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Improved sustainability and ecosystem services from seaweed additions to an old agricultural production system

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Abstract

Throughout the UK, and in other areas of the northern hemisphere, where there has been human settlement from the 17th century onwards, evidence of parallel ridges can still be seen today. These ridges, sometimes called lazy beds, are a remnant of a production system that offered small, often remote communities cropping potential on land that would be considered today as less favourable or unsuitable for production. With a move away from this type of small-scale, labour-intensive production system, over the last century, communities in these areas have generally undergone a shift from self-sustainability to a reliance on the importation of human and animal feed. This has led to abandonment of these cultivation systems. As modern communities become increasingly dis-associated from historic cultural practices, living memory of the management of these systems is also now being lost.

There is an argument in support of restoration of these historic systems, in light of rising global pressures for both sustainable food security and land availability for agricultural production. Such restoration should be underpinned by, scientific understanding as to how these methods were able to provide a sustainable system for cropping and yield over time, and the environmental impacts of these systems.

A project has been established on the island of Grimsay (North Uist) to reinstate a series of abandoned ridges, which have not been worked in over 50 years. As part of this project a series of studies have been initiated to examine the historic management practices (and their impacts) associated with these agricultural systems. A pilot study was run to determine if the traditional use of seaweed (particularly *Ascophyllum nodosum*) was of benefit, or indeed essential, to the longevity of these rotational systems. This trial was placed within the wider context of an experiment investigating the ecosystem impacts of reinstating this type of agricultural practice and its utilisation of local, natural resources.

The findings of the pilot study indicated that historical knowledge is essential in reinstating this type of production, seaweed is both a required and sustainable addition to the system, ecosystem impacts were minimal and that production was both viable and greatly increased when labour was available.

Key words: *Ascophyllum nodosum*, *Avena sativa*, Hebrides, Uist, ridges, lazybeds

Introduction

Agriculture was introduced into Scotland sometime near the fifth millennium BC [1] and has since evolved through many different methods of seedbed preparation. Types of tillage used include ridge and furrow, rig and furrow, cord-rigs, and lazy beds. These different forms of cultivation all share similar characteristics, with some evolving from others.

The Island of North Uist in the Outer Hebrides is the 10th largest of these West coast Scottish Islands. It is a member of the Uists and Barra island group that also includes Benbecula and South Uist. North Uist has a population of 1,254 people [2], however, this is roughly a fifth of the population that occupied this area prior to the highland clearances of the 18th and 19th Century [3]. Combined with the clearances, one of the greatest causes of decline in the island population was the failure of the *Laminariales* (kelp) farming industry, which collapsed in the late 1800s. In common with large parts of the Scottish highlands many inhabitants of these small, remote communities sustained themselves and their families through the practice of crofting. A ‘croft’ is a traditional, small-scale landholding found in the counties of the north of Scotland and its islands. The crofters operated a subsistence form of agricultural production which could be locally highly productive. However, increasing populations and croft rents meant that these families could not rely solely upon crofting to survive so, with the collapse of the kelp industry, one of the only paid industries upon the island, many were forced to emigrate, in particular to Nova Scotia and Newfoundland [4, 5] where evidence of ridge system agriculture can also be seen.

Rotational ridge bed systems, often referred to as lazy beds, were a common form of agricultural practice throughout the Western Isles and other parts of mainland Scotland. With a long history of usage, evidence of them is still apparent within the landscape today (Figure 1)[6]. A ridge is basically a seedbed that has been created by turning over the soil from both sides of a strip of land onto itself, creating an elevated ridge with channels on either side [7]. Ridges can be differentiated from other forms of tillage by the fact that they are dug with hand tools rather than ploughs. The reliance on hand tools, such as the spade, *cas chrom* (a type of foot plough fixed with a piece of iron that acts as a tine) and ristle (this is a sickle plough with one tine or a scarifier) [8] to establish the ridge system meant it was labour-intensive (Figure 2). However, ridging improves soil drainage, can increase depth and increases surface capture of sunlight, thus improving ridge temperature [6]. In the Outer Hebrides a few ridge systems are still in use, but the system is now predominantly utilised for *Solanum tuberosum* (potato) production and the rotational aspect of their use has been largely lost.

The east coast of the Western Isles is dominated by a landscape of rocky outcrops interspersed with relatively small patches of thin, black moss soils to which the term Blackland has recently been applied (derived from the Gaelic *talamh dhubh*). These soils are an organic peaty type that, when left uncultivated, are dominated by *Nardus stricta*, *Molinia caerulea*, with more *Anthoxanthum odoratum* and *Agrostis tenuis* grasses on historical pastures, the sedges *Scirpus cespitosus* and *Eriophorum angustifolium*, heathers *Calluna vulgaris* and *Erica tetralix*, and *Sphagnum* spp, and *Pleurozium schreberii* mosses. The soil is often at least 50 cm deep and has a low pH value (in the range of 4-5) (*ibid*). A full description and definition of the soil is currently under investigation driven by the fact that the Blackland soil has had so many different influences in its creation; from the physical environment on which they lie, to the long-term anthropogenic impact from the addition of organic fertiliser and tillage. Whereas communities established on the western seaboard of these islands had access to the machair plains for cultivation and grazing, those communities established along the east coast had to rely on their ability to cultivate the small patches of Blackland to provide food for themselves and their livestock. Vegetation, soil depth and soil 'wetness forms the basis of a 'Blackland Index' that was developed in conjunction with these studies and can be used by crofters to assess the suitability of land for cultivation without resorting to soil samples and costly analyses.

Potatoes were introduced to the Uists and Benbecula from Ireland by the MacDonalds of Clanranald in 1743, at a time when the populations of the islands were expanding. This resulted in the rapid inclusion of potatoes into existing rotations and an increased reliance on the crop as a food source for both humans and animal consumption. The result was that by the early 1800's the rotation practices on the ridges were based on cropping from potatoes, *Hordeum vulgare* (barley), *Avena sativa* (oats), and *Secale cereal*(rye) with some *Linum usitatissimum* (flax) or *Cannabis* (hemp), and *Brassica rapa* (turnips) followed by a ley period when grass was sown to establish a few years of pasture and to rebuild fertility. Rotations adapted for local conditions and soil quality were adapted, but *Brassica oleracea* (cabbages), *Daucus carota* (carrots), *Brassica napobrassica* (rutabaga), and other pulse and green crops were generally confined to gardens or heavily improved in-bye land. One such rotation on the black, moss soils was described in 1811 as comprising potatoes with manure, to barley, then to oats for two to three years finally undersown with grass seeds for hay then as pasture for young stock in a second and third year [8]. This system was repeated with the pasture phase often extended up to 6 years to rebuild fertility. An earlier description of the rotation was of land manured and turned in the winter, then left fallow until late spring when either barley or potatoes were planted. These would have been followed by two to three seasons of oats after which time the ridge was laid to grass for three to four seasons [9]. The production of grass was the main objective of these cropping activities as it was needed as a food store for the cattle over winter and to improve their summer pasture.

The manure referred to in these accounts was largely derived from seaweed with animal waste added when available. Various accounts of the practices associated with addition of manure have been recorded historically [8-11] and are maintained in existing memory, although rarely practised, to this day. The basic premise of most of these is that seaweeds were collected by cutting at low water during spring tides, with manual movement of the seaweed to above the high water mark. It was then carried to the croft and applied thickly to the surface before cutting a furrow, the soil from which was lifted and laid over the manure to form a new ridge. From casual discussion with current crofting practitioners it would appear that that methods and timings associated with harvesting and application of seaweed might vary from one locality to another or indeed from one crofter to another. Regardless of precise method and timing, historical written and oral accounts indicate that seaweed fertilizer was an important part of the cultivation process and was commonly used throughout the Western Isles[10].

The islands of the Uists are particularly well endowed with an abundance of seaweed. It is estimated that 70 per cent of the total littoral seaweed of Scotland is located in the Outer Hebrides with the most prolific growth being in North Uist. Over 30 per cent of all Scotland's seaweed grows in Lochmaddy and Locheuphiort alone [12]. Two main types of seaweed are found in bays throughout the eastern Uists: Knotted or egg wrack (*Ascophyllum nodosum*) and

Bladder wrack (*Fuscus vesiculosus*). *A. nodosum* is the more abundant of the two and is typically found lower down the shoreline, closer to the water's edge and is the seaweed that was traditionally utilised in these areas for manuring the land. Bladder wrack (*Fucus vesiculosus*) is less common and is typically found higher up on the shore [13].

This paper records a project that was designed to: [a] determine if the production systems described in historical records were viable; [b] assess if they could be re-implemented and [c] to ascertain any associated environmental considerations. The project was established in the present day setting of a reduction in the level of self-sufficiency experienced by the islanders over the past 50 years and the continued pressure from increased fuel, fertiliser and food prices.

Materials and methods

Trial Site

The island of Grimsay lies between the main island of North Uist (to the north) and Benbecula (to the south) and is just over 8 square kilometres (800 ha.) in area. The mean wind speed for the Uists averages 29 km/h (Macaulay Institute for Soil Research, 1982), and the annual rainfall is 130 cm falling on 240 days (east of Scotland: 18 km/h; 87 cm; 170 days). The croft at Kenary is situated on the East cost of the island at 57° 29.100' N, 7° 14.103' W and covers 15.5 ha of which the dominant soil type is Blackland. There is evidence of both historic cultivation on 2.4 ha and ridge formation on 0.6 ha of the croft. The trial site was located on an area of the croft with a southerly aspect and slope of ~11^{o} where there was visible evidence of four ridges running down the slope.

Experimental Design

Three of these ridges were re-dug to a length of 18 m with a cropping width of 0.8 m, the fourth was left intact as a control to compare changes in soil physical and chemical conditions caused by disturbing the ridges (Figure 2). Due to the limited size of the field this aspect was not replicated. A split plot design was established on the dug ridges with the three seaweed manure treatments and an unmanured control as the main plots. Within this, planting with common/white oat (*Avena sativa*), Shetland cabbage (*Brassica oleracea*) and potato (*Solanum tuberosum* Var. Record) was used to establish subplots (Figure 1).

Seaweed Manures

Three seaweed treatments were prepared. Fresh seaweed, *Ascophyllum nodosum*, was collected on the 6 May 2013 from the shoreline adjacent to the croft. The seaweed was harvested at low tide by cutting and then leaving 20 cm attached to the rock to encourage regrowth. Seaweed was removed from the shoreline, washed with potable water, and then applied by hand to plots to provide a surface coverage of ~5 cm depth. Seaweed mass was determined within six 0.25 m^2 quadrats placed across the ridge and was 15.5 kg/m^2.

Rotted seaweed manure was established from a mid-February shore collection of fresh storm wash consisting mainly of *A. nodosum*, but with some bladder wrack (*Fucus vesiculosus*) and toothed wrack (*F. serratus*). It was gathered into a heap above the high water mark, covered with a tarpaulin and left for approximately 3 months until required in May. The resulting rotted amendment was applied by the same method as the fresh, based on advice and instruction from local crofters, to establish a 5 cm deep layer, but rate of application was assessed to be 23.6 kg/m^2.

A seaweed liquor was prepared in two tubs, one filled with fresh *A. nodosum* and the other with slightly rotten weed recovered from the shore. The tubs were raised slightly to enable buckets to fit under the waste outlet. The tubs remained outdoors, exposed to the elements for 2 months and as leachate collected it was collected and mixed together into a single 120 litre lidded bin. Immediately prior to planting the collected liquor was recovered and applied as a drench to the ridge surface with a watering can at a rate of ~2.5 l/m.

Soil, Seaweed and Crop Measurements

Soil samples were taken from approximately 5 to 15 cm from the surface for both the turned and control ridges of the trial site prior to planting (6 May), mid points (15 June and 19 July) and at harvesting (14 September) and returned to SRUC for analysis of Nitrate/Nitrite and Ammonium from KCl extracts using auto analysis [14, 15] and for available phosphorous from Morgans extraction followed by spectroscopic analysis with ammonium molybdate and ascorbic acid colour development [16]. Soil temperature was measured using a HI 145 digital thermometer (Hanna) with a 10 cm probe. Soil moisture was calculated gravimetrically from a homogenised sample of the collected soils as the difference between wet sampled and after oven drying at 105^{o}C for 24 hours and expressed as a percentage moisture of the oven dried soil.

Seaweed samples from the manuring treatments were analysed at SRUC, SAC Consulting's Analytical Services Department and the School of Geosciences. Total mineral content (with a focus on N, S and P) analysis involved oven drying seaweeds at 105^{o}C, grinding and acid digestion of the samples prior to ICP-OES (Optical Emission Spectroscopy) analysis [17].

Crop emergence and plant height data were recorded over the season. At harvest (14 September 2013), the total above ground oat biomass, height and width of individual cabbage plants and potato tuber yields (total and edible) were weighed and recorded for each plot and treatment. The harvested potatoes were subjected to grading by the trial team into those suitable and unsuitable for human consumption. The unsuitable potatoes were considered as discards, although would be used for animal fodder.

Seaweed abundance

The abundance of available seaweed on the east coast of the Uists was measured from nine collection points (Figure 2); two at Loch Portain, two at Loch Euphort (both North Uist), two on Grimsay, two at Petersport on Benbecula and one at Loch Skiport (South Uist). Site selection was determined from ease of access and evidence of historic crofting activity, based on existing local knowledge and the existence of ridges in the surrounding landscape. All sites were visited within 2 hours of low tide and at each site ten 1 m^2 quadrats were randomly placed within the littoral zone from which cut seaweed fresh weight, species prevalence and abundance were recorded.

A separate survey was conducted, only on Grimsay, which focused on seven bays around the island. The sites were chosen using similar criteria to the wider survey. Sites were again visited around low tide and triplicate measures from a 0.25 m^2 quadrat used to establish relative abundance, age and biomass of seaweeds to determine the potential sustainability of long-term use of seaweed fertilisers by the crofts.

Carbon losses, assimilation and stability

To assess the impact of soil disturbance and cultivation on the processes involved in carbon loss and sequestration from the black land soil a static chamber portable infra-red gas analyser (IRGA, PP Systems EGM4 with SRC1 chamber) was used to determine ground level CO_2 concentrations and exchange (assimilation) after initial cultivation of the ground, mid-season and at harvest. In addition, assessment was made at the end of the season of the carbon content of the soils through loss on ignition at 550^{o}C [18] (Carbolite AAF11) to determine if there had been significant loss of carbon from the system.

Statistical analysis

Statistical analysis was performed using GenStat (VSN International Ltd.) and Excel (Microsoft). ANOVA was used to test for differences in data, using the split-plot design with the ridge set as the block, manure treatment as the whole plot and crop as the subplot. The Anderson-Darling test was used to determine if the data was normally distributed. In the case that the data set differed significantly from a normal distribution a transformation was applied to satisfy the assumptions of the model. Data was considered significant at $p \leq 0.05$.

Results

Laboratory analysis of the seaweeds used in establishing the ridges indicated that they were low in N and P, but high in sulphur (Table 1) compared to other manures [19]. Analysis of the seaweed liquor suggested that leaching from rotted seaweed produced more Ca, S, Mg and Na than initially available from the fresh weed as it decomposed, but was similar in K and B (Table 2). The resultant composite bin liquor provided N and P at 44 mg/l and 41 mg/l, respectively, with no nitrate/nitrite N detected.

Soil nutritional analysis indicated that there was no (0.00 µg/ml) nitrate/nitrite N detectable in the soil upon establishment and that at harvest none was detectable in 31 of the 36 treatment plots. Assessment of pre-planting and post-harvest means for nitrate/nitrite were 0.00 and 15.21 µg/g with no treatment effects evident. Ammonia levels were not significantly different among manure treatments or crops at harvest ($P = 0.72$ and 0.97, respectively. Table 3). Finally, at the end of the study it was found that PO_4 was significantly different among manure treatments ($P = 0.02$, Table 3), but not between crops ($P = 0.25$). Average PO_4 concentrations for the control, liquor, and fresh seaweed manure treatments were 59, 54 and 41 µg/g, respectively, compared with an average P in the rotted treatments of 210 µg/g.

Soil moisture was above 100% throughout the study, due to the peat content of the soils, but did not significantly differ among manure treatments or crops. At harvest mean gravimetric soil water content of the control, fresh, liquor and rotted treatments were 292, 399, 365 and 589%, respectively. For the crops, cabbage, oat and potato means of 403, 452 and 262% were calculated respectively, against 452% in the undisturbed ridge.

At planting soil temperature was higher on the ridges (10.3^{o}C, based on 5 subsamples), than in the dugout ditches (9.5^{o}C) or on the undug ridge (9.1^{o}C) within the field site. However, temperature assessments taken during and at the end of the season did not differ among seaweed manure and crop treatments.

At establishment of the treatment plots the soil pH was recorded as 4.6. There was little change in the pH of the soil over the course of the experiment, the exception being a significant rise in pH observed under oats on the rotted seaweed manure treatment at the end of the experiment where the pH increased to 6.3 (Table 4).

Plant establishment was good across all but one plot (a liquid application to potatoes) and there was visual evidence of a growth response to the rotted manure at both 38 and 72 days post planting in all the crops. Harvest indicated that there was an evident treatment effect from the inclusion of seaweed, but that application of the rotted material had the greatest effect (Table 5). The use of fresh seaweed in the manuring of potatoes resulted in the highest percentage of discards at 33%, compared to 5, 18 and 23% discards for rotted, liquor and control treatments, respectively. Cabbages were assessed for height and diameter as the crop was being grown beyond the time-scale of the trials (as winter cattle fodder), but the rotted seaweed treatment produced cabbages that averaged more than twice the height and three times the diameter of the other treatments.

IRGA data indicated that initial digging of the ridges reduced CO_2 exchange from the soil from a mean of 7.3 gCO_2/m^2/hour to 0.6 gCO_2/m^2/hour. This situation was less evident through the season, but at harvest assimilation was repeated with the undisturbed ridge averaging 7.4 gCO2/m^2/hour compared to the cultivated ridges which averaged 0.6 gCO_2/m^2/hour, with no difference between the manuring treatments or crops types. Despite this difference in CO_2 exchange rates, ground level atmospheric CO_2 levels were not different between either seaweed treatments or crops (P = 0.71 and 0.34, respectively, overall mean of 453 ppm, stdev 42) and was similar to the undisturbed ridge (475 ppm).

Loss on ignition determination of carbon in the soils indicated that the soil was of a high carbon content (average of 86%, min 71% and max 97%), but that over the course of the cropping cycle the levels of C had not been significantly ($P = 0.18$) altered by any treatment or crop.

Assessment of the seaweed around the Isles of North Uist from the nine investigated areas returned an average of 11.3 kg seaweed/m^2 of foreshore, of which, average *A. nodosum* coverage was 70%, occupying a total area of ~19040 m^2. This produced an estimated 135 tonnes of available *A. nodosum* across the assessed sites. However, of note was the second site at Loch Portain, which lacked *A. nodosum* and was instead dominated by *Fucus vesiculosus* and *F. spiralis*. This bay was more exposed than the other sites, had fewer large rocks present and it was recorded that there were more freshwater streams flowing into the bay, but it was also noted that there were historic ridges evident less than 200 m from the shoreline.

Assessment of *A. nodosum* coverage of just the selected seven bays around Grimsay was estimated at 23700 m^2. Mean frond length was 35 cm and ranged from 28 to 44 cm. Approximate mean age, based on the number of bladders, was just over 6 years. Abundance varied between 11.2 and 20.8 kg/m^2 with a mean abundance over the entire area of 14.3 kg/m^2, compared to an average for Grimsay in the wider survey of 10.4 kg/m^2, and an approximated total available weight of 338 tonnes.

Discussion

In establishing the experimental platform a great emphasis was placed upon both the historical record and existing oral tradition. The results from the field trial implied that the production systems described in historical records were viable, but heavily reliant on application of seaweed as a fertility building manure or, as is more likely given the low nutritional value of the added manure, a soil structural development medium [13].

In this study the seaweed treatments were rotted, fresh and a liquor derived from rain washed seaweed as it degraded. The fresh seaweed was collected and incorporated into the ridges in close proximity to planting due to time constraints during field visits; this may or may not differ from historical practice. The inclusion of a one-off, initial seaweed liquor application was based on an idea, generated by modern crofters, that it would be easier to apply. This was indeed the case, but a separate study would be required to investigate the full potential for this methodology, e.g. use of in-crop applications to establish if there is a manuring effect to be gained from the liquor. The rotted treatment was the result of covering winter storm recovered seaweed, to prevent rain washing nutrients from the pile as it degraded, and to reduce the nuisance from flies breeding on the pile. Whilst none of these treatments might therefore be considered historically accurate, the range of both historical and current oral recounting of seaweed manuring of the ridges is varied. Historical record implies that the seaweed was probably largely recovered early in the year either from harvesting or from gathering of storm washed weed [8-10]. This was then moved to the croft by hand and dug in when time was available, either by the croft's tenants or itinerant workers moving down the islands. Sowing would have taken place at some time weeks or months after this as the warmer spring weather set in. Given the level of water observed in the soils throughout the study season, burying of fresh seaweed some time prior to planting would likely have a similar effect on the decomposition of the seaweed as occurred under the tarpaulin of the rotted treatment.

The crop planting in this study also diverged from the historical context in regard to recorded rotational sequences; this was due to the limitations of time and a desire to address locally generated production questions. However, the decision to include *A. sativa,* as opposed to *A. strigosa*, was made based on both croft records and historic rotation descriptions, despite the existence of a historic record that reports *A. sativa* rarely yielded grain [9]. A comparison of the two oats is clearly needed to determine what benefit is attained in the system from the choice of *A. sativa* and if the pH change we observed in the soils was due to a chance occurrence or the result of something specific to this cereal in these soils. In addition to this observation, the changes to the initial crop plantings also indicated that a wider range of crop types could be grown in these systems beyond those indicated in the historical records [8], thus offering greater diversity of diet for both current humans and animals reliant on the system.

One of the other limitations to the ridge system of cultivation within a modern setting is the current absence of suitable mechanical equipment. Historically these systems were worked by the crofter and his family [9] or by community groups where by 10-12 men could turn an acre (~ 4047 m^2) with the *cas chrom* in a day [8]. It took three of the research team 3 days to dig, prepare and sow the 3 beds. It could be seen that experience would increase speed of bed preparation as local crofter Mr Ronald John MacLean (instructing the team in the techniques of lazy bed creation), worked considerably faster, but regardless of this the requirement for manual labour may remain a limitation to the re-adoption of this system.

Inclusion of seaweed manure at establishment was essential for an improved return of crop above the seeding rate (Table 5). Assessment of the local seaweed resource implied that the average age of *A. nodosum* on Grimsay was around 6 years. The implication being that harvest of 1/6th of the total available reserve, irrespective of the end use of the resource, within any one year would not adversely affect the long term sustainability of the resource from local use. This would equate to approximately 56 tonnes of harvestable *A. nodosum* per year around Grimsay. Based on our application rates, this would be sufficient to fertilise 3639 m^2 of ridges based on fresh *A. nodosum* application. This area is significantly less than the 0.6 ha of ridges on the croft where our experiment was undertaken, but it is important to remember that; (i) the ridge surface occupies a fraction of between 1/2 to 1/3 of the field due to the construction technique, (ii) seaweed manuring occurred only at the onset of the rotation, once every 6th or 7th year and (iii) not all of the cultivated area may have been under cultivation at the same time throughout the history of the croft. The wider survey implied that similar levels of *A. nodosum* were available in eight of the nine bays surveyed and that in all cases there was evidence of ridges within 200 m of the shoreline. In our studies, as in some of the historical records, the fresh seaweed was harvested from the beach whereas the seaweed that was rotted was recovered from seaweed washed up during a storm event. The nature of collection, harvested versus flotsam collection, would therefore also affect long term sustainability.

The differences in the seaweed used also had a major effect on the crop yields. The rotted seaweed manure was nutritionally similar to the fresh (Table 1), but the output was markedly increased (Table 5). Reasons for this do not therefore appear to be due to nutritional addition from the manure, but are more likely to have occurred due to the manure promoting changes in the soil in which the crops were growing. At harvest it was noted that all the potato tubers were recovered from soil above the manure level and that oat roots rarely penetrated through the manure. Despite this, potatoes recovered from the rotted seaweed plots had more soil adhesion to the skin that those grown in the other treatments. Although not directly measured, some of the harvesters commented on the observation of earthworms and beetles in the rotted treatments, but not elsewhere. These observations suggest that the seaweed manure is changing soil properties that may in turn contribute to an improved plant response. Whether these changes are due to increased microbial proliferation or altered soil structural formation[13] was not determined from this study. However, again the observation that oat at harvest had significantly increased the pH of the soil from a starting point of 4.6 to 6.3 on the rotted seaweed treatments (Table 4) might explain why oat was used in these systems so prolifically, despite reputedly only yielding a grain crop every 1 in 50 years [9] as it may have been one way to raise the soil pH for the subsequent grass crops. It should be noted that the oat crop in this study did produce grain and yet the conditions of the growing season were not considered anything out of the ordinary; further investigation is required to establish if this was a 1 in 50 year event

Some of these characteristics of the soil may also have been responsible for the observed soil nutritional levels during the season. The lack of nitrate/nitrite was possibly due to preferential plant uptake, but is possibly a result of either a lack of nitrification, or denitrification and leaching from these soils, which generally retain a high moisture content due to their peaty nature. Similarly, the high water content, low temperatures and pH of these soils could be a possible reason for the relatively high levels of ammonium in these soils[20]. The water content was also thought to have been an important aspect of the system and the observed results. Although water content was similar between the cultivated and undisturbed ridges, the act of cultivation was believed to have removed sufficient water from the surface of the ridge to facilitate the exploration of the soil by the crop plant roots. It is poignant to remember that the undisturbed ridge was still structurally visible and therefore likely to be draining more than the surrounding uncultivated soil and that the trial site was on a slope of between 11 to 17% with differing depths of soil over the underlying granite. All of these characteristics of the site could explain the lack of difference in the soil moisture content, but the importance of the soil moisture observation is that in this season, as in most others, the raised ridge did not dry out.

The lack of difference in both ground level CO_2 and soil C content were indications that the peat within these soils was not being significantly affected by the act of cultivation or the crop production. A possible reason for this is that, although the soils were disturbed through the actions of reinstating the ridges, manuring and planting, the water content remained sufficiently high to prevent aerobic degradation of the peat and other organic materials within the soil. Another explanation could be that carbon loss was too small to be detected through LOI and may have been liberated as methane and not CO_2. Although not reported here, an attempt was made to recover methane throughout the experiment using another IRGA (CO2Meter, CM-0190), but emissions above the lower limit of detection of the instrument were not detected.

In considering other implications of the re-instigation of ridge production a number of factors need to be considered. The first of these is that the islands have moved from a position of 90% self-sufficiency in food production to one of 95% reliance on food importation over recent decades [21]. Importation of food to the Western Isles is associated with some of the highest levels of food miles, and associated CO_2 emissions [22], in Britain. Cropping on Blackland ridges could offset some of these emissions at a rate of 0.65 kg CO_2/kg food produced [21]. Another factor associated with importation is the financial cost of both human food and livestock fodder. An example of the latter is the current importation cost of a bale of hay at anywhere between £16-£60 compared to £4 on the mainland, (prices as of summer 2014), which would imply that any ability for crofters to produce their own animal fodder could generate considerable financial savings with regard to animal production costs. With this in mind it is worth re-iterating the point that the ridge system of production was primarily for the development of improved grazing and the provision of winter feed for livestock [8, 9].

Whilst this was a pilot study, it has established that there is a good basis and underlying rationale to re-investigate ridge based production systems across historically crofted areas with a view to providing improved localised food security. In addition to investigating the options for re-establishment of the traditional crop rotations there is evidence to support including a wider range of crop species and different varieties in future studies. Seaweed is an essential part of the rotation and the application of rotted material, possibly closely mimicking the historic effects of burying seaweed under wet soils weeks before planting, proved to be effective in stimulating higher crop yields, although not through any obvious nutritional gain. Assessment of the foreshore of the local and wider area implied that sustainable seaweed harvesting could be undertaken to support a rekindling of this type of agriculture and that the impact on the current levels of soil C were negligible.

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Figure 1 Extensive evidence of an abandoned ridge system on the West coast of Lewis near Huisinis.

Figure 2. Photographs of two of the research team (S. Warnick and T-J Marsden) re-establishing the ridges with the use of spades (top). The 3 established and manured ridges on Grimsay with the uncultivated ridge to their left (bottom).

6m

Oat	Oat	Potato
Cabbage	Oat	Potato
Potato	Cabbage	Oat
Potato	Cabbage	Oat
Oat	Potato	Cabbage
Cabbage	Potato	Cabbage
Potato	Potato	Oat
Potato	Cabbage	Oat
Oat	Oat	Cabbage
Oat	Oat	Cabbage
Cabbage	Potato	Potato
Cabbage	Cabbage	Potato

Cabbage	Cabbage	Oat
Cabbage	Cabbage	Potato
Potato	Potato	Cabbage
Potato	Potato	Cabbage
Oat	Oat	Oat
Oat	Oat	Potato

Figure 3**:** Plot and crop lay out upon the three ridges as they ran 18 m top to bottom and West to East (left to right) on the field. The un-dug control ridge was located to the West (left of this diagram). Grey stippling indicates liquor application, light grey fresh, *A. nodosum* application and dark grey rotted seaweed application applied at 2.5 l/m, 15.5 kg/m^2 and 23.6 kg/m^2, respectively.

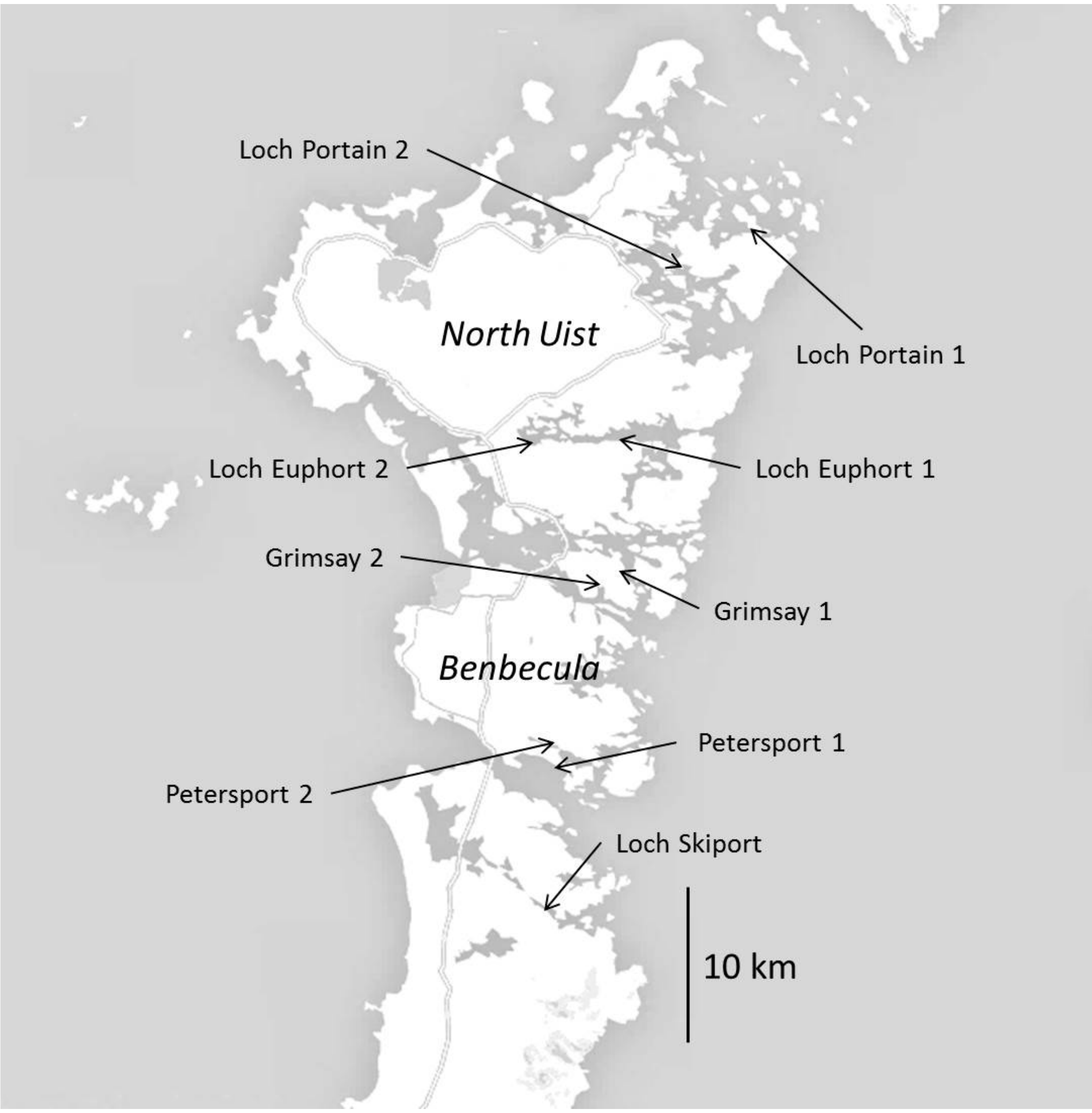

Figure 4: Edited Google Map showing site locations used in the wider seaweed survey

Table 1: Chemical analysis of fresh and rotted *A. nodosum* samples collected in N. Uist and used in the trial. Values are for dry matter (DM). *Rotted Kelp values, provided by the Machair Life project, are presented for comparison. Na was not tested for in their analysis (NT)

	Fresh	Rotted	Kelp* (rotted)
% DM	35	22	17
% N	0.5	0.4-1	0.79
% P	0.08	0.06-0.17	0.20
% Ammonia N	<0.01	<0.01	0.074
% K	0.8	0.4	0.7
% Na	2.3	3.3	*NT*
mg/kg Cu	6	21	27
mg/kg S	27400	32900	37700

Table 2**:** Outcome of analysis of liquor collected from the outflow of a bath of fresh and rotted *A. nodosum* collected at various time points (days) after establishment of the baths given in mg/l. The resultant bin into which the liquors were pooled was also analysed. *Sulphur analysis was not UKAS accredited

	Fresh				Rotted				Bin
Days	0	14	45	63	0	31	40	49	
Phosphorus	1	13	50	17	2	9	25	22	29
Potassium	250	696	943	1290	600	640	982	920	1150
Calcium	73	93	86	126	226	196	367	361	157
Sulphur*	428	812	851	1190	1470	1150	1600	1610	3830
Magnesium	169	211	160	241	479	379	626	606	442
Sodium	2390	2050	1150	1470	4000	2940	4240	4110	2840
Iron	1	0	1	<0.3	1	1	1	1	<0.3
Manganese	0	0	0	0	0	0	1	1	0
Boron	3	2	2	1	3	3	5	5	3
Copper	0	0	0	0	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	0	0	0	0	0	0	0	0	0

Table 3: Mean ammonium and phosphate levels for recorded soil sampled from oat and potato plots at harvest in each crop treatment. For comparison, ammonia and phosphate on the uncultivated ridge were 39 and 42 ug/g, respectively. The rotted seaweed treatment had a significant (*P<0.02) effect on available phosphate under oats and potatoes.

Treatment	Ammonium µg/g		Phosphate µg/g	
	Oat	Potato	Oat	Potato
Control	172	116	55	62
Fresh	123	162	38	45
Liquor	176	204	31	76
Rotted	137	133	309*	112*

Table 4: pH of soil using a 1:2 soil to water volume extraction from plots (3 manure treatments and control) on cultivated ridges sampled at 38 (a), 72 (b) and 129 (harvest, c) days after sowing. Mean pH values from three replicates are given. pH of soil from control ridge was determined as averaging 4.6. *A significant change in pH was detected under oats manured with rotted seaweed at manure, crop and interaction levels (ANOVA $P<0.05$)

	Cabbage		Oat			Potato		
	a	b	a	b	c	a	b	c
control	4.6	5.0	4.5	4.8	4.5	4.9	4.8	4.3
fresh	4.8	5.0	4.5	4.8	4.8	4.7	4.8	4.6
liquor	4.7	4.9	4.8	5.0	4.9	4.7	4.8	4.6
rotted	4.5	4.7	4.1	4.5	6.3*	4.8	4.8	4.7

Table 5: Final yield of Potato tubers and whole crop recovery of Oat from the seaweed treated ridges (values are the mean of 3 plots). Mean cabbage height and diameter from all surviving cabbages measured in September 2013

		Treatment			
		Control	Fresh	Liquor	Rotted
Potato	Weight (kg)	2.11	1.78	1.26	6.60
	Discard weight (kg)	0.14	0.59	0.22	0.29
	Edible weight (kg)	1.97	1.18	1.04	6.32
Oat	Weight (kg/m)	0.04	0.07	0.08	0.91
Cabbage	Height (cm)	11	17	13	43
	Diameter (cm)	14	30	21	92