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REVIEW

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Back to the future: Using ancient Bere barley landraces for a sustainable future

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Societal Impact Statement

Bere is an ancient barley (*Hordeum vulgare* L.) that was once widely grown in northern Britain, where its ability to grow on poor soils and under challenging climatic conditions made it a valuable staple. By the end of the 20th century, Bere had largely been replaced by higher-yielding modern varieties and only survived in cultivation on a few Scottish islands. This article reviews the recent revival of Bere, driven by its use in high-value food and drink products and multidisciplinary research into its genetics, valuable sustainability traits and potential for developing resilient barley varieties.

Summary

In Britain, modern cereal varieties have mostly replaced landraces. A remarkable exception occurs on several Scottish islands where Bere, an ancient 6-row barley (*Hordeum vulgare* L.), is grown as a monocrop or in mixtures. In the Outer Hebrides, the mixture is grown for animal feed, and cultivating it with traditional practices is integral to the conservation of Machair, an important coastal dune ecosystem. In Orkney, Bere is grown as a monocrop, and in situ conservation has recently been strengthened by improved agronomy and new markets for grain to produce unique foods and beverages from beremeal (flour) and malt. In parallel, a recently assembled collection of British and North European barley landraces has allowed the genotypic and phenotypic characterisation of Bere and several associated multidisciplinary studies. Genotyping demonstrated Bere's unique identity compared with most other barleys in the collection, indicating an earlier introduction to Scotland than the Norse settlement (c. 9th century AD) suggested previously. Valuable traits found in some Bere accessions include disease resistance, an early heading date (reflecting a short period from sowing to harvest), the ability to grow on marginal, high pH soils deficient in manganese and tolerance to salinity stress. These traits would have been important in the past for grain production under the region's challenging soil and Atlantic-maritime climatic conditions. We discuss these results within the context of Bere as a genetic, heritage and commercial resource and as a future source of sustainability traits for barley improvement.

KEYWORDS
Bere, crop genetic resource, ex situ conservation, genotyping, heritage, in situ conservation, phenotyping, sustainability

1 | INTRODUCTION

Discussions around the term 'landrace' (e.g., Negri et al., 2009; Villa et al., 2005; Zeven, 1998) usually include the concept that it is a cultivated, genetically heterogeneous variety that has evolved in a specific ecogeographical area and is therefore adapted to local conditions, management systems and ways in which it has been used (Casañas et al., 2017). As a result of their adaptations, landraces are a potentially valuable source of crop diversity for producing new or improved varieties (Dawson et al., 2015; Maxted et al., 2020; Newton et al., 2011), and considerable attention has been given to conserving them ex situ, in germplasm collections, and in situ by continued growing on farms in their area of origin. Both approaches are important, but the latter has the added advantage of allowing landraces to continue to evolve under changing conditions (Bellon et al., 2017). While significant crop diversity is still maintained in landraces cultivated in their centres of domestication (Bellon et al., 2017), many are also maintained in adopted home ranges. These include Europe (Raggi et al., 2021; Veteläinen et al., 2009), where, however, relatively few cereal landraces are grown, especially in northern Europe (Hammer & Diederichsen, 2009; Raggi et al., 2022). In this context, the survival in cultivation and recent commercialisation of Bere, an ancient Scottish barley (*Hordeum vulgare* L.) (Scholten et al., 2011), are remarkable. In this review, we describe the re-discovery of Bere by researchers and commercial end-users and discuss this within the context of its history, conservation and potential for further utilisation.

2 | HISTORY OF BERE

2.1 | Early history

Bere is a 6-row hulled spring barley that has long been associated with Scotland (Jarman, 1996) but was also grown in the north of England (Gerard, 1633) and Ireland (Porter, 1850). In Scotland, it was especially important in the isolated archipelagos of the Outer Hebrides, Orkney and Shetland (Figure 1), where local production of grain and straw was vital for the self-sufficiency of remote communities (Martin, Brown, et al., 2023). Two important adaptations of Bere to local conditions are likely to have favoured its continued cultivation: its ability to produce a crop in a short period (Martin, Brown, et al., 2023) and the tolerance of some types to sandy, high pH, manganese-deficient soils (Schmidt et al., 2019). The former was necessary because of the region's short, cool growing season (Chappell et al., 2017) and the need to complete harvesting in September to avoid weather-related crop losses. Bere's tolerance to manganese-deficient sandy soils was crucial because these are widespread in coastal parts of most islands (Cope et al., 2020) and were favoured for cropping because they could be cultivated earlier and more easily than heavier land. Coastal locations also provided access to seaweed used as fertiliser (Brown et al., 2020).

Cereal cultivation started in the Scottish Isles around 3500 BC with the introduction of agriculture and the Neolithic way of life (Bishop et al., 2010). Despite its northern remoteness, Orkney had a thriving and complex Neolithic society based on the cultivation of barley (Bishop et al., 2010). It is unclear when Bere or its progenitor was first introduced to Scotland, but it may have been as early as the Bronze Age (c. 2500–800 BC; Drosou et al., 2022).

Historically, Bere was a multi-use crop. and prior to the development of a cash economy, its grain was used for in-kind payments and land rentals. Grain was also milled into flour (beremeal) or malted for brewing or, from the 16th century, for distilling. Bere straw was used for animal bedding and feed and was also made into rope (*simmens*) used for thatching. Bere's importance in everyday Scottish life during the 18th century is reflected in the poems of Robbie Burns, Scotland's national poet (Martin et al., 2009). These celebrate its use for making two iconic Scottish products—beremeal bannocks (Figure 2c), a type of flat bread, and whisky. Whisky distillation was often a cottage industry in Scotland until the end of the 18th century and added value to local barley (Devine, 1994). Bere continued to be commonly used by distilleries, especially in the Highlands and Islands, until around the middle of the 19th century.

2.2 | Decline in Bere

The decline of Bere cultivation in Scotland probably started during the 18th century (Hay, 2012) and occurred earliest in the more productive lowland areas in the south and east, where improved agricultural practices were first adopted. These included drainage, the application of lime, and the use of rotations and improved crop selections. The gradual adoption of the potato (*Solanum tuberosum* L.) also reduced the need for Bere as a food staple. By 1912, the decline in Bere cultivation was well advanced, and the area grown in Scotland was only about 5% (4228 ha) of the national barley area (Board of Agriculture for Scotland, 1913). Significantly, 48% of the Bere area was on Orkney and Shetland, where no other type of barley was recorded. The decline continued during the 20th century, and by the end of the century, there was probably only about 50 ha of monocrop Bere grown on Orkney, Shetland and the Outer Hebrides. Abandonment of Bere resulted from many factors, including reduced arable cropping and less demand for beremeal because of the increased availability of wheat flour (Martin, Brown, et al., 2023). Agricultural mechanisation also contributed, however, as quicker field operations effectively extended the cropping season, allowing the adoption of modern varieties that required a longer cropping season but did not have Bere's agronomic shortcomings

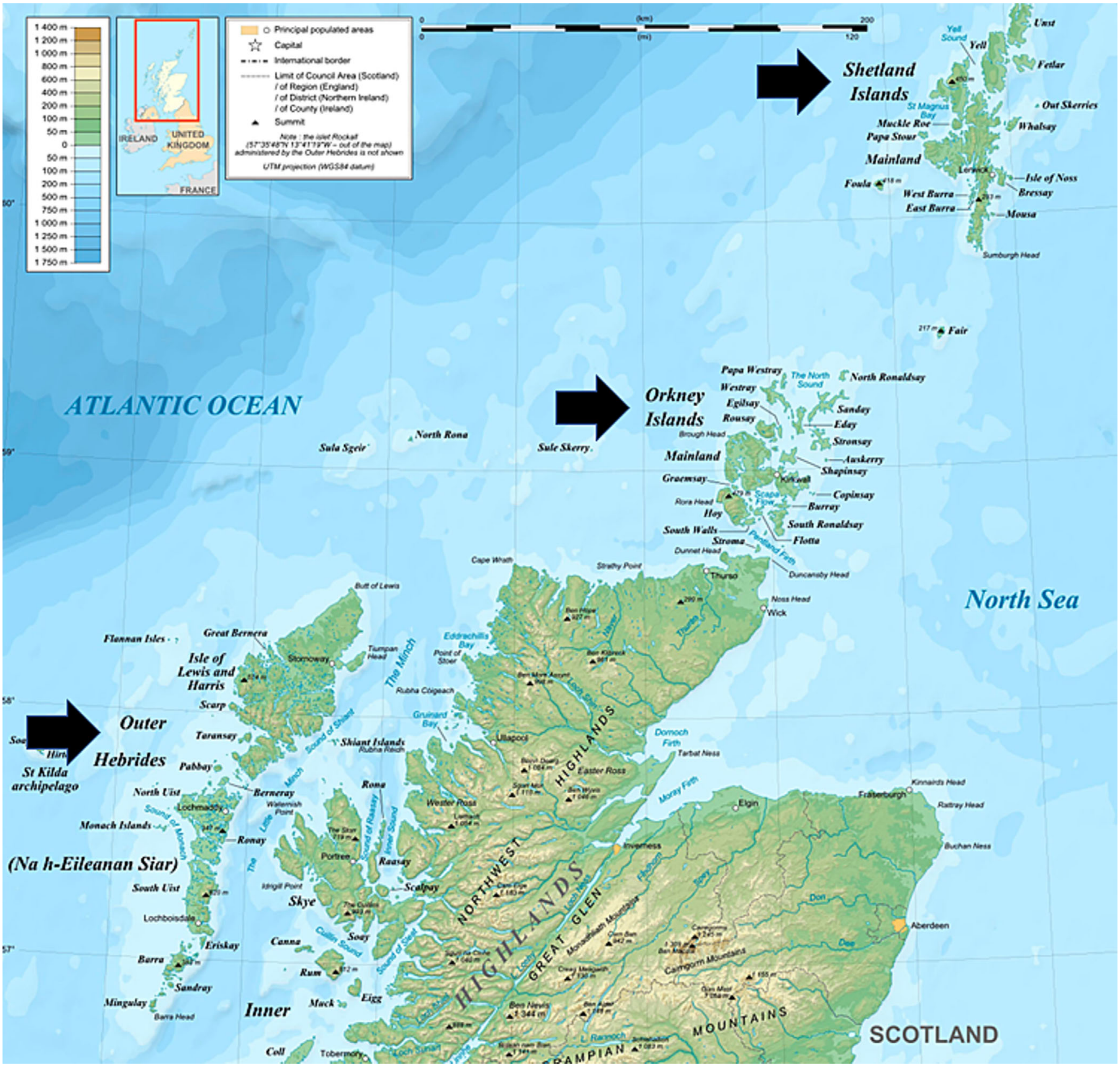


FIGURE 1 Map of northern Scotland showing the main island archipelagos (black arrows) where Bere is grown. From north to south: Shetland, Orkney and the Outer Hebrides. The image was sourced from Scotland_topographic_map-en.jpg (2400 × 3450) (wikimedia.org) and originally produced by Eric Gaba. The complete attribution is provided in Note S1. (Adapted from Martin, Shoemark, et al., 2023).

(Martin, Shoemark, et al., 2023). These included its low yield and long straw, which made it very susceptible to lodging, especially under high fertility conditions. On some manganese-deficient land, the introduction of foliar sprays of manganese also made it more viable to use modern varieties, which lacked Bere's adaptation to these conditions.

2.3 | Survival of Bere through the 20th century

Despite the general decline in Bere cultivation through the 20th century, a new way of using Bere in a crop mixture together with landraces of Hebridean rye (*Secale cereale* L.) and Small oat (*Avena strigosa* Schreb.) appears to have developed over the century in the Outer Hebrides (Hance, 1952). Here, the sandy coastal soil is part of a unique fixed dune habitat of global significance (Owen et al., 2000) called Machair[1] (Nature Scot, 2023), and the combination of low input cereal cropping with organic fertilisers and fallow years is crucial for maintaining its characteristic flora and fauna (Angus & Dargie, 2002). While all species in the mixture tolerate the

[1]There are about 25,000 ha of Machair grassland globally, of which 17,500 ha occur in Scotland and the remainder in western Ireland (BRIG, 2008).

FIGURE 2 Aspects of Bere value chains in Orkney. (a) Ripe heads of Bere ready for harvesting; (b) Barony Mill which produces beremeal; (c) beremeal and a beremeal bannock; (d) Bere grains sprouting during the production of malt; (e) single malt whisky produced exclusively from Bere; (f) Bere straw bales which are an important by-product used for livestock bedding.

manganese-deficient Machair soils, another advantage is that they have different adaptive capacities to the deficiencies and excesses of soil water that can occur (Smith, 1994), with Hebridean rye being the most tolerant of dry conditions. Agricultural census data (Scottish Executive, 2002) suggest that in 2002, about 160 ha of the mixture were grown on the Outer Hebrides, which would all have been used as overwintering animal feed.

Bere continued to be grown as a monocrop on Orkney and Shetland, and by 2002, the areas cultivated were about 9 and 4 ha, respectively (Martin, Shoemark, et al., 2023). On Orkney, this was grown for a local watermill, Barony Mill (Figure 2b), which produced beremeal for a small local market. Since 1998, the mill has been run by the local community through the Birsay Heritage Trust (BHT).

3 | RECENT GROWING OF BERE

3.1 | A Bere renaissance on Orkney (2002–2020)

By 2020, on Orkney, the area of Bere had increased eightfold to about 73 ha. This resulted from a small expansion in the market for beremeal and the development of new beverage markets, particularly whisky and beer, using Bere malt (Martin & Wishart, 2015).

3.1.1 | New markets

Bere's low grain yield requires a higher grain price than that of modern barley to cover its production costs (Martin et al., 2009). This makes Bere an expensive option for alcohol production, which is compounded by the lower alcohol yield of its malt (Martin et al., 2009) and by mash volumes having to be reduced because of their density. Nevertheless, distilleries consider that it contributes a unique flavour to whisky, and its well-documented links with the pre-20th-century distilling industry and early brewing make Bere attractive for marketing. Its Orkney provenance is also important, especially for Orkney end-users but also for companies that embrace provenance and terroir (Halland et al., 2020; Kyraleou et al., 2021; Martin, 2016). Many Bere products also take advantage of its heritage cache, particularly its association with the Norse and Vikings. By 2020, approximately 200 t of Bere from Orkney were used annually for malt whisky production. The release of the first single malt whiskies made entirely from Orkney Bere started in 2012 (Figure 2e) and these are now sold internationally (Martin & Wishart, 2015). Whisky is a high-profile Scottish product that in 2017 was exported to 180 markets worldwide, earning £4.4 billion (Scotch Whisky Association, 2018), and single malt Scotch whiskies[2] are at the premium end of this market. Bere whiskies have been important for raising the crop's profile and demonstrating its value as a commercial resource. For distilleries, there have been two main financial advantages of using Bere. Firstly, Bere spirit is considered to mature and develop complexity early, and several Bere whiskies were released after only 6 years' maturation. Secondly, because of their uniqueness, they can be sold at a premium, and at

[2]According to the Scotch Whisky Association (https://www.scotch-whisky.org.uk/discover/faqs/), single malt Scotch whiskies represent about 11% of Scotch whisky exports and are defined as Scotch whiskies that have been distilled by batch distillation in a copper pot still at a single distillery using water and malted barley without the addition of any other cereal; they must also be bottled in Scotland.

10 years of age, this can be almost twice the price of a distillery's standard product of this age. The availability of Bere malt on Orkney has led to new products, including a very successful Bere malt vinegar.

By 2020, about 15 t per year of Bere were used for milling, with the main markets for beremeal being local bakeries on Orkney and numerous craft food outlets in mainland Scotland producing biscuits and breads to which the addition of beremeal adds a distinctive flavour. There has been a modest increase in demand for beremeal since 2002, which has been driven by the same premium-market forces as for beverages and by the perception of beremeal as a healthy alternative to wheat flour. Product development and labelling have been helped by nutritional analyses of beremeal and Bere grains (Chappell et al., 2017; Theobald et al., 2006), which highlighted their high levels of fibre, certain minerals (iron, iodine and magnesium) and vitamins (folate, pantothenic acid and thiamine). Barony Mill is Orkney's last functioning watermill and Scotland's only producer of beremeal, which adds value to it as an artisanal product but also limits the scale of production.

3.1.2 | Bere supply chains

Orkney's Bere is produced by two supply chains (Figure 2) run by the Agronomy Institute (AI) and BHT. Both maintain their own lines of Bere and work with growers who either lease out their land or grow Bere for the supply chain. The development of supply chains was facilitated by Orkney's relatively high level of agricultural mechanisation and the availability of batch grain dryers. Guidelines for growing Bere under modern conditions were produced by the AI following several years of field trials (Martin et al., 2010) and have been important in achieving reliable grain production, allowing contract growing. One of the most important research findings was that higher yields and more secure harvesting could be achieved by adopting early sowing—in April rather than the traditional mid-May date (Martin et al., 2010). In earlier times, May-sowing allowed growers to first sow oats, which have a longer cropping period than Bere (Dodgshon, 2004), but this is no longer necessary because less oats are now grown and mechanisation has speeded up field operations. The trials also highlighted the susceptibility of Bere, which has long straw, to serious lodging in high fertility fields, especially when additional nitrogen fertiliser was used. Lodging makes harvesting more difficult and can be accompanied by grain germination, making it unsuitable for malting. Because only modest increases in yield resulted from the use of other inputs like fungicide and growth regulators, a low-input approach to growing Bere has mostly been adopted (Mahon et al., 2016; Martin et al., 2010). While the income from selling grain is a major incentive for growing, straw (Figure 2f), used for both feed and bedding, is a valuable by-product.

3.2 | Recent growing of Bere on Shetland and the Outer Hebrides

In contrast to Orkney, the area of Bere grown on Shetland has declined since the early part of the 21st century and was only about 0.1 ha by 2020 (Martin, Shoemark, et al., 2023). While cereal cultivation is more constrained in Shetland by poor soils and a more challenging climate (Martin, 2015), other factors have also contributed to the failure to develop Bere. These included the lack of a functioning water mill, which might have produced local beremeal, and a shortage of significant grain drying facilities. Furthermore, the high cost of sending grain for malting was a major disincentive for using local Bere in beverages. Similar constraints prevented the development of Bere grain markets on the Outer Hebrides, and in both locations, there was a lack of local facilitating organisations, like the AI or BHT, to help promote and commercialise the crop.

Most of the Bere grown on the Outer Hebrides is within the landrace mixture. Bere is valued for its nutritional contribution to the mixture but is earlier maturing than the rye or the oat, so there is a tendency for these to dominate (Smith, 1994). This may be placing selection pressure on Bere, as most of the Bere harvested in the mixture will come from late-maturing plants. This may explain why many accessions of Bere from the Outer Hebrides tend to mature later than those from the Northern Isles (see days to heading in Figure 3, for example). The value of the landrace mixture to growers is that it provides local overwintering animal feed that is cheaper and more sustainable than importing feed. The mixture is therefore crucial for local livestock production, and its tolerance to local soils is one of the main reasons cited for its continued cultivation (Martin, Shoemark, et al., 2023). Modern cereal varieties lack this tolerance (Schmidt et al., 2019) and are usually not grown.

4 | GENOTYPING, PHENOTYPING AND FUTURE USE OF BERE BY PLANT BREEDERS

4.1 | Genetic enlightenment

Since 2007, the James Hutton Institute has built up a heritage barley collection consisting of landraces and locally adapted cultivars from Scotland, other parts of Britain and Scandinavia (here used to refer to Denmark, Norway, Sweden and the Faroe Islands). The Scottish material includes 37 Bere accessions (Cope et al., 2021), including representatives from the Outer Hebrides, Orkney and Shetland.

The relationship of Bere to other barleys in the heritage collection has been examined in three genotyping studies (Drosou et al., 2022; Schmidt et al., 2019; Wallace et al., 2019), followed by population genetic analyses using STRUCTURE analysis software. All studies showed that the majority of the Bere accessions formed a discrete group that was distinct from the other accession groups, and in the two studies with the widest range of Bere accessions (Schmidt et al., 2019; Wallace et al., 2019), the Beres separated into three clusters corresponding to accessions from the Outer Hebrides, Orkney and Shetland (Figure 4). All studies found that the barleys most closely related to Bere were several Scandinavian 6-row accessions. Nevertheless, the new genetic analyses and archaeobotanical data (Bishop et al., 2010) are considered (Drosou et al., 2022) to make an 8th-century AD Scandinavian introduction of Bere to Scotland

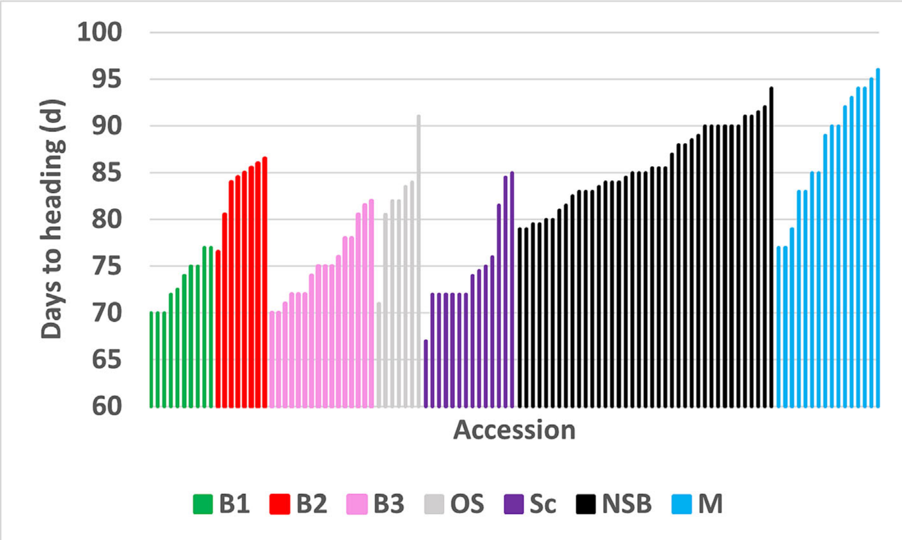


FIGURE 3 Days from sowing to heading for selected accessions in the James Hutton Institute's heritage barley collection. In the figure, accessions have been colour-coded according to the following barley types: Bere from the Northern Isles (B1, green); Bere from the Outer Hebrides (B2, red); Bere of unrecorded provenance (B3, pink); other Scottish landraces (OS, grey); Scandinavian landraces (Sc, purple); non-Scottish British landraces (NSB, black); modern elite cultivars (M, blue). Heading dates are the mean of observations on two plots (2.0 m × 1.0 m) of each accession from a trial sown in Orkney on April 21, 2017. The identity of accessions and details of the trial are provided in Note S2.

(Jarman, 1996) less likely than one in the Bronze Age or earlier. Intriguingly, all studies showed the same exception to the separation of Bere and Scandinavian accessions, which resulted from two Faroese landraces falling within the main Bere group (Figure 4), and it is thought that this may reflect an introduction of Bere to the Faroes (Drosou et al., 2022; Wallace et al., 2019). While this type of research helps to explain the development and spread of landraces, it is clear that tracing their complex stories is challenging.

4.2 | Phenotyping and future use of Bere

Phenotyping of the Hutton's heritage barley collection has helped to identify several adaptations in Bere that have made it such a valuable crop for so long on the Scottish islands.

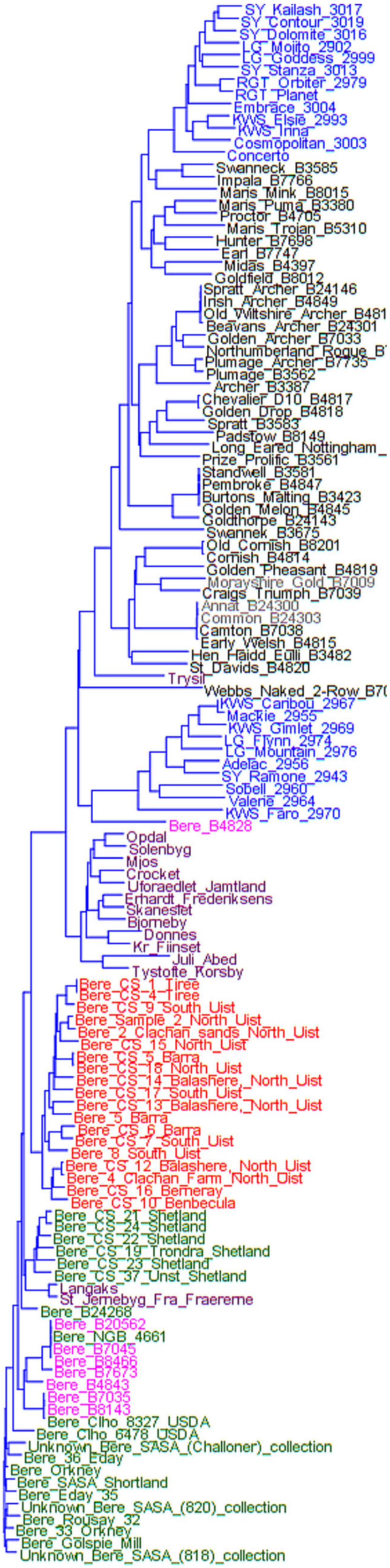
Bere's ability to produce a crop of grain in a short period requires a short period from sowing to heading (i.e., ear emergence), and this trait has been recorded for the heritage collection (unpublished results; see Figure 3 and Note S2). Amongst British landraces, most Bere accessions from the Northern Isles (Orkney and Shetland) and Scotch Common, a 2-row Sottish barley landrace, are exceptional in their earliness, which is similar to that of several 6-row landraces from Scandinavia. Here, too, the very short cropping season creates a particular need for barley, which matures quickly (Martin et al., 2017).

On Machair soils, Bere has been shown to have a superior ability to acquire manganese and maintain plant productivity compared with modern varieties (George et al., 2014). Further investigations (Cope et al., 2020; Schmidt et al., 2019) with a wider range of barley demonstrated that the adaptation to growing on manganese-deficient soils was present in several Bere accessions but not all and was absent in other barley landraces or modern barley varieties. On manganese-deficient soil, modern elite varieties grew very poorly (Figure 5a) and failed to produce grain (Figure 5d), while adapted Bere accessions were characterised by more vigorous, greener growth (Figure 5b), higher concentrations of manganese in leaves, greater Photosystem II (PSII) efficiency (determined by chlorophyll *a* fluorescence; Figure 5c) and a good grain yield (Schmidt et al., 2019). They also had higher foliar concentrations of zinc and copper, which are often low on such soils. The occurrence of this trait amongst Bere accessions from the Outer Hebrides, Shetland and Orkney suggests either that the adaptation was present in the original barley from which Bere has evolved or that it developed independently in the three island groups, in which case different mechanisms for the adaptation may exist. The absence of the trait in accessions collected from areas without manganese-deficient soils suggests that it confers no advantage on such soils.

Tolerance to salinity stress is limited in the elite barley cultivar pools and is becoming increasingly important as climate change results in larger areas of salinity-affected soil (Cope et al., 2022). In a study investigating tolerance to salinity stress (Cope et al., 2022), elite cultivars showed a greater adverse response to salinity compared with landrace lines, amongst which one Bere line from Shetland showed particularly high tolerance.

Rhynchosporium is amongst the most important diseases of barley globally and can cause yield losses of 10%–45% (Cope et al., 2021). It is especially prevalent in cool, high-rainfall areas and would be expected to be serious in maritime northern areas where Bere is grown, but interviews with Bere growers (Mahon et al., 2016; Martin et al., 2010) have usually not suggested any concern about foliar diseases. Screening of the Hutton's heritage collection for resistance to *Rhynchosporium* (Cope et al., 2021) showed that Bere accessions produced smaller but more necrotic lesions, and three lines consistently showed reduced levels of infection when challenged by isolates of *Rhynchosporium* from different parts of the UK. Genotyping of the Beres, followed by a genome-wide association study (GWAS), identified four chromosome regions containing promising novel candidate genes for resistance to *Rhynchosporium* (Cope et al., 2021). If confirmed and identified, these novel resistance genes could be valuable in producing elite cultivars with new resistance to the disease.

So far, it appears that Bere harbours several traits and polymorphisms that could be used in developing improved barley cultivars



with resilience against future environments. These traits could even be deployed in association with one another to develop lines with resistance to both abiotic and biotic stress. The need for a research and development 'pipeline' to exploit sustainability traits from landraces of Bere was recently published in an opinion piece (Schmidt et al., 2023). This outlined a targeted breeding programme connecting old cultivar collections with state-of-the-art gene discovery and phenotyping to provide new resources for future needs. As a prelude to this and to better understand the genetic basis for some of Bere's traits, crosses have been made between selected Bere accessions and elite 2-row barley varieties. The F6 populations derived from these crosses contain phenotypes exhibiting a wide range of characteristics for traits, including tolerance to manganese-deficient soils, straw length, days to heading and number of rows of grain in the head, as well as novel combinations of these characteristics (unpublished results).

5 | EXPLORING THE PAST

Bere's long history of cultivation in the Scottish Isles makes it a valuable resource for probing many aspects of historic and ancient cropping and food and drink production. These studies have strengthened the crop's heritage status and indicate that Bere may have been grown beyond Britain and Ireland.

5.1 | Probing the antiquity of Bere

A key question for the heritage status of Bere is how and when the barley from which it evolved first reached Scotland. Although genotyping studies (Drosou et al., 2022; Wallace et al., 2019) have provided important clues, a valuable addition would be the development of methods to confidently identify Bere in the archaeological record. Elsewhere, genotyping of DNA extracted from ancient barley grains has been possible (Hagenblad et al., 2017), but grains from most Scottish sites have been preserved by charring, which results in poor DNA preservation (Bunning et al., 2012). An alternative approach using geometric modern morphometrics (GMM) to investigate grain

FIGURE 4 Genetic relationship between the ancient Scottish barley, Bere, and a range of British and Scandinavian landraces and modern barley varieties. Hierarchical clustering based on a simple matching similarity matrix using 9K iSelect SNP chip (Schmidt et al., 2019) was used to group the 128 barley (*Hordeum vulgare*) accessions (see Note S3 for further details). In the figure, accessions have been colour-coded according to the following barley types: 2-row elite cultivars (blue); 2-row non-Scottish British landraces (black); 2-row Scottish landraces (grey); 6-row Scandinavian landraces (purple); Bere from the Outer Hebrides (red); Bere from the Northern Isles (green); Bere of unrecorded provenance (pink). The figure includes varieties from several modern plant breeding companies identified by the following abbreviations: KWS group (KWS), Syngenta seeds (SY), Limagrain UK (LG), RAGT seeds (RGT).

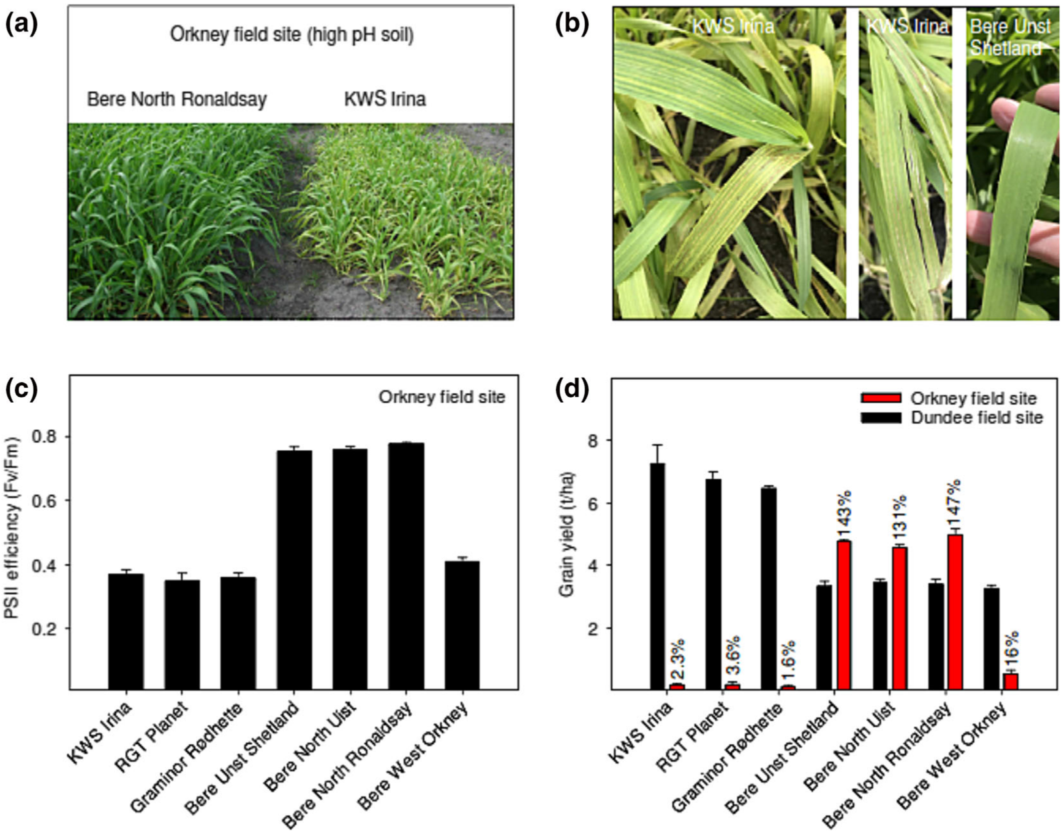


FIGURE 5 Results from field trials comparing the growth of the ancient Scottish barley, Bere, with other types of barley on sites with contrasting availability of soil manganese (Orkney, deficient; Dundee, sufficient). (a) Visual appearance of a Bere accession adapted to growing in manganese deficient conditions (left) and a modern variety lacking this trait (right). (b) Severe foliar manganese deficiency symptoms of interveinal chlorosis and necrotic aligned interveinal spots in the modern variety KWS Irina (left) together with wind-damaged leaves (centre) compared with unaffected leaves of a Bere accession from Shetland (right). (c) Photosystem II (PSII) efficiency (Fv/Fm) measurements for the youngest fully developed leaves of Orkney-grown plants showing the high Fv/Fm values of three Bere accessions adapted to manganese deficient growing conditions (Bere Unst Shetland, Bere North Uist and Bere North Ronaldsay) contrasted with lower values for Bere West Orkney and three modern varieties lacking the trait. Bars represent the standard error of the mean. (d) Grain yields for the barley types shown in (c) from trials at sites with contrasting soil manganese status in Dundee and Orkney. In the figure, modern varieties produced by the plant breeding companies KWS group and RAGT seeds are preceded by the initials KWS and RGT, respectively. (Figure reproduced from Schmidt et al., 2019).

shape was therefore developed by Wallace et al. (2019) using the Hutton's heritage barley collection. Analysis of the GMM data, even from charred grains, produced very similar results to those from genotyping followed by cluster analysis (Wallace et al., 2019), indicating the potential of the methodology for detecting a distinctive GMM Bere signature in archaeobotanical samples. Although the need for many well-preserved grains and the time taken to prepare them have restricted the method's use, new techniques like 3-D imagery combined with machine learning may make similar studies more viable in the future.

5.2 | Bere—a North Atlantic barley?

There are several indications that the significance of Bere may extend beyond Scotland and Ireland to the wider North Atlantic region, which was linked for several hundred years from about the 9th century AD by a common Viking/Norse language, culture and trade network (Perdikaris & McGovern, 2007). Both genotypically and phenotypically, Bere from the Northern Isles is very similar to the Faroese landraces Langaks and Stjernebyg (Drosou et al., 2022; Wallace et al., 2019), and the similarity of Faroese barley to Bere is also suggested by visitors' accounts (Trevelyan, 1835; Williamson, 1970). One possible explanation for this (Drosou et al., 2022) is that Bere may have been taken to the Faroes by early Viking settlers, many of whom came from settlements in Scotland and Ireland (Als et al., 2006). Bere may even have been cultivated there before this, as there was pre-Viking settlement with barley cultivation in the 4th–8th century AD (Church et al., 2013) and a tradition of Irish anchorites settling North Atlantic islands around this time (Arge et al., 2005). Iceland was also settled by a significant number of people from Viking colonies in Scotland and Ireland (Zori, 2016), and so, again, Bere may have been taken there during the early settlement or later through trade, which was the case by the 13th century (Barrett et al., 2000).

Genotypic analysis has indicated that Bere may have been grown beyond the North Atlantic, as two Polish landraces show evidence for gene flow from Bere (Drosou et al., 2022), suggesting hybridisation between Bere and local barley. This might reflect the export of Bere to northern Europe while the Northern Isles were under Norwegian and Danish control or may have resulted from strong historic links between Scotland and Poland (Drosou et al., 2022). Further afield, Bere was taken to North America and grown on the east coast (Briggs, 1978) and probably to Canada (Martin et al., 2009).

It is likely that more will be discovered about the origins and movement of Bere and its wider importance as new archaeological and historical techniques and research foci come online and genotyping and associated analyses of germplasm collections become more common (Milner et al., 2019).

5.3 | Survival and loss of ancient types of barley on North Atlantic islands (AD 1200–2000)

Although similar types of barley to Bere were grown in Iceland and the Faroes from the Norse settlement in the 9th century, only Bere on the Scottish Isles survived in cultivation into the 21st century. While this outcome has undoubtedly resulted from many factors, temperature is likely to have been important, given the high latitude of the islands and the transition from the mild conditions of the Medieval Climate Anomaly (MCA; c. AD 950–1250; Hughes & Diaz, 1994) to the colder conditions of the Little Ice Age (c. AD 1570–1900; Matthews & Briffa, 2005). This was investigated for the period 1200–2000 AD (Martin, Brown, et al., 2023) by combining temperature thresholds for Bere grain production with tree-ring-based reconstructions of annual cropping season temperatures and historic information on grain production, harvest failures and famines. The most favourable reconstructed cropping season temperatures occurred in the Scottish Isles, but even here, crop failure and/or famine occurred in about 12% of years from 1256 to 1836, and about half of these years had reconstructed temperatures likely to result in very low yields (Figure 6; Martin, Brown, et al., 2023). While demonstrating an important association with temperature, this also suggests that other factors, most likely weather-related, also adversely impacted crop production.

Despite the climatic challenges to barley cultivation in the Scottish Isles over the last millennium, their higher cropping season temperatures compared with Iceland and the Faroes likely resulted in more frequent adequate yields and successful harvests. This allowed greater reliance on Bere for food and more frequent surpluses of grain, which were used for export, brewing or distilling. In contrast, the Faroes and Iceland were dependent on imported barley to supplement local production (Guttesen, 1999; Zori et al., 2013). Imports became increasingly attractive (Mehler, 2011) as local productivity declined because of climate and labour shortages (Riddell et al., 2018; Streeter et al., 2012), leading to barley abandonment around 1500 AD in Iceland and in the 20th century in the Faroes (Martin, Brown, et al., 2023).

The use of data from modern Bere crops in the above study (Martin, Brown, et al., 2023) demonstrates how extant ancient crop types can be used to better understand the impact of past changes in growing conditions. Such studies can contribute to the developing field of genome-environment associations (GEAs; Cortés et al., 2022) and may even help identify strategies for adapting to future changes in climate, particularly as warming in the North Atlantic is resulting in renewed interest in barley cultivation in the region (Martin et al., 2017).

5.4 | Experimental archaeology

The growth characteristics of Bere are likely to be much closer to those of barley grown in earlier times in the north of Britain than modern varieties, and this makes it very suitable for experimental archaeology investigations in this region.

One such study included an investigation of the effects of seaweed fertilisation on Bere. Apart from significantly increasing grain production (Brown et al., 2020), this resulted in increases in several elements and isotopes in grain and straw (Blanz et al., 2019), highlighting the need for these effects to be considered in archaeological interpretations, especially for palaeodietary and provenance reconstructions in coastal areas.

With many historical sources documenting the importance of Bere for brewing in Ireland (Flavin et al., 2023), Bere from Orkney was used together with traditional recipes and methods to recreate a 16th-century Irish beer. Detailed analyses showed that the beer was comparable in strength to modern beers, and given the large quantities consumed daily, it would have been a significant source of energy but also had the potential to result in considerable inebriation. This raises several social and cultural questions around beer consumption at this time (Flavin et al., 2023).

6 | DISCUSSION

6.1 | Bere and people

Unusually for such an ancient crop, Bere continues to be grown commercially on farms in Scotland's Northern Isles, particularly Orkney and the Outer Hebrides, providing income from straw and grain on the former and a local source of overwintering animal feed as part of a crop mixture on the latter. As such, it generates value for the farmers on these archipelagos, demonstrating that landraces can still make a valuable contribution to farms, even in countries with advanced agricultural systems. Nevertheless, the islands where it is grown are all in peripheral, less favoured areas,[3] the number of growers is small—probably around 200 in the Outer Hebrides and

[3]The European Union (EU) introduced the less favoured area (LFA) designation to support farming in difficult production conditions. When the United Kingdom was in the EU, Scotland's LFAs were defined by the presence of poor land with lower than average production and areas with dwindling populations dependent on agriculture (https://www.data.gov.uk/dataset/a1ba43dd-569c-47e9-9623-21664aaf49ff/less-favoured-areas).

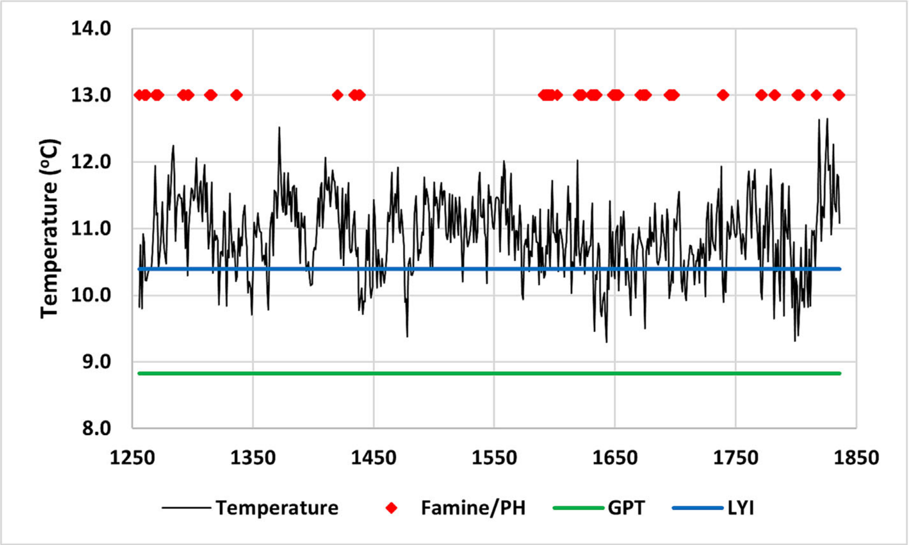


FIGURE 6 Reconstruction of the annual cropping season (April 15–September 30) temperature from AD 1250 to 1850 for the Scottish Isles and the occurrence of years when famine or poor harvests (famine/PH) were recorded in Scotland. The grain production threshold (GPT) and low yield indicator (LYI) are threshold temperatures for Bere below which no grain production and low yields, respectively, would be very likely (Martin, Brown, et al., 2023). In Orkney, poor harvests were documented in the 1630s, 1674–1676, 1690s, 1739–1740, 1782 and 1801–1803 and for most of these years the reconstructed cropping season temperature was below the LYI. In the figure, cropping season temperature was calculated from cropping season day degrees in Martin, Brown, et al. (2023).

fewer than 10 in Orkney—and it is mostly grown on marginal land (Martin, Shoemark, et al., 2023).

In the Outer Hebrides, the landrace mixture value chain is short and provides growers with feed for overwintering cattle, which reduces their need for costly imports, making local beef production viable and allowing high-quality meat to be produced for the local market and hospitality industry.

For Bere grain produced on Orkney, there are many beneficiaries, apart from growers, along the value chains (Figure 2). For food products, these include Barony Mill, numerous bakeries and ultimately consumers provided with Bere products or beremeal, both of which have a distinctive taste and nutritional profile (Theobald et al., 2006) and provide an alternative to wheat flour or oatmeal. Bere food products therefore contribute to increased dietary diversity, which can have positive effects on health and wellbeing (Dwivedi et al., 2017). Bere grown in Orkney for distilling or brewing benefits a relatively small number of malting companies, breweries and distilleries, but beverage products reach a large number of consumers. For example, Bere whiskies are marketed internationally, and well over 100,000 bottles were sold between 2012 and 2022. Both food and drink Bere products provide many enterprises in the Scottish tourism sector with unique, high-provenance offerings.

6.2 | Bere and society

Prior to the 20th century, there was a long tradition in both the north of Britain and northern Europe of using barley for food (Newman & Newman, 2006) because it was more suited than wheat to the region's cool climate. Bere is probably the last ancient European barley still in cultivation, with an unbroken link to this culinary tradition. Also, the availability of beremeal and the preservation of recipes for using it (Ashworth, 2017) allow traditional Scottish barley products to be authentically produced. Furthermore, as an important source of malt, Bere was used for both brewing and whisky production. Since the early 20th century, whisky has been an iconic Scottish product, but its Scottish roots probably go back to at least the end of the 15th century (Moss & Hume, 2000). In the Highlands and Islands, Bere was at the heart of the early industry and would have been used by domestic producers, legal distillers and large numbers of illicit distillers who were renowned for making some of the best quality whisky (Devine, 1994; German & Adamson, 2019). Growing Bere and using it for food and drink products therefore provide an important link with the past and a unique expression of local heritage. 'Tradition' is frequently cited by growers of Bere (Mahon et al., 2016; Martin, Shoemark, et al., 2023) as one of their motives for growing the crop, and heritage is important for marketing most Bere products.

'Tradition' is also linked to the strong and distinctive cultural identities, reinforced by remoteness, of the present Bere growing regions: in the Outer Hebrides, this is Gaelic, while in the Northern Isles, which did not become part of Scotland until 1469, there is still a strong Norse/Scandinavian influence. Superimposed on these cultural identities, especially in the Outer Hebrides and Shetland, is crofting, a small-scale, low-input system of agriculture, land tenure and management (Martin, Shoemark, et al., 2023). In the Scottish Isles, especially the Outer Hebrides, much of the arable crofting land is on Machair. Given the unique ability of Bere and the other cereals in the landrace mixture to tolerate these soils, these have become some of the most important areas for the survival of Bere and the landrace mixture, and growing the crop is intertwined with crofting/small-scale farming, the cultural identity of these islands and conservation of the Machair ecosystem.

On Orkney, where crofting is less prominent, Bere survived in cultivation into the 21st century because of the production of beremeal by Barony Mill in the parish of Birsay. With the remains of several earlier mills in the Birsay area, this has clearly been a key location for growing and milling Bere since at least the Norse occupation, when it was an important power base for the Earldom of Orkney (Bates et al., 2020). So, again, tradition and heritage appear to have been important for its conservation. Coincidentally or not, Birsay is also close to the United Nations Educational, Scientific and Cultural Organisation (UNESCO) heritage site, 'Heart of Neolithic Orkney' (Downes et al., 2005), linking the area to early Orkney agriculture. Apart from conserving Bere and producing beremeal, Barony Mill is an important heritage centre where the traditional machinery, knowledge and skills needed for beremeal production are preserved and passed on to new generations.

6.3 | Bere and planet

Climate change resulting from human activities and greenhouse gas emissions is having a major detrimental global impact on both agricultural production and biodiversity (Ortiz et al., 2021). At the same time, agriculture is a major source of greenhouse gas emissions through land use change and intensive agriculture, and food systems are the major source of habitat and biodiversity loss (Benton et al., 2021). Radical changes in agriculture, including cropping, are required to reduce these adverse effects while at the same time producing sufficient, healthy and sustainable food (Dwivedi et al., 2017) for a rising world population and increasing agricultural resilience to extreme weather events resulting from climate change. Low-input and abiotic- and biotic-stress resilient landraces, like Bere, will probably be a major source of traits required by plant breeders to achieve this transition (Hernandez et al., 2020; Marone et al., 2021; Newton et al., 2010; Schmidt et al., 2023).

Research into traits in Bere that are likely to be of value to plant breeders has already identified adaptations to manganese-deficient soils (Cope et al., 2020; Schmidt et al., 2019), salinity (Cope et al., 2022) and resistance to the foliar disease *Rhynchosporium commune* (Cope et al., 2021) as being of potential value. Earlier research also indicated that some types of Bere may have tolerance to acidic soils (Ellis, 2003; Stølen & Andersen, 1978), and, considering the crop's association with sandy, coastal soils, some Bere accessions may also have tolerance to water-deficit (drought) conditions. Currently, the trait that is closest to utilisation is Bere's adaptation to growing on manganese-deficient soils. Globally, manganese deficiency is common on alkaline soils and is a particular problem in northern Europe, the United Kingdom, Anatolia, southern Australia, parts of China and Texas, where yields can be reduced by 25%–60% (George et al., 2014; Schmidt et al., 2016). Although there are several examples of traits from landraces being incorporated into new varieties (Marone et al., 2021), there are difficulties in doing this (Langridge & Waugh, 2019; Schmidt et al., 2023), so landraces are not fully exploited by plant breeders (Kumar et al., 2020), and there are delays in releasing new varieties (Hernandez et al., 2020). Nevertheless, in the future, new approaches like gene editing, genomic selection and speed breeding are expected to shorten the time it takes to incorporate traits like tolerance to manganese deficiency into elite varieties (Schmidt et al., 2023).

As a genetic resource, on-farm conservation of Bere is important for its preservation and continued evolution. On the Outer Hebrides, the critical role of the landrace mixture in conserving the Machair and its associated biodiversity (Angus & Dargie, 2002; Walton & MacKenzie, 2009) provides another important reason for continued in situ conservation. There are, however, major threats to both the Machair ecosystem and the landrace mixture. Damage from increasing populations of geese and deer to both the landrace mixture and its seed sources is a growing threat to its continued cultivation (Martin, Shoemark, et al., 2023). Future climate change effects are also potentially very serious and include sea-level rise, increased storminess and winter precipitation, and reduced summer rainfall leading to more frequent drought conditions (Angus & Hansom, 2004).

6.4 | Implications for policy and practice

6.4.1 | Policy

Surprisingly, the continued growing of Bere on the Outer Hebrides and the revival of the crop in Orkney have occurred without specific financial support to growers aimed at landrace conservation. It has happened because of the value generated by the crop. This is in sharp contrast to Shetland, where the crop generates little value and where growing Bere has almost been abandoned (Martin, Shoemark, et al., 2023), demonstrating the difficulty of in situ conservation of landraces under these circumstances without financial support measures.

Despite the apparent success of the continued growing of Bere on both the Outer Hebrides and Orkney, there are significant threats to its continued on-farm in situ conservation. In the Outer Hebrides, these include damage by geese, climate change and the possible detrimental effects on the Machair of a wider adoption of some modern agricultural practices (Angus & Hansom, 2004; Owen et al., 2000; Walton & MacKenzie, 2009). On Orkney, there is a risk of overdependence on a small number of commercial markets, and there are also only two producers of seed that grow similar lines of Bere, possibly with restricted genetic diversity.

Given the insecurities in the Bere value chains in Orkney and the Outer Hebrides, conservation could be improved by transferring the models of on-farm conservation that occur there to other islands and developing more short value chains. This would require investment in local processing facilities to food-grade standards and a greater availability of Bere seed, especially lines suited to specific locations and end-uses. As a conservation variety on the UK National List (FERA, 2010), marketing of seed from Bere is permissible within its region of origin, designated as the Highlands and Islands. A recent workshop run as part of an EU consortium project on underutilised crops (RADIANT; https://www.radiantproject.eu/reports/) concluded that safeguarding the future of Bere will require concerted action and most likely a 'strategic action plan'. This should address the threats and issues identified above and would require linked funding support from regional and national governments and local development agencies. Within the United Kingdom, agriculture is a devolved policy area, and so the above strategy could be included in Scotland's developing post-Brexit agricultural policy.

6.4.2 | Practice

The success over the past 20 years in raising Bere's profile and increasing its use and the area grown (in Orkney) provides a valuable case study of landrace conservation with relevance to other locations. A major asset has been Bere's versatility, which has allowed it to be grown for different end-uses in Orkney and the Outer Hebrides, providing more options for growers and value chains. Another significant contributor to this success has been the breadth of activities undertaken and the range of disciplines and collaborations involved.

During the recent commercial revival of Bere, BHT has transformed Barony Mill into a heritage centre for both Bere and beremeal. Assisted by marketing support, the characterisation of beremeal's nutritional profile (Chappell et al., 2017; Theobald et al., 2006), baking properties (Martin et al., 2009) and recipes (Ashworth, 2017), the Trust has extended the small local market for beremeal to other parts of Scotland, achieving international recognition for it by engaging with groups like Slow Food and its Ark of Taste Programme (Saladino, 2021).

For developing sustained beverage markets for Bere, long-term commercial collaborations with malting companies, breweries and distilleries have been particularly important, allowing joint solutions to some of the difficulties of using Bere and demonstrating commercial commitment and belief in Bere. This helped counter initial scepticism about using a barley not on the UK's Recommended List of malting varieties for whisky production. The release of the first single malt Bere whiskies (Martin & Wishart, 2015) helped change attitudes, and since then Bere has been used by several other distilleries and malting companies.

Use of Bere in a global product like single malt whisky has helped raise its profile, which has been reinforced by marketing, especially where a 'grain to glass' approach has been adopted. This has resulted, for example, in the inclusion of information about the crop on Bere whisky packaging and discussions about Bere and related topics on distillery websites and social media platforms. Commercialisation and recent articles and books on whisky (e.g., Broom, 2022; Buxton, 2017; Hornsey, 2017) have therefore taken Bere and landraces to new audiences.

The successful commercialisation of Bere required the development of reliable supply chains. Underpinning this was an agronomy research programme that developed robust recommendations for growing the crop, enabling larger areas of Bere to be grown and harvested successfully and profitably (Martin et al., 2010). Supply chain development also required appropriate machinery, contractors and collaborating growers with spare land (Martin et al., 2009).

The phenotypic and genetic characterisation of Bere has been greatly helped by having access to a comprehensive collection of Bere accessions originating from different geographical locations, agroecosystems and time periods and having a wider collection of heritage and modern barley for comparison. A demonstration of Bere's tolerance to manganese-deficient soils (Cope et al., 2020; George et al., 2014; Schmidt et al., 2019) and the potential importance of this for developing more resilient modern barley established Bere as a valuable genetic resource.

Several multidisciplinary studies have helped raise Bere's heritage profile and have taken it to new research areas, notably archaeology (Wallace et al., 2019), experimental archaeology (Blanz et al., 2019; Flavin et al., 2023), biomolecular archaeology (Drosou et al., 2022) and climate change (Martin, Brown, et al., 2023).

The model developed in Orkney of assisting in situ conservation of a landrace by developing food and drink markets and new value chains has potential for replication in other countries and has influenced similar initiatives in northern Norway and the Faroes (Halland et al., 2020; Martin, 2016). In these areas, there are also well-adapted landraces but few modern varieties suitable for local conditions.

7 | CONCLUSIONS

Recent research and commercialisation activities with Bere have rediscovered its historic importance to Scotland, especially the Scottish Isles, and supported a culinary cultural revival of Bere as a source of beremeal—one of the last European barley flours—and malt for beer and whisky production. The continued cultivation of Bere in both the Northern Isles and Outer Hebrides can be attributed to the diverse ways it can be used by growers and end users and, especially, its adaptations to the region's climate and marginal soils. In some locations, there are still no better-performing modern varieties. Additionally, in the Outer Hebrides, traditional cultivation of a cereal landrace mixture including Bere provides an important ecosystem service that is crucial for conservation of the Machair's biodiversity.

In situ conservation of Bere and the landrace mixture could be strengthened by exploiting the potential of these crops to be grown more widely on Scottish islands for greater on-farm use or sale of grain. This could be encouraged within an integrated strategy for landrace conservation on Scottish islands, which should also address threats to future sustainable growing posed by geese, climate change and modifications to traditional cropping practices.

An extensive, new collection of Bere and other heritage barley accessions held by the James Hutton Institute has enabled a diverse range of multidisciplinary studies that have helped to establish the distinct identity of Bere and indicated an ancient introduction to the Scottish Isles. Crucially, the collection has allowed the identification of several traits in Bere, especially its ability to grow in manganese-deficient soils, of major significance for the development of more sustainable and resilient barley varieties, underlining Bere's value as a genetic resource.

AUTHOR CONTRIBUTIONS

Peter Martin, Timothy S. George and Joanne Russell developed the concept. Peter Martin, Timothy S. George, Joanne Russell, John Wishart, Michael Wallace, Pietro P.M. Iannetta and Lawrie K. Brown all contributed to producing the manuscript, which was co-ordinated by Peter Martin.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author on reasonable request.

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