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Soil-landscape endemism: The Glasserton Rigs of the Machars Peninsula, Scotland

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ABSTRACT

This paper describes an endemic soil-landscape — the Glasserton Rigs, which are situated on the southern end of the Machars Peninsula in south-west Scotland. The Glasserton Rigs are limited in extent to about 25 km^2. In this once glacial environment, the Glasserton Rigs are an extensive arrangement of thin, elongated rocky ridges of vertically dipping Silurian greywacke with common strike, together with an equally complex distribution of greywacke- and glacial-till-derived soils upon and between them. The soils of the Glasserton Rigs are not necessarily rare or unique; however their arrangement and occurrence in this particular landscape are quite unique and consequently endemic. For that reason, the Glasserton Rigs are of high cultural value.

1. Introduction

Soil endemism is a concept that articulates the terms of reference for the existence of rare, unique, or endangered soils. As defined by Bockheim (2005), endemic soils are restricted in range based on the unique confluence of soil forming factors operating at broadly varying spatial scales. It is proposed in this study that there be a further broadening of the endemism concept to include that of soil and landscape endemism. Based on soil and geomorphological studies carried out on the Machars Peninsula in southern Scotland, this paper describes the occurrence of a situation where the constituent soil classificatory units are not necessarily endemic, yet the manner in which they are distributed and arranged is indigenous. We name this endemic soil-landscape pattern the Glasserton Rigs (after the localised region in which they occur; *rig* is a Scots word, in this context meaning ridge). Here, soil entities and parent materials which are common throughout the peninsula (Bown and Heslop, 1979) occur in a unique pattern largely determined by the micro-topography of the landscape.

Some basis for conceptualising soil-landscape endemism may be expressed through Fridland (1974) who described the notion of soil areals and soil combinations as the basis of describing soil organisation. Soil areals are the landform-dictated distribution patterns of soil classification units. The homogeneous areal has only one soil type in it, and is surrounded by other areals, sporadically spotted areals have minute and biogenic "spots" of different classification units, while regular cyclic has physical processes that re-distribute soil (such as cryoturbation or colluviation). These areals then are able to be combined together to make six types of soil combinations, with either high or low contrast between the constituent parts and links that are bilateral, unilateral or poorly expressed/absent. The components of soil combinations are genetically related, and their repetition creates the structures that make up what Fridland calls the "soil mantle". Hole (1978) also discussed this concept, describing a comparable notion of soilscapes, which are composed of polypedons (or individual soil types). The difference between the soil combinations and soilscapes is that the soil combinations are specific shapes of patterns, while the soilscapes are general patterns that are not necessarily of a specific shape or originate from topography.

The aim of this study, from field work, and post-field work analyses is to describe the physical occurrence and features of the Glasserton Rigs. Further, through digital soil mapping we aim to map the distribution or pattern of soil types in detail within the Rigs.

2. Materials and methods

2.1. Environmental setting

What is described as the Glasserton Rigs is believed to be localised mainly on the southern tip of the Machars Peninsula, Scotland, around Whithorn (54°43′58″N, 4°24′57″W). In area, the Machars Peninsula

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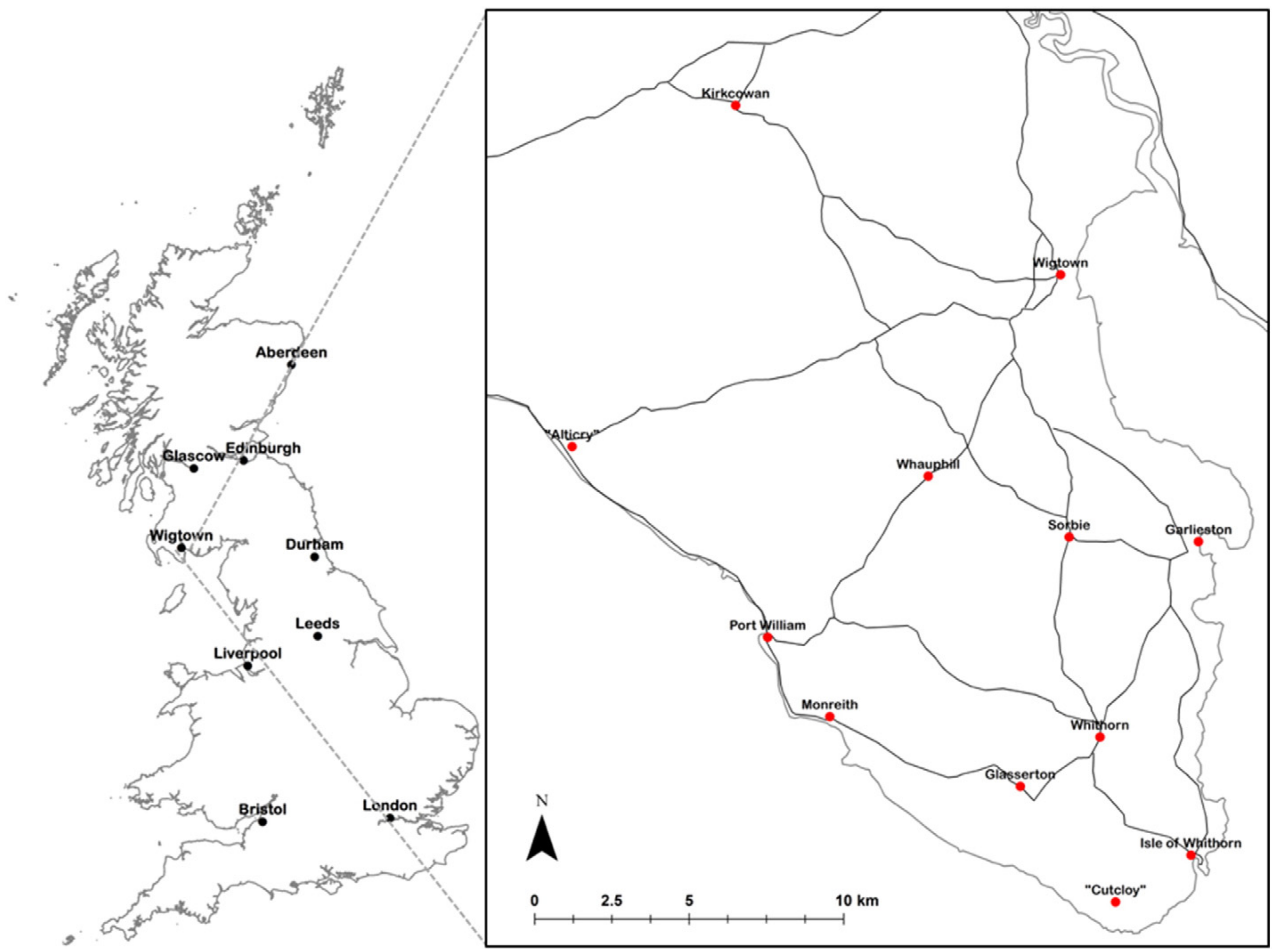

Fig. 1. The Machars Peninsula (with geographical reference to Britain) in southern Scotland with localities. Farmsteads are indicated by “name”.

covers just over 800 km^2 (Fig. 1). The most important land use activity upon the Machars is agriculture that is mainly in the form of dairy and beef farming and associated cropping that supports this industry (Bown and Heslop, 1979).

The climate of the Machars is typical of south-west of Scotland and is influenced by its proximity to the warm North Channel and Irish Sea (Bown and Heslop, 1979). Mean annual air temperature is just below 10 °C. The Machars has a historic growing season of approximately between 260 days (at Newton Stewart at the north of the Peninsula) and 300 days (from the Mull of Galloway). Although the Mull of Galloway is further west than the Machars it lies at similar latitude to the tip of the peninsula (Bown and Heslop, 1979). Despite reliable rainfall in the area (mean average precipitation $\approx$ 1200 mm), the channel networks are unable to have a substantial stream head catchment as it is at the tip of a peninsula.

The underlying geology is Silurian greywackes and mudstones of the Hawick Group (Barnes, 2008) from ~435 Ma. At the southern tip of the Machars Peninsula there are the Ross (Wenlock epoch) and Carghidown Formations (upper Llandovery epoch) which are Greywackes (beds dominantly less than 0.5 m thick) with interbedded mudstones including some red mudstone beds which distinguishes them from the more northern and older Kirkmaiden Formation (also Llandovery epoch) by the presence of the red mudstone beds (Barnes, 2008). The geological boundary between the Carghidown and Kirkmaiden formation runs more-or-less in a north-east/south-westerly direction from the east to the west coast, passing just south of Glasserton and Whithorn (see Fig. 7). The most important feature is that the beds have a strike of about 45° east of north, and are dipping about 80° from the horizontal (almost on edge).

The Machars is generally a low lying peninsula with a maximum elevation of about 250 m a.s.l., in the north of the study area. For most of the peninsula, the elevation seldom rises above 100 m. The relief is generally low and rolling, yet moderately steep slopes are more frequent on the south-western seaboard. In this landscape of flats and gentle slopes with rock outcrops, drumlins up to 30 m high and 700 m long also occur (Salt and Evans, 2004). A distinctive topographical feature, particularly on the southern end of the peninsula is the occurrence of an undulating relief of micro-topographical highs and lows of thin, rocky outcrops or ridges (Bown and Heslop, 1979). It is these features that are of interest to this study and the description of the Glasserton Rigs below.

2.1.1. Physical description of the rigs

Fieldwork was conducted in the study area during the northern hemisphere summer of 2013. To begin to describe the physical characteristics of the rigs and the patterning of soils upon them, a desktop study was initiated to delineate the rig features in this landscape. Using colour aerial photography coupled with a 5 m LiDAR (Light Detection and Ranging)-derived digital elevation model polygon features were drawn within a GIS to delineate the locations of the thin ridge features. The aerial photography was helpful due to the association

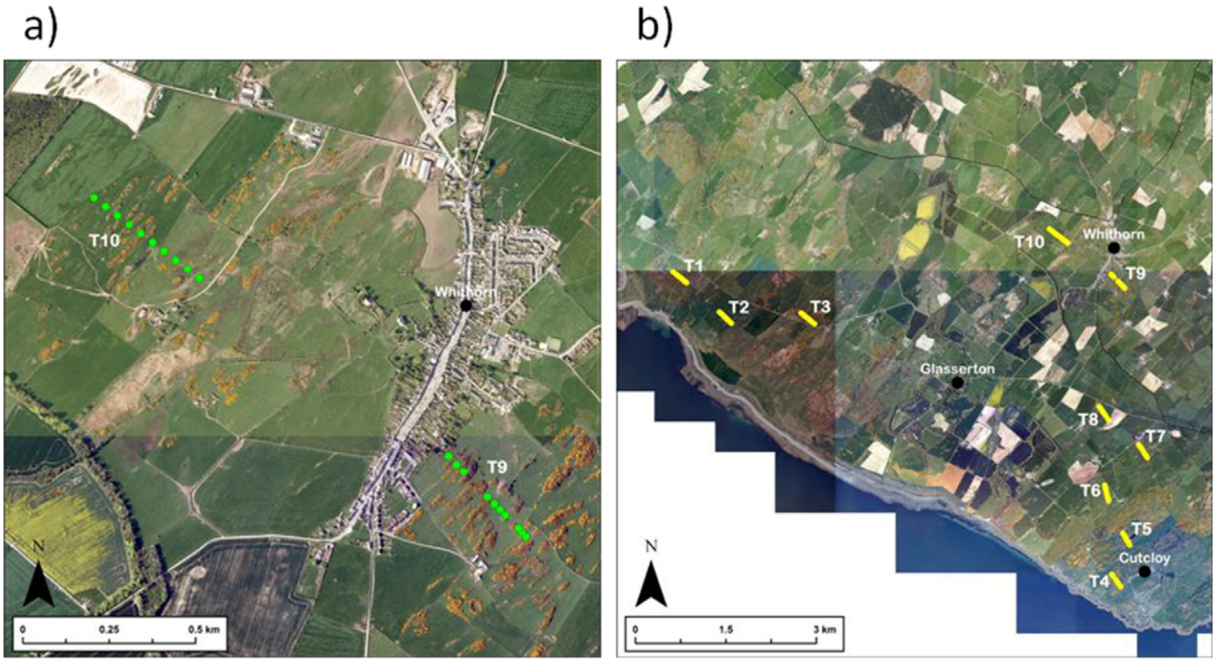

Fig. 2. a) An example of some rig features that can be easily delineated by their co-association of the yellow flowering gorse plant especially in the southeast corner. Green dots indicated sites for soil sampling. b) Locations of all the sampling transects used in this study, N.B. T3, T4 and T10 were not sampled.

between the yellow colouring of (Spring-)flowering gorse bushes (*Ulex europaeus*) and the thin rocky outcrops. Fig. 2a illustrates the example of co-existence between of the thin ridge features and flowering gorse in an area south and north-west of Whithorn. During the fieldwork and familiarisation with the landscape, additional rig features undetectable from either the DEM or aerial photography were drawn within the existing GIS map.

After the delineation step, ten randomly drawn transects of 300 m length were placed perpendicular to the major axis of the rigs (Fig. 2b), however, limited access reduced this number to seven. For each transect, 10 points were placed at equal distances for the intention of soil sampling and observation at these locations. This sampling configuration changed slightly due to issues of accessibility and/or to capture other landscape positions that would otherwise have been un-sampled with the equidistant sampling, i.e., crest, top-slope, mid-slope, toe-slope, valley positions, etc.

A soil pit was dug using an excavator machine at each location along the transects. Pits were dug to a depth of 1 m, or until bedrock was encountered. As in Bown and Heslop (1979) all soils observed were classified using the Scottish soil classification system (Soil Survey of Scotland, 1984). Mapping by Soil Survey of Scotland is based on soil series, ideally members of a genetic soil group, and in a soil association. Soil associations are comprised of a group of series derived from similar rock types and occurring together in a related pattern in the landscape, frequently in the form of a hydrologic sequence. For our purposes, from observations made in the field, the soil type was matched to the nearest soil series comprehensively described in Bown and Heslop (1979).

2.1.2. Spatial analysis of the Glasserton Rigs

From the map delineating the rig features across the study area, the shape parameters of area, length, and orientation were calculated. Using this data in addition to spatial coordinates of the features, spatial point pattern analysis (Diggle, 2003; Baddeley and Turner, 2005) was used to describe the geographical arrangement of the Glasserton Rigs throughout this study area. Specifically, this analysis involved calculating the statistical moments of the shape parameters, in addition to determining the spatial intensity of the rigs (expected number of rig features per unit area). These analyses were performed using the spatstat package (Baddeley and Turner, 2005) that is implemented from the R statistical computing software (R Core Team, 2013).

2.1.3. Digital soil mapping

Digital soil mapping was used in this study as a means to map the soil pattern as it occurs across the Glasserton Rig soilscape. Mapping of soils of the Machars Peninsula by Bown and Heslop (1979) was performed to quite intricate detail both in terms of the number of polygons per unit area, and the description of the various soil series that occur in this area. This map has since been digitised within a GIS (J. E. Collins, 2013).

Despite the very detailed mapping of soils across the Machars, one of the issues that was encountered is the prevalence of mapped soil complexes — the aggregation of soil series as a compromise between an intricate spatial distribution of soils and scale at which mapping occurred — coinciding with the general distribution of the rig features under study in this research. It is such that the rigs are near exclusively located within the mapped soil complexes, Achie, Glenlee and Ervie. These are all mineral soils of the Ettrick Association (soils derived from Ordovician and Silurian greywackes and shales) that are differentiated from each other in terms of topographical situation.

It was our intention therefore to disaggregate these soil complexes to the soil series level using the new information about the locations of the rig features (described in Section 2.1.1), and the soils that were described upon and around them during the fieldwork component. Described later in more detail, the soils upon the rigs all corresponded more-or-less to skeletal Ettrick soils (WRB Leptosols; IUSS Working Group WRB, 2007), which are a very shallow and rocky member of the Ettrick Association. A soil spatial prediction function (McBratney et al., 2003) was fitted to determine the distribution of soil series across the area not upon the rig features i.e. areas between and surrounding the rocky outcrops. The target variables for this digital soil mapping procedure were the classified observed soil series (from the fieldwork component), and the predictor variables (covariates) being derived from a digital elevation model (DEM) and its derivatives, in addition to the red, green and blue bands associated with the aerial imagery covering the study area. Specifically the variables extracted from the DEM included: altitude above channel network, slope curvature, length and gradient variables, terrain wetness index, and multi-resolution valley bottom flatness index. Finally, a 'distance to the nearest rig feature' covariate was also created and used for the modelling. While the DEM and derivatives were pertinent for modelling the soil series distribution as a function of topography, the aerial imagery bands were used as surrogates for vegetation and land use patterns. Landsat satellite imagery is commonly used in that regard, but for this study was unsuitable due to spatial resolution of these images which at 30 m was deemed to be too coarse. This study used multinominal logistic regression as the prediction model structure, as it is commonly used in soil categorical modelling exercises. Kempen et al. (2009) describe the theoretical underpinnings of these models for digital soil mapping applications. Model parsimony was determined using forward and backward stepwise model selection using the Akaike Information Criterion (AIC) (Akaike, 1974). Soil series mapping was performed on a 10 m by 10 m point grid. The total number of sites used for spatial modelling in this study was 68 (from the seven transects that were sampled). Because of this relatively small data set, leave-one-out cross-validation (LOCV), an external model validation routine, was used to assess the predictive accuracy of the modelling. The overall accuracy and Kappa statistics were the model performance statistics calculated and were estimated for the model incorporating all samples, and for the LOCV.

3. Results and discussion

3.1. Physical description of the Glasserton Rigs

Soil sampling and observation were performed upon 7 of the 10 planned transects for this study. From Fig. 2b the sampled transects were T1, T2, T5, T6, T7, T8, and T9.

The Glasserton Rigs are a soilscape (or mosaic) made prominent by a complex distribution of thin, rocky ridges. Fig. 3 shows an aerial view of the rigs from an image extracted from Google Earth. This image is taken from the southern tip of the Machars Peninsula and shows T4 (unsampled) in the background and T5 in the foreground. The image illustrates the elongated linear patterning of the complexly arranged features covered in vegetation. As described in the methodological section regarding the environmental setting, the rigs are found on Silurian greywackes. On the rigs themselves the beds are almost vertical relative to the ground surface (Fig. 4A).

The rigs have steep inclines to the sides, forming micro-topographical highs, approximately 5 m higher than the local landscape, but gently slope downwards at each end. Between the ridges are depressions, which occasionally open out into flats. Most of these flats have been drained and used for intensive agriculture such as cropping.

The ridges are believed to have been formed through plucking and abrasion by glaciers (Bown and Heslop, 1979; Salt and Evans, 2004). They are found on elevated parts of the landscape, and (more densely and pronouncedly) above the seaside cliffs where they would have acted like a fulcrum as the glacier was going over a precipice. In these areas there would have been greater pressure from the glaciers passing over the landscape. The process of plucking and abrasion is believed to result from higher pressure being applied to a conducive geology, which is exhibited in our field site (Lindström, 1988). The area was affected by the late Devensian Last Glacial Maximum, which occurred between 26 and 15 ka BP, along with large parts of the rest of northern Europe and North America (Clark et al., 2009). Studies undertaken throughout the nearby Cree Valley ice source area, north-west of the Machars based on ^{10}Be dating of the exposure ages of rock have estimated that the ice sheet had almost (or completely) disappeared by 15 ka BP in this area (Ballantyne et al., 2013). There is a strong indication that in the last glacial maximum three equidirectional ice flows passed over this area all parallel with the geological stratification (see Fig. 8 of Salt and Evans (2004)). This is probably the primary cause of the rig landscape, plucking out less resistant beds and retaining more recalcitrant ones.

Although the rigs are covered in soil, it is thin (though sometimes can measure to around 30 cm depth) and there are some small areas of exposed rock (Fig. 4B and C). The underlying rock is frost shattered probably from the late Pleistocene glaciation and subsequent Holocene periglaciation. The thin soils are often high in organic matter. The coarse fragments of a landscape's soil were used to ascertain whether it is till, or formed in situ, or via colluvial or alluvial processes. The coarse fragments found during field work, from both their angularity and size, indicate mainly in situ formation on the rigs, and very short path colluviation on the catenae between the rigs. There was also some evidence of glacial till such as the occurrence of rounded (Evans et al., 2005; Geikie, 1882) greywacke rocks, which were found predominantly between the ridges on the soil surface or buried in the soil itself (Fig. 4D

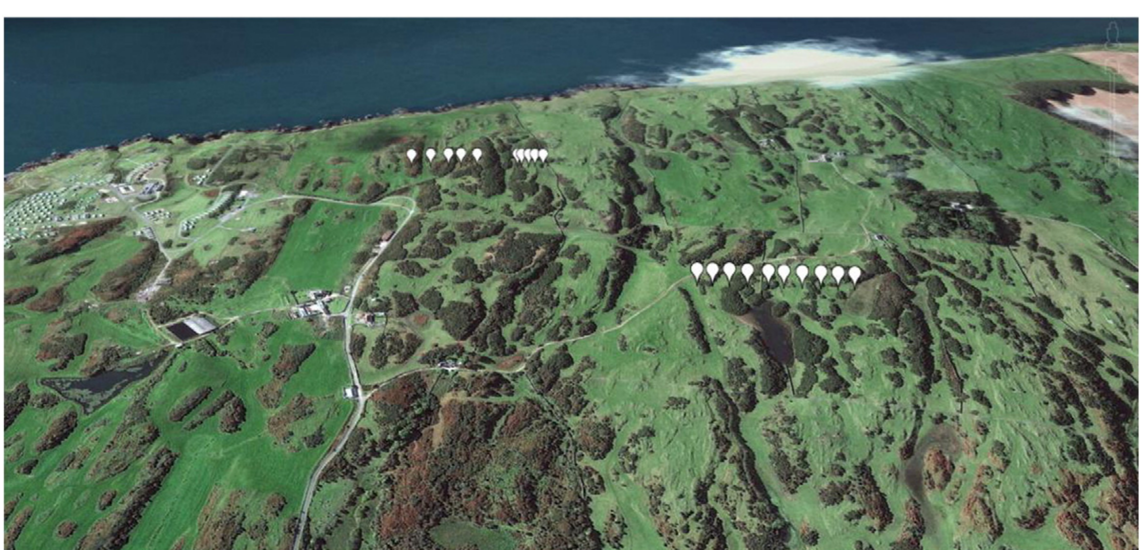

Fig. 3. Aerial image, facing due west, taken from Google Earth of the Glasserton Rig feature around Cutcloy Farm on the southern tip of the Machars Peninsula. T4 in the background and T5 in the foreground.

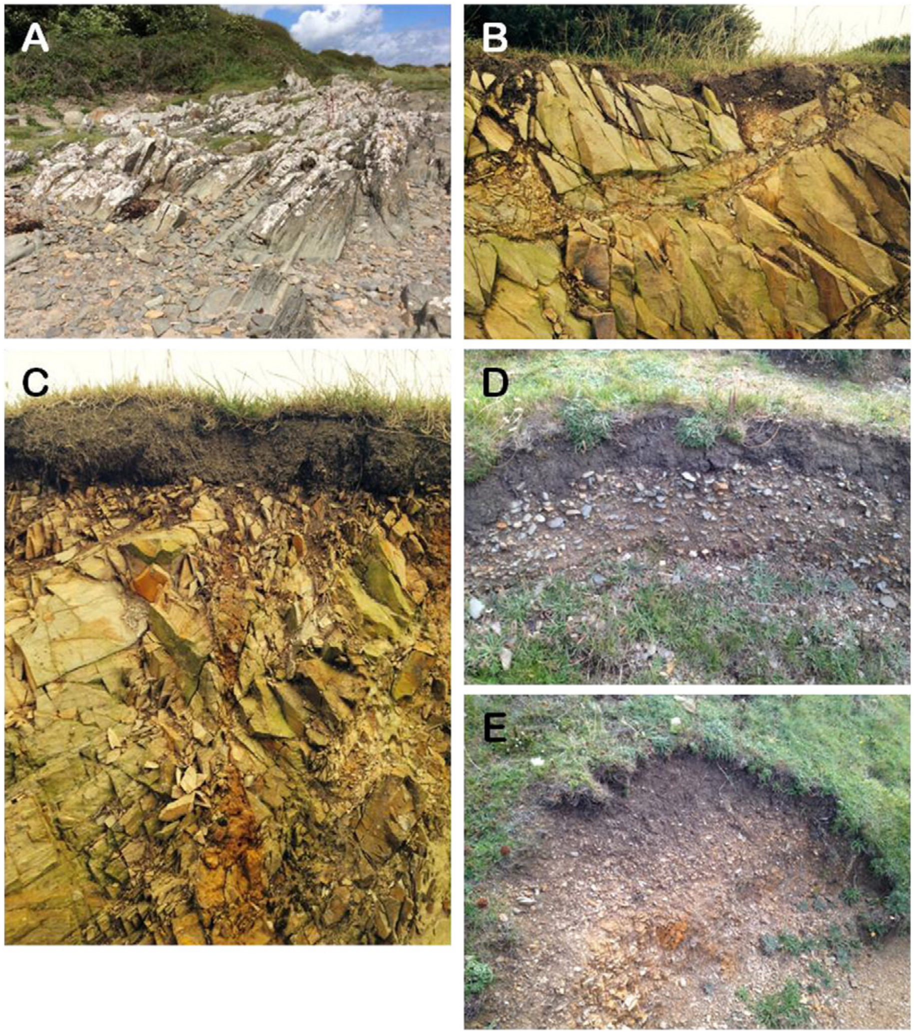

Fig. 4. Photos of the important physical and morphological feature of the Glasserton Rigs. A) A Glasserton Rig displaying the vertically dipping Silurian greywacke. B) Soil cover upon the rigs is generally skeletal or very thin. C) Sometimes soil cover upon the rigs can be as thick as 30 cm, and is often very organic. D) Soil cover between the rig features is often formed in situ and by colluvial processes related to the weathering of the greywacke parent material. E) Sometimes the soil material is derived from glacial till and/or alluvial processes as can be noted by the rounded rocks with this soil profile.

and E). More detailed morphometric work on coarse fragments is required to further elucidate the local and erratic sources.

On the rigs, where there is just exposed rock, there are angular coarse fragments, with a normal size range of 6 mm to 200 mm and above 50% by volume, mostly depending upon the local conditions that act upon the weak and fissile frost-shattered rock. The thin topsoil horizon will also have angular soil fragments, but normally in the 6–20 mm range and in 10–50% by volume. In between the ridges the fragments are a mixture of angular, sub-angular and sub-rounded, and range in size from 6 mm to 200 mm. The mineralogy, size and shape indicate that they are mainly carried down from the rigs as colluvium, along with weathered fine earth. Pedogenesis then occurs, causing divergence into differing soil types depending upon the hydrological conditions. The surface horizons tend to have rounded rocks (which may indicate some final influence of glacial transport and deposition), but also the greater levels of plant roots (mostly 2–10% of volume, but 10–50% of volume in a significant majority of cases).

3.2. Spatial pattern of the Glasserton Rigs

Delineation of the ridge features resulted in 4016 individual objects being drawn with a GIS. Fig. 5a shows the resulting map of these features. From this map, the ridges are exclusively situated upon the southern tip of the Machars Peninsula, extending northwards to the village of Sorbie. From spatial point analysis of the features, their intensity (Fig. 5b) is most concentrated to the west of the Isle of Whithorn and especially around the farmstead of 'Cutcloy'. The intensity of the ridge features is as great as 227 features per square kilometre. Other significant agricultural fields with ridges with this same spatial intensity are situated northwest of the hamlet of Glasserton. These ridge-dominated fields, and especially around Cutcloy farm, are what the authors would describe as the archetypal example of the Glasserton Rig landscape. Smaller areas of similar feature intensity also exist northwest and southeast of Whithorn, and at the midway point between Garlieston and Whithorn, and near Sorbie.

The general shapes of the ridges are that of elongated linear features. On average they are around 80 m long, and 26 m wide. Fifty percent of the ridges are orientated 42 and 63° clockwise from north reflecting the glacial activities and processes that have occurred upon the Machars. A summary of the rig shape parameters is provided in Table 1.

3.2.1. Soil pattern of the Glasserton Rigs: fieldwork

From our field classifications, the soil associations upon and surrounding the ridges i.e. the Glasserton Rig soilscape, are soils of

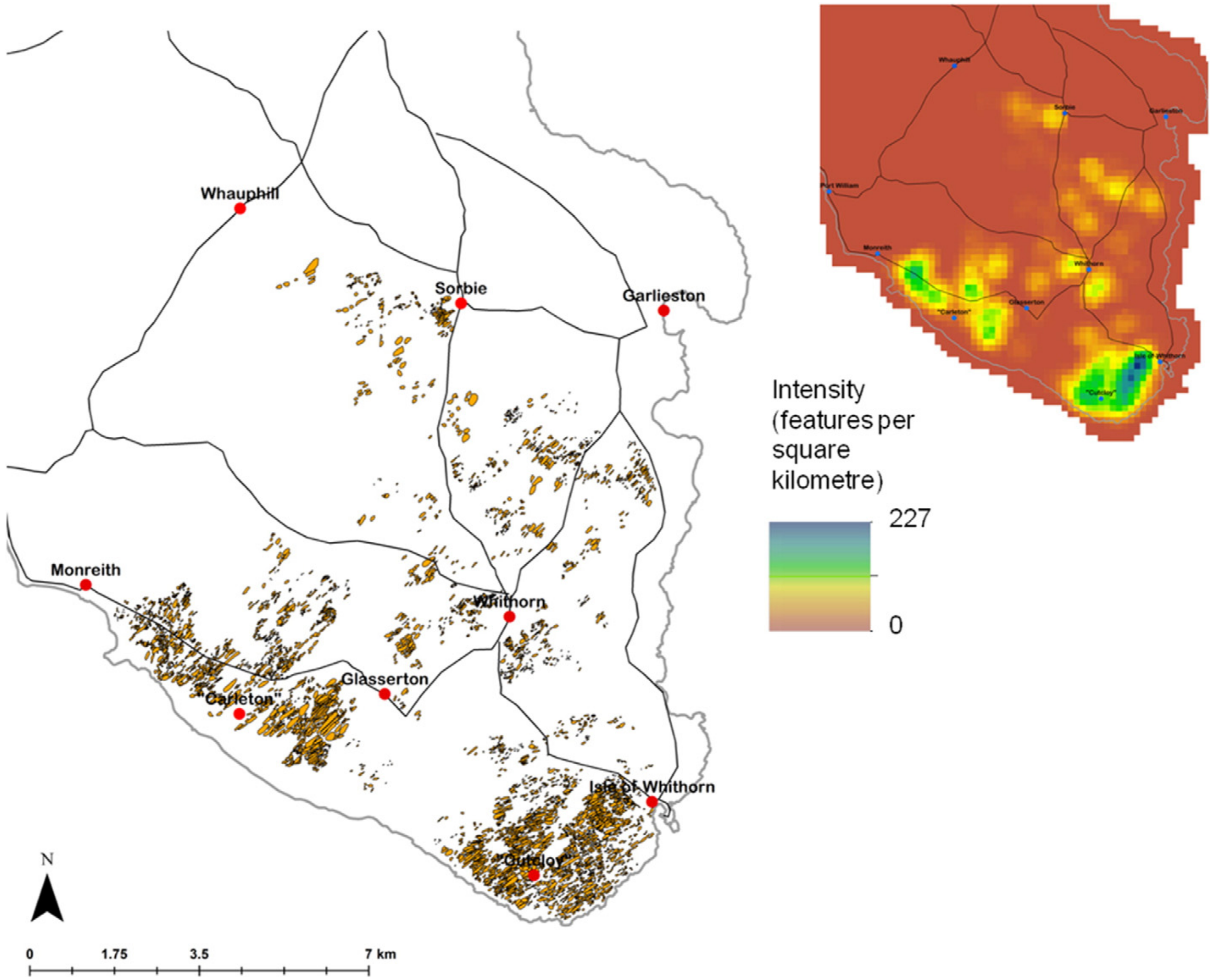

Fig. 5. Map of the individual ridges of the Glasserton Rig landscape as delineated within a GIS, and their spatial intensity (number of individual ridges per square kilometre).

the Ettrick Association which are described in detail by Bown and Heslop (1979). The Ettrick Association soils, as noted above, are developed from Ordovician and Silurian greywacke and shale and drifts derived from them.

Upon the ridges the soil cover was classified as skeletal Ettrick soils (WRB Leptosol). Of the 68 soils classified in this study, 35% were of the Linhope Series which corresponds to freely drained soils of the Ettrick Association. These brown-grey soils (WRB Cambisol) occurred at all topographic positions, but most prevalent on the upper slopes, and mid-to-lower slopes, and occasionally on crests. Imperfectly draining soils that were encountered included the Altimeg Series. Altimeg Series soils, which are derived from the weathering of their greywacke and mudstone parent materials, were exclusively found upon flats and open depressions in the landscape. The Littleshalloch Series, poorly draining soils of the Ettrick Association (WRB Gleysol) were found in the open depression areas of the landscape. Anthropic alteration of soils was also observed during our investigations, notably from cultivation and draining of the landscape. Such alterations were highlighted in the open depression areas of the landscape where the Littleshalloch Series would generally be observed, but had clearly been drained and put under cultivation. Of the soils investigated, less than 5% of the soils were classified as this anthropic variant of the Littleshalloch Series.

In some situations, soils were classified as being derived from glacial till as evidenced by the roundedness of stones within the soils (Fig. 4D).

Table 1
Statistical moments of the rigs as derived from the GIS and spatial point analysis.

	Length (m)	Width (m)	Orientation (° clockwise from N)	Perimeter (m)	Area (km^2)
Minimum	9	3		23	3×10^{-5}
1st quartile	39	15	42	95	5×10^{-4}
Median	64	22	52	150	1×10^{-3}
Mean	80	26	55	180	2×10^{-3}
3rd quartile	101	32	63	229	2.4×10^{-3}
Maximum	608	153		1284	4.5×10^{-2}

Subsequently 6% of the soils were classified as Kedslie Series, which are an imperfectly draining stagnosol. Freely draining soils of glacial till origin were also encountered, and appear to be a variant of the Linhope Series. These brown earth soils amounted to 28% of the soils classified in this study, and were found mainly on the lower slopes but also occurred on occasion on the crest and mid-slope positions.

In this soilscape, small pockets of organic soils were also encountered. These soils are found on gentle slopes of the rigs that have extensive established gorse (*U. europaeus*). The leaf litter from these plants makes up the soil fabric which is held together by the roots. The gorse must be mature, and on a suitable slope. If the slope is too steep it would be eroded, if too gentle then it probably would have been removed to increase productive grazing.

3.2.2. Soil pattern of the Glasserton Rigs: digital soil mapping

The target variables for digital soil mapping were the previously described and observed soil series (and variants): Altimeg, Kedslie, Linhope, Linhope-variant, Littleshalloch, Littleshalloch-variant, skeletal Ettrick soils, and organic soils. Fig. 6a displays the spatial pattern of the soil complexes as mapped by Bown and Heslop (1979). Fig. 6b displays the complex pattern of soil series within these complexes which was created from the combination of delineating the rocky outcrop features, and digital soil mapping, which was based on soil observations made in the field. The covariates used in the spatial prediction model were: derived from the digital elevation model — elevation, flow direction, catchment area, profile curvature, multi-resolution ridge top flatness and multi-resolution valley bottom flatness (Gallant and Dowling, 2003), morphometric

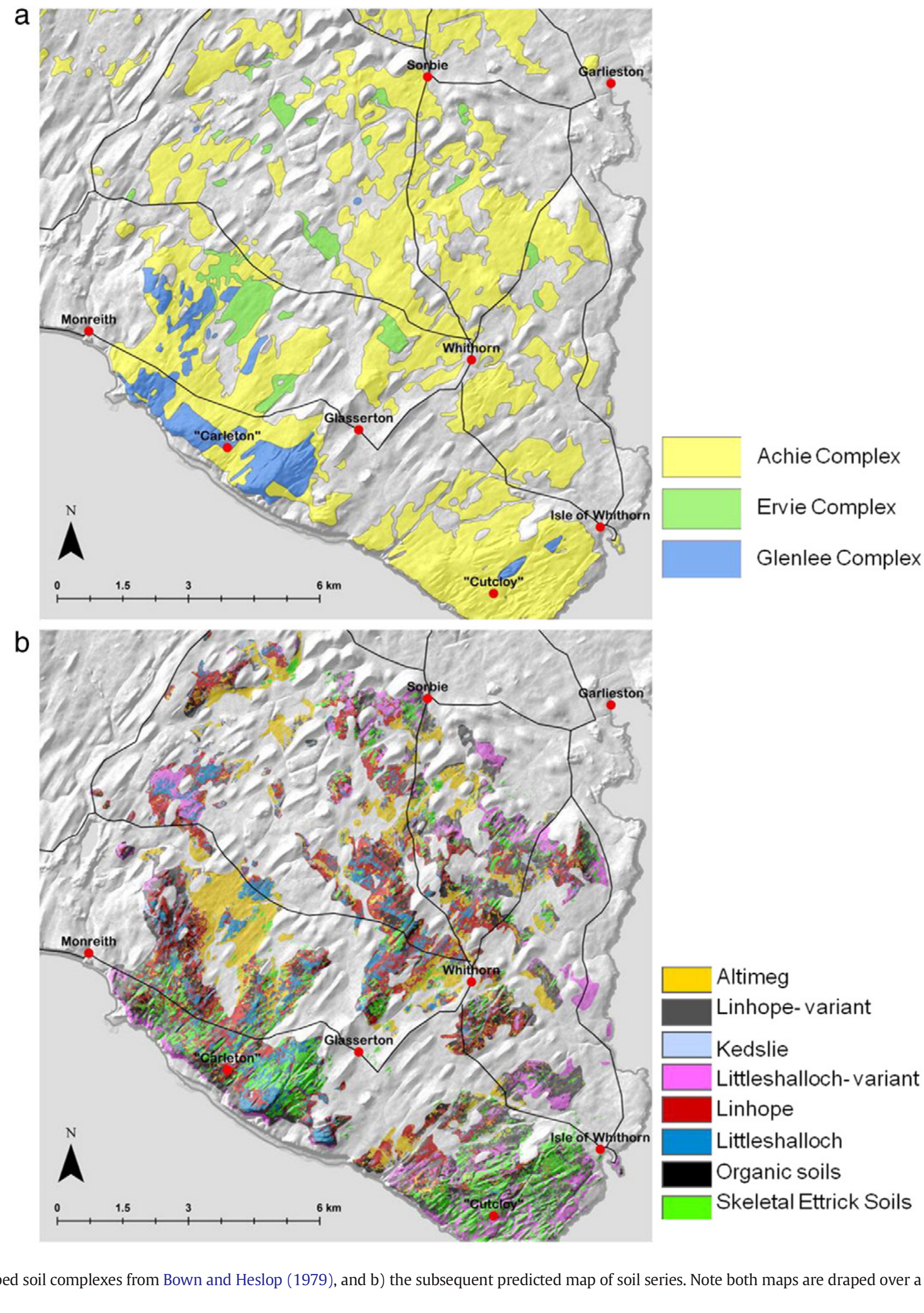

Fig. 6. a) Mapped soil complexes from Bown and Heslop (1979), and b) the subsequent predicted map of soil series. Note both maps are draped over a hillshaded DEM.

protection index and openness (Yokoyama et al., 2002), and the red and green bands from the aerial imagery. The overall accuracy of the model was 64% with a Kappa statistic of 0.51. However the generalisation ability of the model as assessed using LOCV showed an overall accuracy of 25% with Kappa statistic of 0.03.

Undoubtedly the soil pattern within this Glasserton Rig soilscape is extremely complex. This was an observation from the field and reflected in our soil classification. With such complexity it is difficult to disentangle a clear relationship between soils and topography, where despite the soil variability, the terrain is relatively flat. Distinguishing between soils derived from in situ weathered greywacke and glacial till may also be a limitation of the model too. Some association with land use and soil series was observed — for example the anthropic variant of the Littleshalloch Series — yet the best spatial information available to differentiate the different land use or type was limited to the RG bands of the aerial imagery.

Despite some limitations regarding the accuracy of the modelling, the resultant map of soil series displays some intriguing soil and landscape relationships which will need to be further verified in future studies. Other than the organic soils (although there are some exceptions), the mosaic of soils as depicted on the map show that no one soil series is intimately associated with the linear ridge features that are a prominent feature of this landscape. The soil series of the Ettrick association are also not exclusively situated towards a particular region within the study area. Of note however, is the occurrence of Altimeg soils in more open parts of this landscape, with an example being the relatively large area of these soils to the east of Monreith. The Altimeg soils do not tend to be within close proximity to the rocky outcrop features, but do occur when the rock outcrops are of lesser intensity such as to the north-west of Whithorn. While the anthropic variant of the Littleshalloch Soil Series occurs in association with the ridge features, particularly to the southern end of the peninsula, it is notable that they also occur prominently in the more open areas of the landscape which may be a reflection of land use type in those areas. More generally, 14% the rig landscape is estimated to be the rocky ridges with skeletal soils. 17% of the other soils mapped in this landscape are Altimeg Series, 18% Linhope Series, 19% variant Linhope Series, 4% Kedslie Series, 10% Littleshalloch Series, 11% anthropic variant of the Littleshalloch Series, and 7% organic soils. The organic soils are diffusely distributed throughout the study area.

The mapped soils, particularly where the ridges are of high density, appear to show an association between soil series and geology (despite it not being used explicitly in the modelling). Soil series on the southern tip of the peninsula amongst the skeletal soils of the Ettrick association are frequently either the variants of the Linhope and Littleshalloch Soil Series. The coarse depiction of geological formations as shown in Fig. 7a

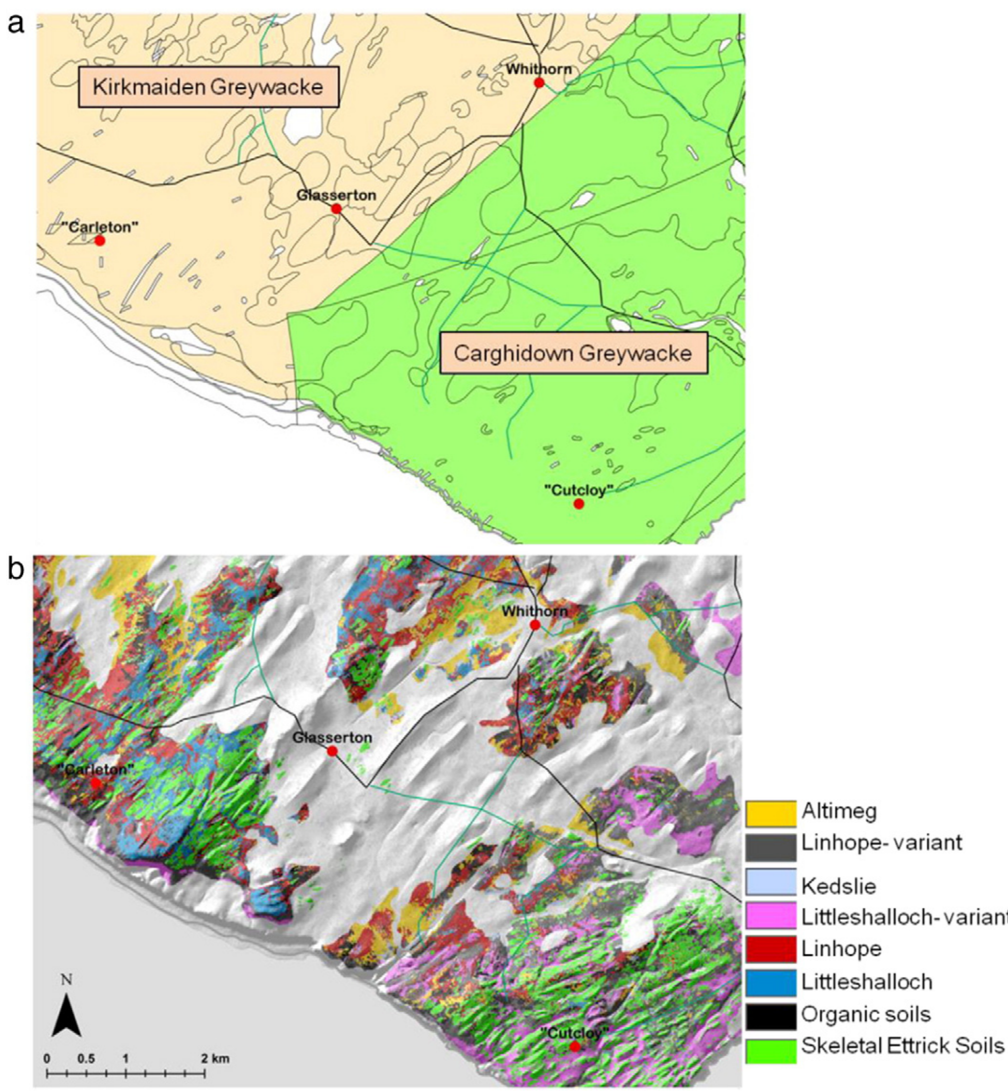

Fig. 7. Maps are centred on the southern and south-western area of the Machars Peninsula. Map a) displays the dominant geological formations, while map b) displays the pattern of predicted soil series. Geology mapping courtesy of British Geological Survey.

indicates the parent materials in this specific area to be Carghidown greywacke (Barnes, 2008). To the north-west of the southern tip, a different pattern of soils occurs upon the rigs amongst the skeletal soils. Here the Littleshalloch, Linhope, and Linhope-variant Soil Series have a close spatial association with each other. The geology in this area is predominantly the older Kirkmaiden greywacke. While differences in the geology (based on the mapping from Barnes (2008)) are a possible explanation for differences in the predicted soil patterns. The inclusion of gamma radiometric mapping in future studies may be beneficial — or at least provide an explicit opportunity to investigate the phenomenon — to spatial modelling in this landscape, as such data is directly related to the mineralogy and geochemistry of the parent material *and* its degree of weathering (Dickson and Scott, 1997). Distinguishing the geochemical differences between soils, together with distinguishing whether the soils are formed in situ from greywacke or from glacial till (from greywacke) will be invaluable additions to future spatial modelling exercises in this complex soil landscape.

3.3. Summary of the Glasserton Rig soil landscape

The images in Fig. 8 are conceptual illustrations of the Glasserton Rig soil landscape or soilscape. The rigs consist of a dense pattern — where their intensity can be over 200 features per square kilometre — of elongated rocky ridges of vertically dipping Silurian greywacke. These are on average, 80 m long, 26 m wide, and up to 5 m higher than the local landscape, with high profile curvature, running in a common SW–NE direction (Fig. 8B). The ridges are mantled by a thin skeletal soil (Fig. 8A1) (Leptosols). Between the ridges soils are commonly Cambisols and Gleysols derived predominantly from residual and colluvial greywacke. Although in some areas there is some glacial till derived from these same parent materials. The areal percentage of the Glasserton Rig landscape that is ridges is approximately 14% of total extent of this landscape.

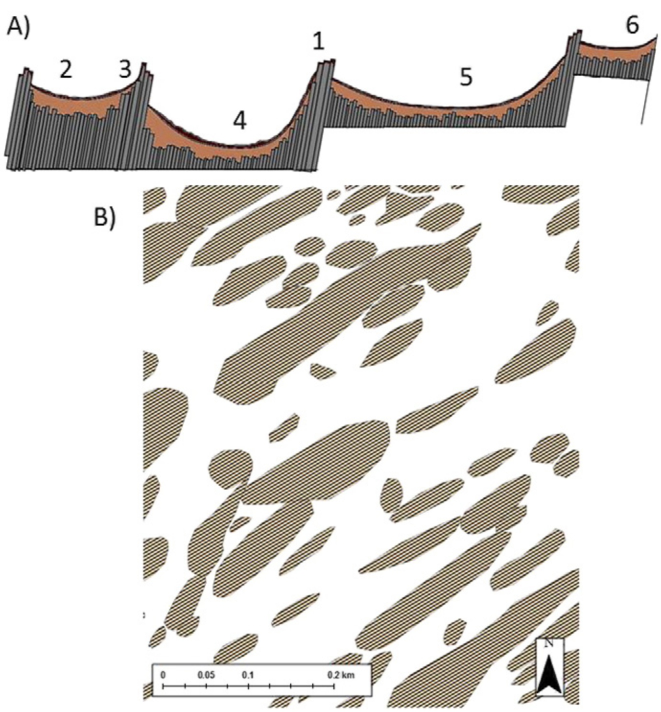

Fig. 8. A) Conceptual landscape cross-section illustration of the Glasserton Rigs with vertical exaggeration. A1) Relatively flat landscape incised by vertically dipping rocky ridges mantled with a thin cover of soil. Exposed rock is sometimes evident, particularly to the sides of the ridges. A2) Given the close proximity of the ridges, and assuming soil is freely drained, this would commonly be a Linhope Soil Series. A3) Where slope is not too steep and if vegetation is dense, peat-like soils would occur here. A4) Considering this position in the landscape, the poorly drained Littleshalloch Soil Series would occur here. Otherwise, if alteration of the drainage regime had occurred, then anthropic variant of the Littleshalloch Soil Series would be likely. A5) The imperfectly drained Altimeg Soil Series is generally associated with more open and flatter areas of soil cover. A6) Some soils in the Glasserton Rig soilscape are derived from glacial till. Here the Kedslie Soil Series might occur if this area is imperfectly draining. B) The spatial arrangement of the Glasserton Rigs consists of a dense pattern of elongated rocky ridges. These are on average, 80 m long, 26 m wide, and 5 m higher than the local landscape, with high profile curvature, running in a common SW–NE direction.

There is a possibility that there might be an area of Glasserton Rigs in the Stewartry of Kirkcudbright, in or around the Parishes of Kirkmabreck and Anwoth, centred on the village of Borgue (54°49′42″N, 4°08′02″W). These are to the north-east across the Bay of Wigtown and lie on the same geological formations and have a similar orientation as for those situated on the Machars Peninsula. Unpublished field sheets supplied by the James Hutton Institute show large tracts of the Achie complex in this area. Additionally, using aerial imagery, a distinguishing characteristic may be the spatial intensity of the rig features is significantly greater on the Machars Peninsula than in the Stewartry of Kirkcudbright. Future studies are required to investigate the soilscape similarities and contrasts between both areas in more detail.

4. Concluding remarks

This study has described the physical characteristics of what is believed to be an endemic soil landscape: the Glasserton Rigs — with its complex mosaic of soils imprinted upon and surrounded by an extensive arrangement of thin elongated rocky ridges. The soils and geology in this landscape are common. Yet the soils that do occur here are distributed in a unique pattern largely determined by the micro-topography of the landscape.

Nevertheless, this landscape is an area which is under continual change by way of anthropogenic forcings. For example, many of the more open areas between the rigs have been drained in order to increase the amount of land that is available for productive agriculture. Mostly they are drained using either hand constructed subterranean channels formed by slated greywacke or modern perforated polyethylene pipes (Barnes, 2008). This drainage significantly changes the nature of pedogenesis and subsequently the properties of the soil, a case in example being the anthropic variant of the Littleshalloch Soil Series. Besides the continual draining of the landscape since the 1780s, a significantly less subtle change upon the Glasserton Rig landscape is the removal and levelling of the smaller ridges with large cultivation equipment in the 1970s to 1990s. Now, more recently and significantly, with the intensification of agriculture, particularly for dairying, and the need to run larger grass-cutting and harvesting machines, the removal of the larger ridges (with their radii of curvature being too small for the grass-cutting machines and forage harvesters), has resulted in the flattening of the landscape and soil mixing with heavy earth moving machinery, as can be observed in Fig. 9. This practice has essentially brought once marginal land into viable agricultural production throughout many areas of the Machars Peninsula. This is a classic example of what Hyams (1952) termed 'Man as a Soil Maker'.

Bringing previously undisturbed soils or soils within marginal lands into some sort of production is obviously not an uncommon phenomenon world-wide. However, as world-wide pressure on soils is likely to increase over time, management of them for posterity will become of greater importance. It is estimated that the extent of the Glasserton Rig landscape is only about 25 km^2 (based upon spatial intensity of the rigs being greater than 50 features per km^2). While the soils that are found upon and the around the rigs are not rare or unique (Ditzler, 2003), we believe this soilscape to be both rare and unique, and parts of this landscape should be recognised and protected (Drohan and Farnham, 2006). This soil-landscape is quite localised and limited in extent and by definition — endemic. The recognition that the Glasserton Rigs are an endemic soil-landscape emphasises that not only should the soils be valued for their potential for agricultural production, but also valued for their high cultural significance.

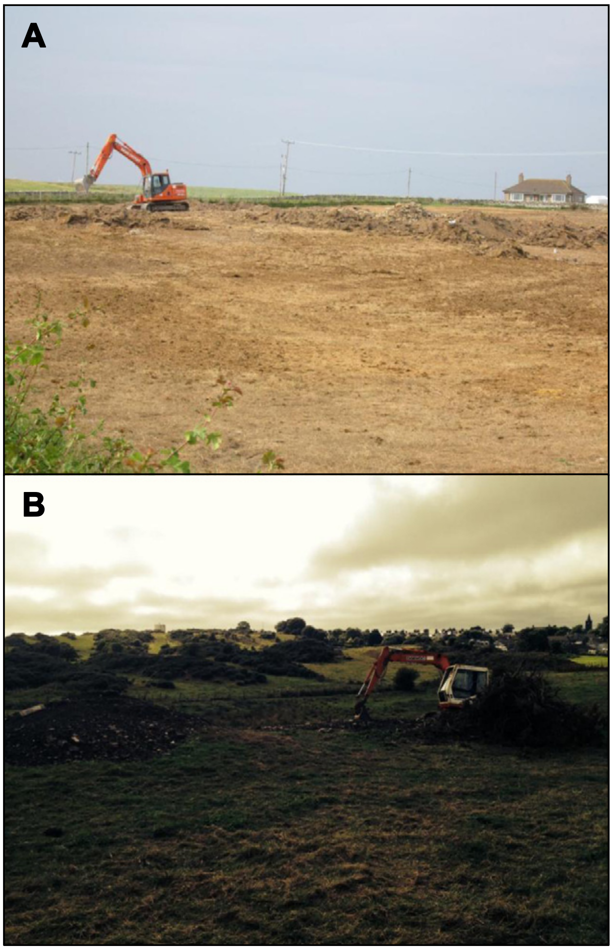

Fig. 9. Man as soil maker: a landscape under change. A) Heavy earthmoving machinery removing the rocky ridges of the Glasserton Rigs and subsequent levelling of the land for agricultural, largely pasture, production. B) Removal of rig features with excavator in foreground with good examples of rig features on display in the background.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geodrs.2014.10.002. These data include Google maps of the most important areas described in this article.

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control 19 (6), 716–723.

Baddeley, A., Turner, R., 2005. Spatstat: an R package for analyzing spatial point patterns. J. Stat. Softw. 12 (6), 1–42.

Ballantyne, C.K., Rinterknecht, V., Gheorghiu, D.M., 2013. Deglaciation chronology of the Galloway Hills Ice Centre, southwest Scotland. J. Quat. Sci. 28 (4), 412–420.

Barnes, R.P., 2008. Geology of the Whithorn, Kirkcowan and Wigtown District. Memoir of the British Geological Survey. British Geological Survey, Keyworth, Nottingham.

Bockheim, J.G., 2005. Soil endemism and its relation to soil formation theory. Geoderma 129 (3–4), 109–124.

Bown, C.J., Heslop, R.E.F., 1979. The Soils of the Country Round Stranraer and Wigtown. Macaulay Institute for Soil Research, Aberdeen, Scotland.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. Science 325 (5941), 710–714.

Collins, J.E., 2013. Fine scale soil mapping using glacial landforms: a field study in the Machars Peninsula, Scotland(Honours Thesis) The University of Sydney, Australia.

Dickson, B.L., Scott, K.M., 1997. Interpretation of aerial gamma-ray surveys: adding the geochemical factors. AGSO J. Aust. Geol. Geophys. 17 (2), 187–200.

Diggle, P.J., 2003. Statistical Analysis of Point Patterns, 2nd ed. Hodder Education Publishers, London.

Ditzler, C., 2003. Endangered soils. National Cooperative Soil Survey Newsletter No. 25, November, pp. 1–2.

Drohan, P.J., Farnham, T.J., 2006. Protecting life's foundation. Soil Sci. Soc. Am. J. 70, 2086–2096.

Evans, D.J.A., Clark, C.D., Mitchell, W.A., 2005. The last British Ice Sheet: a review of the evidence utilised in the compilation of the Glacial Map of Britain. Earth Sci. Rev. 70 (3–4), 253–312.

Fridland, V.M., 1974. Structure of the soil mantle. Geoderma 12 (1–2), 35–41.

Gallant, J.C., Dowling, T.I., 2003. A multiresolution index of valley bottom flatness for mapping depositional areas. Water Resour. Res. 39 (12), 1347.

Geikie, A., 1882. Textbook of Geology. Macmillan, London.

Hole, F.D., 1978. An approach to landscape analysis with emphasis on soils. Geoderma 21 (1), 1–23.

Hyams, E., 1952. Soil and Civilisation. Thames and Hudson, London.

IUSS Working Group WRB, 2007. World reference base for soil resources 2006. First update 2007. World Soil Resources Report 103. FAO, Rome.

Kempen, B., Brus, D.J., Heuvelink, G.B.M., Stoorvogel, J.J., 2009. Updating the 1:50,000 Dutch soil map using legacy soil data: a multinomial logistic regression approach. Geoderma 151 (3–4), 311–326.

Lindström, E., 1988. Are roches moutonnées mainly preglacial forms. Geogr. Ann. 70 (4), 323–331.

McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping. Geoderma 117 (1–2), 3–52.

R. Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Salt, K.E., Evans, D.J.A., 2004. Superimposed subglacially streamlined landforms of southwest Scotland. Scott. Geogr. J. 120 (1–2), 133–147.

Soil Survey of Scotland Staff, 1984. Organisation and methods of the 1:250,000 soil survey of Scotland. Handbook 8. The Macaulay Institute for Soil Research, Aberdeen.

Yokoyama, R., Shirasawa, M., Pike, R.J., 2002. Visualizing topography by openness: a new application of image processing to digital elevation models. Photogramm. Eng. Remote Sens. 68 (3), 257–265.