. Duda, P.E. Hart, Pattern Classification and Scene Analysis, John Wiley & Sons, Chichester, 1973.
[15] H. Evershed, On the Agriculture of the Islands of Shetland, Transactions of the Highland and Agricultural Society of Scotland VI (4th Series), 1874.
[16] A. Fenton, The Northern Isles: Orkney and Shetland, John Donald, Edinburgh, 1978.
[17] A. Fenton, The Shape of the Past 1. Essays in Scottish Ethnology, John

Donald, Edinburgh, 1985.
[18] A. Fenton, The Shape of the Past 2. Essays in Scottish Ethnology, John Donald, Edinburgh, 1986.
[19] J.M. Hodgson (Ed.), Soil Survey Field Handbook: Describing and Sampling Soil Profiles, Technical monograph no. 5, Soil Survey of England and Wales, Harpenden, 1976.
[20] G.W. Horgan, Mathematical morphology for analysing soil structure from images, European Journal of Soil Science 49 (1998) 161-173.
[21] Insightful, S-Plus Programmer's Guide, Data Analysis Products Division, Insightful Inc., Seattle, WA, 2001.
[22] T. Irvine, The Island of Papa Stour, Zetland, Parish of Walls, 1846.
[23] J.D.D. Kemp, Observations on the Islands of Shetland, and their inhabitants: and, on the climate, soil, state of agriculture, fisheries, etc. of that country: with hints for their improvement, Charles Stewart, Edinburgh, 1801.
[24] R.A. Kemp, Role of micromorphology in paleopedological research, Quaternary International 51/52 (1998) 133-141.
[25] R.C. Littell, G.A. Milliken, W.W. Stroup, R.D. Wolfinger, SAS System for Mixed Models, SAS Institute Inc., Cary, NC, 1996.
[26] G. Low, A Tour Through the Islands of Orkney and Shetland (1774), 1879.
[27] W. Mykura, J. Phemster, The Geology of Western Shetland, Memoirs of the Geological Survey of Great Britain, HMSO, Edinburgh, 1976.
[28] W. Mykura, D. Flin, F. May, British Regional GeologydOrkney and Shetland, HMSO, Edinburgh, 1976.
[29] Old Statistical Account of Scotland, 1791-1799. <http://stat-acc-scot.edina.ac.uk/stat-acc-scot/stat-acc-scot.asp>
[30] Ordnance Survey, 1:2,500 scale maps of Papa StourdFirst Edition, 1886.
[31] Ordnance Survey, 1:2,500 scale maps of Papa StourdSecond Edition, 1901.
[32] J.C. Pape, Plaggen soils in The Netherlands, Geoderma 4 (1970) 229-255.
[33] C. Peters, M.J. Church, C. Mitchell, Investigation of fire ash residues using mineral magnetism, Archaeological Prospection 8 (2001) 227-233.
[34] G.P.S. Peterson, The Toon a Bragasetter and its Surrounds (Map MS.), 1995.
[35] I.A. Simpson, W.P. Adderley, A micromorphological perspective on archaeological site formation processes, in: J.H. Larsen, P. Rolfsen (Eds.), HalvdanshaugendArchaeology, History and Natural Environment, University of Oslo, Special Publication 3, University of Oslo Press, Oslo, 2004.
[36] I.A. Simpson, O. Vésteinsson, W.P. Adderley, T.H. McGovern, Fuel resource utilisation in landscapes of settlement, Journal of Archaeological Science 30 (2003) 1401-1420.
[37] I.A. Simpson, W.P. Adderley, G. Guðmundsson, M. Hallsdóttir, M.Á. Sigurjersson, M. Snæsdo´ ttir, Soil limitations to agrarian land production in pre-modern Iceland, Human Ecology 30 (2002) 423-443.

[38] I.A. Simpson, Relict soil properties of anthropogenic deepened top soils as indicators of infield management in Marwick, West mainland, Orkney, Journal of Archaeological Science 24 (1997) 365-380.
[39] R.S. Skirving, On the Agriculture of the Islands of Shetland, Transactions of the Highland and Agricultural Society of Scotland VI, 4th Series (1874) 229-264.
[40] B. Smith, Toons and Tenants: Settlement and society in Shetland 1299e1899, Shetland Times, Lerwick, 2000.
[41] Soft Imaging System, User's Guide AnalySIS, Soft Imaging System, Münster, 2002.
[42] Soil Survey for Scotland, The Soils of Northern Scotland, MLURI, Aberdeen, 1982.
[43] Soil Survey Staff, Soil Taxonomy, Second ed., Agriculture Handbook no. 436, USDA-NRCS, Washington DC, 1999.
[44] T. Spek, An evaluation of dating methods for plaggen soils in the Netherlands and Northern Germany, in: A. Verhoeve, J.A.J. Vervloet (Eds.), The Transformation of the European Rural Landscape: Methodological Issues and Agrarian Change, Brussels, 1992, pp. 72-91.
[45] G. Stoops, Guidelines for the analysis and description of soil and regolith thin sections (Monograph and CD-Rom), Soil Science Society of America, Madison, WI, 2003.
[46] W.P.L. Thomson, Fetlar Funzie, A Shetland run-rig township in the nineteenth century, Scottish Geographical Magazine 86 (1970) 170-185.
[47] A.J. VandenBygaart, R. Protz, The representative elementary area (REA) in studies of quantitative soil micromorphology, Geoderma 89 (1999) 333-346.
[48] W.N. Venables, B.D. Ripley, Modern Applied Statistics with S-Plus, third ed. Springer, New York, 1999.
[49] W.R. Whalley, P.B. Riseley, P.B. Leeds-Harrison, N.R.A. Bird, P.K. Leech, W.P. Adderley, Structural differences between bulk and rhizosphere soil, European Journal of Soil Science 56 (2005) 353-360.
[50] B.J. Winer, D.R. Brown, K.M. Michels, Statistical Principles in Experimental Design, McGraw Hill, New York, 1991.
[51] World Reference Base, World Reference Base for Soil Resources: Introduction. ISSS Working Group RB, J.A. Deckers, F.O. Nactergaele, O.C. Spaargaren (Eds.), ISSS, ISRIC, FAO, Acco, Leuven, 1998.