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The elm is dead! Long live the elm! New developments for elm conservation in Scotland

By Euan AD Bowditch and Elspeth Macdonald

Abstract

Elm species across the world have been ravaged by Dutch elm disease (DED) and there seems to be general pessimism about the ecological and economic contributions of the elm, and ultimately its survival. Some optimism exists, however, about the potential for selective breeding of elm that demonstrates resistance to DED. In the spirit of thinking globally and acting locally, this paper builds upon prior proposals for a wych elm (*Ulmus glabra*) conservation strategy for Scotland. A new analysis of the (macro) distribution of elm across Scotland is presented and the need for more information about the (micro) distribution of the species and its genetic structure, within both infected and disease-free woodland, is highlighted. This will help researchers define and understand the ecological positioning of the species and its restoration potential if reliable DED-resistant planting stock becomes available. Clonal material from trees which have survived DED will figure prominently in breeding programmes, but refuge areas may be required to supply clones with other distinctive adaptive traits and genetic variation. Sequencing the elm genome will play a crucial role in understanding variation, and identifying adaptive traits that can aid DED resistance. A survey of environmental professionals found that many underestimate the extent of the surviving elm resource in Scotland. At the same time, elm was viewed as an important native woodland species for biodiversity, structure, amenity and timber which is thought to be worth restoring on a landscape scale.

THE AUTHORS

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Introduction

Forest health is a global issue that threatens the forestry sector, biodiversity and rural economies. Forest pests and pathogens that target numerous tree species are on the increase in the UK, with many iconic species on the frontline (Freer-Smith & Webber, 2017). Some pests and pathogens have devastated key species, resulting in irrecoverable landscape damage and changes in woodland structure, while others exist relatively unnoticed.

Most tree disease outbreaks capable of wiping out significant proportions of a species' population are aggravated by travel and trade, which can rapidly advance disease progress across landscapes and continents that would have otherwise taken centuries or millennia (Martín et al., 2019).

Some scientists have suggested that an evolutionary approach to tree disease management should be adopted, stating that, with time, ecological processes will find a new structure and equilibrium, adjusting to the loss of species and trivialising any human intervention efforts (Ennos, 2015). While this approach offers one long-term perspective, the significant impact of human activity and the potential cumulative effects of management and research into tree diseases should not be discounted. The complex interactions between humans and their environment may cause the spread and development of aggressive pathogens, but these interactions can also formulate actions and behaviours that could reduce and prevent further wide-scale devastation (Folke et al., 2016; Carpenter et al., 2019).

Dutch elm disease (DED) is caused by a fungal pathogen (*Ophiostoma* spp.) which is disseminated by bark beetles (*Scolytus* spp.). Nearly a century on from the first outbreak of DED in Britain in modern times, we still struggle to understand and manage the spread of the disease and are vulnerable to a large outbreak again. The reach of DED is global, with outbreaks and continual management issues being faced in various countries including the USA, New Zealand and Sweden. This paper discusses the current status of DED in Scotland and the recent foothold of the disease in the Highlands.

Elm in Europe

Three species of elm are native to Europe, all of which are susceptible to DED. Field elm (*Ulmus minor*) is a variable species with a natural range extending across Europe and into Central Asia, northern Iran and north-west Africa. Several single-species clone selections of ancient origin, that were formerly recognised as species in their own right, are now classified as field elm (Martín et al., 2019). These include the iconic English elm (formerly *U. procera*), which genetic studies have shown to be a field elm clone first introduced to Britain 2,000 years ago (Gil et al., 2004). White elm (*U. laevis*), which has a natural range extending from central France to the Urals, is only found in Britain as an ornamental or street tree.

The one elm species that is truly native to the UK is wych elm (*Ulmus glabra*) which grows in the northerly and sub-montane areas of Europe (**Figure 1**). In Britain, this species is mostly found in Scotland (Brasier, 1996). In the southern part of its distribution the species is found in upland areas, earning its name of 'mountain elm' (Collin et al., 2000).

Wych elm favours moist forests with rich soils, and riparian areas within semi-boreal and temperate climates (Collin et al., 2000; Thomas et al., 2018). In Britain's National Vegetation (NVC), wych elm was only constant in W8e the lowland ash-dog's mercury (*Mercurialis perennis*) woodland, herb Robert (*Geranium robertianum*) sub-community, the W8 sub-community encountered most in Scotland. In Scotland it was also recorded in W7 common alder-ash-yellow pimpernel (*Lysimachia nemorum*) woodland, a riparian community; W9 upland ash-rowan-dog's mercury woodland, and W10 oak-bracken-bramble woodland, but was never constant (present in 80% or more of samples) in these types (Rodwell, 1991).

Wych elm is not abundant or dominant anywhere within its range, being described as a non-gregarious tree which has important landscape and amenity value (Thomas et al., 2018; Martín et al., 2019).

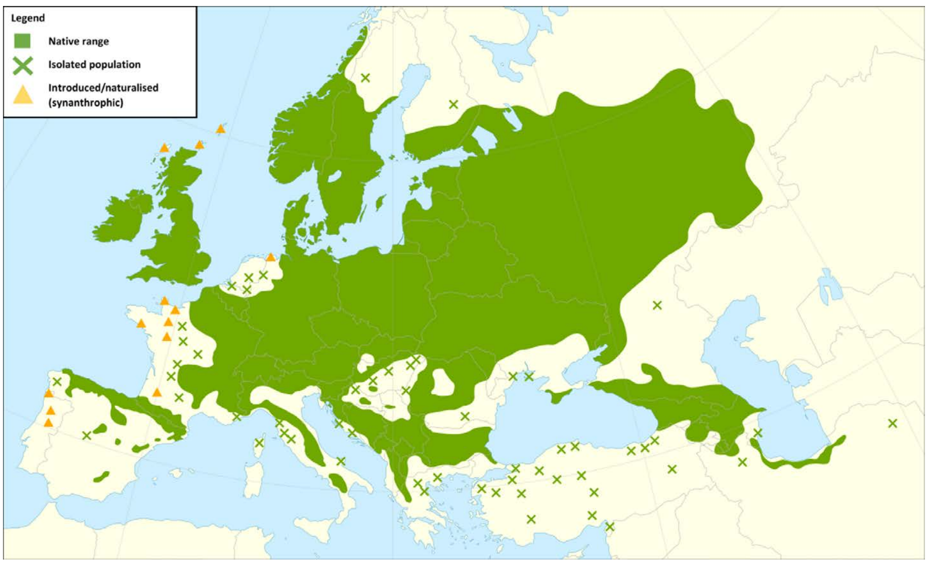

Figure 1. European wych elm (*Ulmus glabra*) range (Caudullo et al., 2017).

Dutch elm disease in northern Europe

Although DED has devastated elm populations in Sweden (Menkis et al., 2016), both Finland and north-eastern Russia remain unaffected, with no records of the presence of *Scolytus* spp. This is thought to be mainly due to the low volume of trade in untreated wood products and saplings for planting (Hannunen and Marinova-Todorova, 2016). In Estonia, the health of elm species has deteriorated and the presence of DED has been confirmed (Jürisoo et al., 2019). It was thought to have potentially been transmitted through trade in wood products from neighbouring countries (La Porta et al., 2008). A recent study of multiple areas in Estonia found, for the first time, the presence of *Ophiostoma novo-ulmi* subspecies *novo-ulmi* and *americana*, which appeared to be more aggressive toward wych elm than towards white elm in both vitality and mortality of trees (Jürisoo et al., 2019). DED has also been detected in Latvia, where *O. novo-ulmi* was discovered in 62% of wych elm and 34.5% of white elm; as in Estonia, both subspecies of *O. novo-ulmi* were identified (Matisone et al., 2020).

DED in the UK

Archaeological evidence has suggested that DED may have been a contributory factor to the period of Neolithic elm decline which saw a sudden, deep and prolonged reduction in elm across Europe, together with climatic and anthropogenic factors (Batchelor et al., 2014). In modern times, there have been two distinct incursions of DED in the UK. The first took place during the 1920s–40s, when the *O. ulmi* fungus caused a European epidemic (Gibbs & Brasier, 1973). The second occurred from 1962 onwards when *O. novo-ulmi*, a more aggressive species of the pathogen, caused devastation to the British elm population (Brasier & Kirk, 2001).

The spread and impact of DED continues to be a problem, and management of the disease has been largely unsuccessful. Pockets of healthy elm survive in the UK and seemingly resistant specimens are being cultivated, monitored and trialled in various locations (Brookes, 2016; Resistant Elms, 2020). Elm trees tend to remain uninfected by DED until they have matured, normally between 15–20 years old. This has been highlighted by numerous management authorities, as cycles of renewed infection have been identified after periods of relatively low activity, re-emerging via successional patterns (Potter et al., 2011; Brighton and Hove City Council, 2019; Isle of Man Government, 2020).

The case of DED in Britain highlights the devastating impact pests and diseases can have on woodlands and landscapes across diverse scales (from local to pan-continental), resulting in the loss of important and iconic tree species where future planting is viewed as futile (Potter et al., 2011). The response to DED may also provide lessons for dealing with subsequent outbreaks (Tomlinson & Potter, 2010). It has been suggested that underestimating the severity of the outbreak, and a lack of coordination and management at national level, were major failures in appropriately responding to the threat of DED (Potter et al., 2011).

English elm suffered the greatest losses to DED in Britain, while the spread of the disease into wych elm, most prominent in northern areas and Scotland, was slower. This is despite research showing that wych elm is more susceptible to the fungus and is favoured by the beetle over other elm species, (Anderbrant et al., 2017). It is thought that a less favourable climate has contributed to the slower spread of DED northwards into wych elm (Brasier, 1996; Coleman et al., 2016).

A recent study (Hessenauer et al., 2020) has suggested that individual host trees play an important role in the functional capacity of the DED pathogens, highlighting the vital work of identifying, recording and breeding individual trees with potential innate resistance.

Elm in Scotland

There is optimism that elm species have a part to play in the future of Scottish woodlands, as an element of a diverse native mix of species that enhances resilience to potential threats. DED has only recently spread into areas of the northern Highlands, a landscape dominated by extensive open upland areas, where wych elm can be found in fragmented broadleaved woodlands. However, the spread of DED is increasing and it has recently jumped across to Ullapool on the west coast, extending the previous DED zone (identified by Scottish Forestry) by 40 miles.

The aim of the study reported here was to collate and build on the limited information available about the spread of DED in the Highlands, and to identify possible strategies for elm conservation.

Methods

A mixed-methods approach was used to gather data on the distribution of elm species and the spread of DED. Research included analyses of data from the Native Woodland Survey of Scotland (NWSS); a survey of environmental professionals; land manager interviews and site visits.

GIS mapping

The NWSS (Forestry Commission Scotland, now Scottish Forestry, 2014) was the central dataset for this analysis. A pivot table was created for all records of elm in Scotland, using the species-structure table, and then split into former Forestry Commission Scotland (FCS) conservancies, which were further sub-divided into Highland electoral districts (OS, 2021) to assess the population dynamics at local levels. All elm records were compiled and presented in a distribution map, which also quantified the percentage of elm present in a stand, as a proportion of total woodland cover. Near-neighbour and cluster analyses were then performed to highlight any significant spatial relationship between the areas. Subsequent analyses examined the age structure of elm species and deer browsing pressure.

Survey – environmental professionals

An online survey was designed to assess a diverse range of topics about elm species and DED in Scotland. This included open and closed questions on:

- current knowledge of the species and history
- current knowledge of DED and history
- ecology and related species
- use and products
- attitudes and perceptions
- locations of healthy, unhealthy and infected specimens.

The survey was sent out to a wide range of forestry and environmental public-sector organisations, NGOs and private estates across Scotland. In total, 80 surveys were returned; all responses were kept anonymous and assigned a number. Results were collated and converted to charts with any open text answers being grouped in relation to the questions and run through thematic analysis in NVivo (QSR International Pty Ltd).

Interviews

Eight interviews and four site visits took place with land managers and owners with experience and knowledge of elm and DED. These interviews helped to flesh out local knowledge about the extent, history and timeline of DED in the Highlands, as well as areas of elm woodland or healthy specimens. During interviews, the landowner or manager showed the researcher areas of the estate or land where both healthy and DED-infected elms were situated, describing

Table 1. Elm and native woodland area extrapolated from the NWSS by former FCS conservancies (Scottish Forestry, 2014).

Region	NWSS woodland area (ha)	NWSS broadleaved woodland area (ha)	NWSS area of elm (ha)
South Scotland	40,798	31,240	452
Central Scotland	40,010	31,620	445
Perth and Argyll	100,407	68,674	393
Grampian	58,347	24,188	229
Highlands and Islands	161,265	51,479	338
Scotland	400,827	207,202	1,857

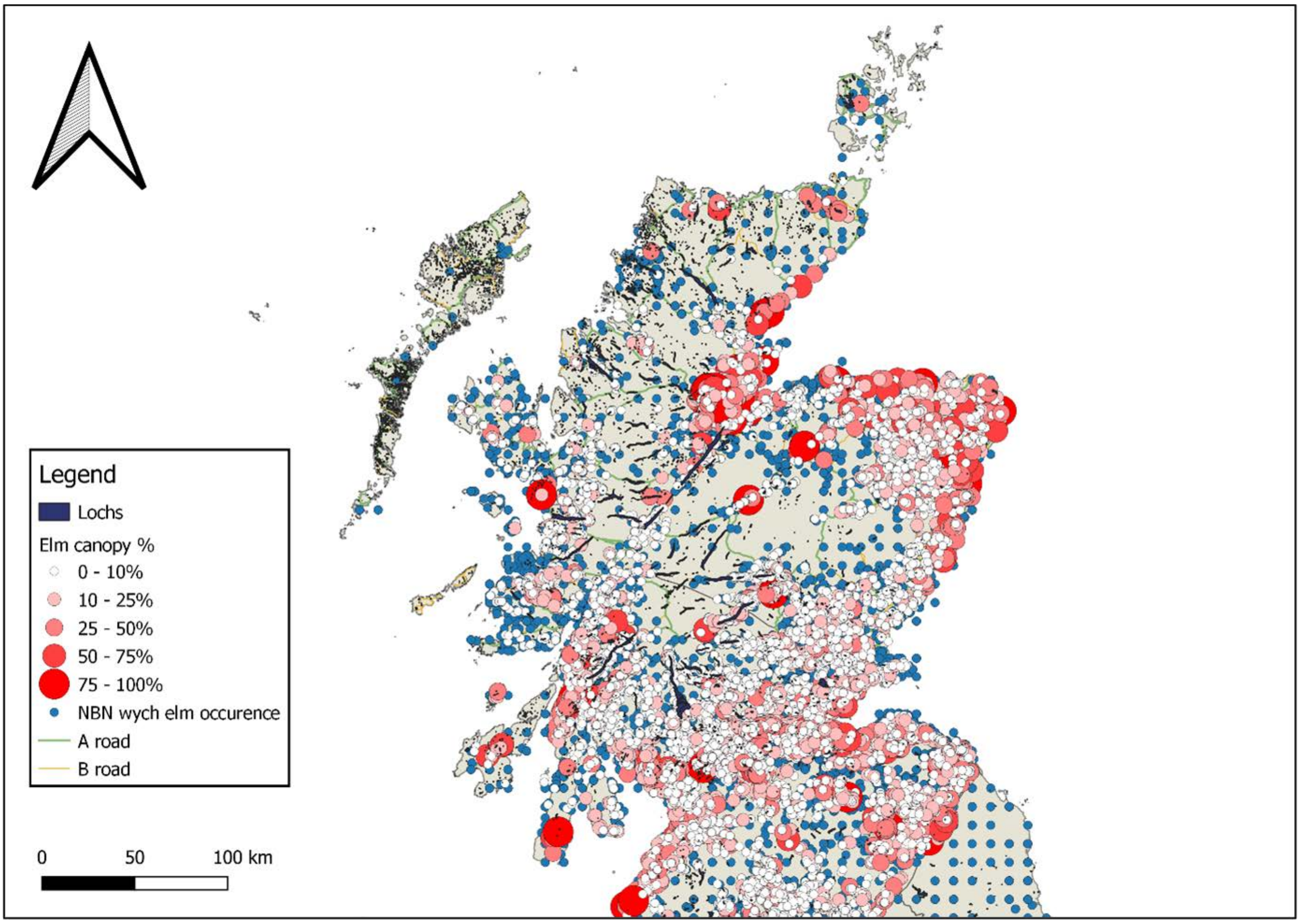

Figure 2. Distribution map of wych elm in northern Scotland. Percentage ranges in the legend represent the proportion of elm present in a woodland polygon (Scottish Forestry, 2014; National Biodiversity Network Atlas, 2021).

past and present management responses, as well as future elm management and use. Interviews were recorded, transcribed and thematically analysed.

Results

Extent, distribution and condition of elm woodland (NWSS and NFI data)

Elm woodland in Scotland extended to 1,857ha, which represented 0.13% of national woodland cover. Of this 338ha were in the Highlands (0.11% of woodland cover)(Scottish Forestry, 2014). Elm accounted for 0.9% of all broadleaved species in Scotland (43% was birch). **Table 1** shows the breakdown of elm resources over former FCS conservancy boundaries, in comparison to native woodland and native broadleaved woodland areas in Scotland.

When analysing the percentage of elm canopy cover in woodlands (**Table 2**), the Highlands had the second highest area with 25%+ canopy cover and the highest area with 50%+. This was more than double that of any other Scottish conservancy, indicating that the Highlands had a significant proportion of established elm wood structures.

The distribution of woodland containing elm, categorised by estimated elm canopy cover percentage, is shown in **Figures 2 and 3.** The main concentrations of Highland elm are at the east end of Loch Ness and around

Table 2. Percentage of elm component in various woodland types, based on data from the National Forest Inventory (NFI) (FC, 2011) and the Native Woodland Survey of Scotland (Scottish Forestry, 2014).

Region	Elm in broadleaved woodland (%)	Elm in native woodland (%)	Count of woodland areas with elm	Elm canopy cover* (%)	Area with 25%+ elm canopy cover (ha)	Area with 50%+ elm canopy cover (ha)
South Scotland	1.4	1.1	3,968	4.2	153.85	21.72
Central Scotland	1.4	1.48	3,393	3.9	108.5	12.99
Perth and Argyll	0.57	0.39	3,220	3.4	62.77	22.79
Grampian	0.95	0.39	1,908	5.4	75.42	24.88
Highlands and Islands	0.66	0.21	1,911	4.9	100.83	45.93
Scotland	0.9	0.48	14,400	4.35	501.37	128.31

* Elm canopy cover is an estimate of the canopy area of elm (in any woodland containing elm), as a proportion of total canopy area.

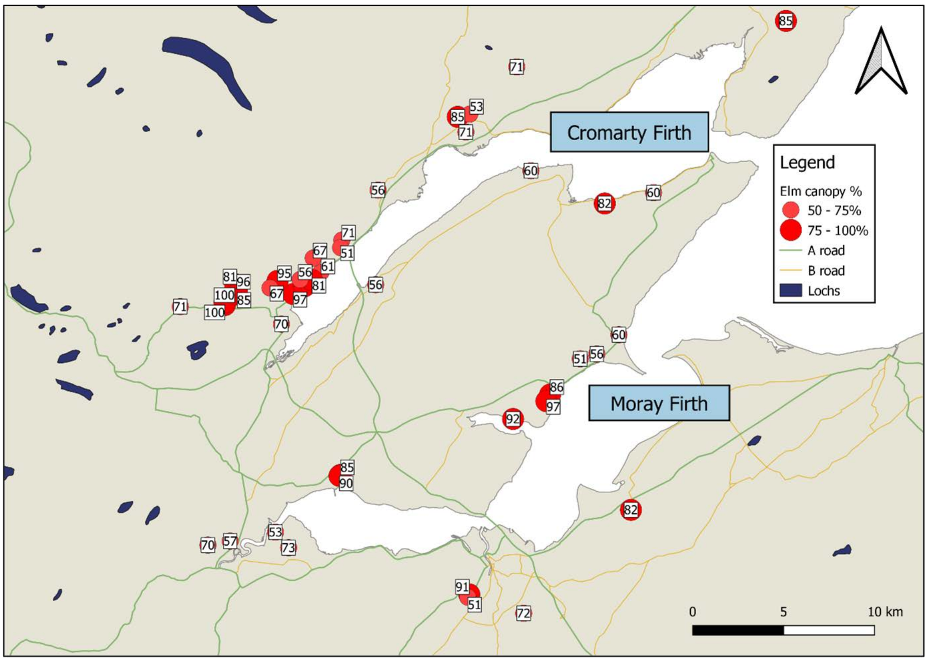

Figure 3. High density of elm canopy cover around three east coast Highland Firths (Scottish Forestry, 2014). Boxed numbers represent percentage of elm cover in a woodland area.

the Black Isle, on the basalt soils of Ardnamurchan and Morvern and on the Sleat peninsula on Skye. In the 25%+ and 50%+ of canopy cover categories, the Cromarty Firth, Black Isle, Dingwall and Loch Ness show the largest areas; these are all within the known DED zone.

Woodland population linkages run up the east coast of the Highlands into a large density of elm around the Loch Watton area in Caithness. Another linkage follows the Caledonian Canal down to Fort William from Loch Ness. An additional corridor appears to be emerging from the Dornoch Firth along the Kyle of Sutherland and northward along the A9. The Ardnamurchan cluster links to small snaking populations northward along the west coast to the Loch Carron area.

Figure 4 illustrates that areas of elm woodland are subject to medium to high grazing levels, with only 5.5% of the area subject to low levels. This informs **Figure 5** that compares the structural succession of elm for both Scotland and the Highlands, highlighting the lack of regeneration and pole stage trees in the Highlands in comparison to the Scottish average, which could be the result of heavy browsing. The majority of the Highland elm resource (62.4%) is mature trees. This could also indicate the greater survival rate of trees to maturity in the Highlands due to the short timeframe of DED in these areas.

Spread of DED in Highlands and Islands (information from survey and site visits)

Baseline data provided by FCS in 2016 tracked DED as far north as Dornoch, and the westerly extent as far as Beauly and Drumnadrochit, with evidence of vectors travelling in from the east from Aberdeenshire and from the south via the A9. There has been speculation as to why the disease has taken longer to reach and penetrate through the Highland landscape, with possible reasons including the tolerance of wych elms, fragmented woodland populations, relative lack of human infrastructure, a less favourable climate for the beetle and a lower intensity of travel compared to other areas of Scotland. However, the rise in popularity of wood burners around 15 years ago could have expedited the spread of the disease, as firewood is an identified vector in countries with similar DED issues. The transit of elm logs, especially those that have not been debarked on site at extraction, can provide a vector into areas where DED has not yet reached. Transport of trees and logs across the landscape creates a leapfrogging effect, delivering beetles, larvae and fungi to locations that would have taken them years (maybe decades) to reach without

Figure 4. Deer browsing pressure on elm woodland in the Highlands (Scottish Forestry, 2014).

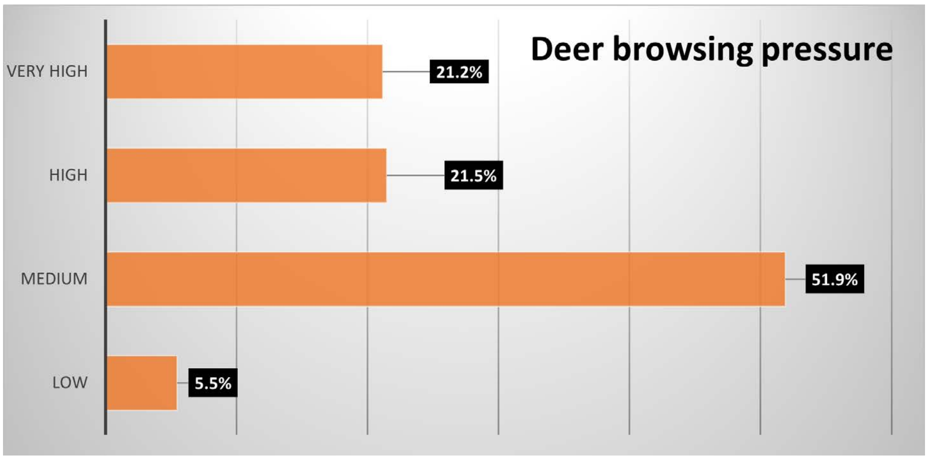

Figure 5. Successional structure of elm population over Scotland and the Highlands (Scottish Forestry, 2014).

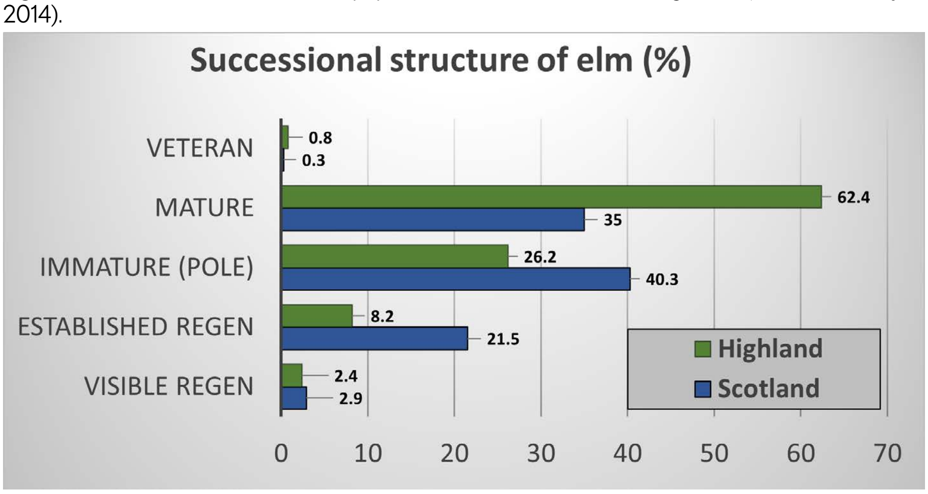

Figure 6. *Scolytus* (beetle galleries) and DED infected elm stem.

human assistance (Gadgil et al., 2000; Brasier, 2008; Tomlinson & Potter, 2010; Potter et al., 2011; Santini et al., 2015; Wainhouse and Inward, 2016)(**Figure 6**).

Current information from this research and reports by Scottish Forestry staff have identified DED as far north as Helmsdale and Wick and as far west as Ullapool, and have also witnessed advancement down the Great Glen to Invermoriston and Fort William. The main vectors of DED appear to be the A9 traversing the entirety of the Highlands from Perth in the south to Thurso and Wick (A99). Additionally, the A82 travels south-westerly from Inverness all along the Great Glen by the side of Loch Ness. The A96 linking Aberdeen to Moray and Inverness, and the A835 linking Inverness to Ullapool also appear to be vectors for DED spread, given the timeline of disease emergence.

As with the DED-infected populations, areas with healthy and uninfected wych elm are unmapped and also geographically dispersed. Healthy populations of wych elm have been observed within infected areas, with even neighbouring trees remaining healthy while others around them die (**Figure 7**). Whether this takes the form of field resistance (trees less attractive to the beetle) or genetic resistance (possessing inherent resistant traits) will require further investigation, as will the surrounding species, land uses and landscape. A key factor in assessing surviving specimens is developing background information on how long areas have been infected and the speed at which the disease has been spreading. It may be that healthy individuals will succumb as the disease spreads.

Populations in the north (beyond Brora) and west of the Highlands were only confirmed as infected in 2020. Populations in Caithness and Sutherland remain mostly healthy, as do populations in the relatively isolated Ardnamurchan area, especially around the coast. The islands of Skye, Raasay, Rum and Canna, Isla, Mull and Arran have mature populations of healthy elms. The most extensive and high-density areas of elms in the Highlands are:

- Fort William and Ardnamurchan
- Aird and Loch Ness
- Black Isle
- Wester Ross, Strathpeffer and Lochalsh
- Cromarty Firth
- Dingwall and Seaforth
- East Sutherland and Edderton.

Many of these areas are highly infected but would merit further surveying for healthy individual specimens or clusters.

Importance of wych elm to natural heritage (survey and interview data)

Most land professionals assumed that elm was a rarity and any that exist are infected with DED. Most referred to elm in the past tense, 'as a memory', no longer an active component of native woodland structures; a lament to a lost species. Landowners held this view more strongly than most, believing remining specimens to be under a death sentence and that it was only a matter of time before they succumbed to the disease. This may be true, as infected trees will often produce healthy secondary growth, which survives for some time but usually succumbs to DED in 10–15 years (Brasier & Webber, 2019). Natural regeneration and juvenile trees are also vulnerable to transportation of DED through grafted root connection from nearby infected mature trees, meaning the beetle and larvae need not be present and active to spread the fungus within a local area or cluster of woodland (Menkis et al., 2016).

The perception of elm as a disappearing tree species was demonstrated by an art exhibition in 2018 centred on drawings of dead and dying elms around Cromarty, one of the most densely populated areas of elm in the Highlands. This exhibition displayed the plight and impact of DED and its perceived legacy, with no mention or hint that elm still survives amongst the damage and deterioration, with healthy mature elms a few hundred yards from infected trees offering hope for restoration.

Despite the assumption of the elm's untimely demise, many land professionals recognised its important role in supporting biodiversity in a region sparsely populated with mixed broadleaved woodland:

'it's a vital component for mixed habitats', also as, 'an important species, which is leaving a gap that cannot be filled by other species in its place'. One respondent highlighted that 'if we keep losing key broadleaf species to pests and disease without responding, what will we have left in the way of native woodland?'

The rapid spread of DED and loss of elm seem to be mostly associated with England and central and southern Scotland, with the Highlands being forgotten:

'I thought that we did not have elm to be infected, especially in more northerly parts of the country, outwith the natural range'.

Other professionals were more acquainted with the occurrence of the species:

'I see elm every day when I travel to work and in different places where I work, healthy ones too, and regeneration'.

Such statements support the need to capture casual observations, from this geographically-dispersed knowledge base of where elm still thrives, into long-term monitoring plots.

All survey respondents were in agreement about the value of elm as a landscape tree, a key species in native woodland structures and for biodiversity, as it supports many specialist species.

'Its loss has become more important with the arrival of ash dieback, because ash often substituted for elm. Lowland [NVC] W8/9 woodland used to be called ash-elm woodland and now both principal species are liable to be lost, which is ecologically devastating ... It can be locally important as a landscape tree.'

Other respondents were more succinct and focussed on the aesthetics of the tree: 'Magnificent ... Beautiful ... Rare ... Majestic ... Precious and Iconic'.

Although many survey respondents feared for the future of elm as a widely functioning component of ecosystems on a national level, they highlighted that elm can still play an important role in more dispersed local landscapes:

'It's an important farmland and hedgerow species, but also important as a riparian species particularly in west ravine woodlands.'

Riparian areas, straths and glens, and the boundaries of arable land, were the most common and suitable locations for elms identified by respondents (barring native woodland structures).

Most of the respondents had a high awareness of DED and admitted that their knowledge of elm as a species 'was connected to DED and its infamous legacy'. As a result, memory of elm and current knowledge are strongly associated with an aggressive and efficient disease or as a highly vulnerable species. Respondents emphasised the strong link between wych elm and Scotland, stating that:

'it is a part of Scotland's natural heritage and should be safeguarded against threats and seen all over the landscape'.

Elm – the timber product

As a timber, elm is viewed as highly valuable and versatile. It is historically an important British timber used for ship building, and is prized for its strength, flexibility and water resistance (Albion, 1952; Bass, 1992; Coleman, 2009; Burton, 2013). According to survey respondents, elm was historically adapted for many uses including cladding, wheels, water pipes and drains, coffins and even for piers. Now the timber is used either for specialist furniture and small wood crafts, or woodfuel.

Only 30% of processors from the Association of Scottish Hardwood Sawmillers (ASHS) specifically milled elm, with a sporadic supply. An individual elm tree from the Black Isle was sold for £13,000 in 2013; while this is an exceptional price it also highlights the value of elm as a timber product, with the rarity of supply due to DED, and burr wood driving up the value.

'Elm can be a highly decorative timber, and quite sought after as the Dutch elm disease spreads ... there is an element of rarity value of course'.

Sawmillers who used elm stated that price varied depending on the quality, anywhere between £120–£200/m^3, and thought that wych elm was an untapped timber which could develop into a valuable niche market within Scotland. Processors agreed that:

'*Ulmus glabra* produces beautiful straight trunks ... yielding excellent stable timber ... and its colour, figure, grain, strength, stability once kiln-dried, in short, provides desirable and beautiful appearance'.

Discussion – elm resilience, restoration and future

The last century has been a turbulent one for elm species across the globe, with millions of trees succumbing to DED and remaining populations still as vulnerable to infection today as they were when DED first emerged. However, there are many people and organisations that remain impassioned and continue to work towards the restoration of elm. Despite the knowledge of elm locations in the Highlands and Islands of Scotland, there has been no holistic survey to track infected, stressed and healthy individuals and areas of elm. Most of this information comes from individual observation and anecdote. The current expanding line of the infected area will probably reach all parts of the UK, but even within the most densely-infected zones across Scotland, individual trees survive while neighbouring trees succumb to DED.

There is a clear will to address the plight of the elm, even in the face of pessimism and assumption that all elms are living on borrowed time. The species is prized for its wood, which is extremely versatile and sought after, and would

Figure 7. Dead elm from DED (left) and healthy elm (right) within 50 feet of one another in the Loch Ness area.

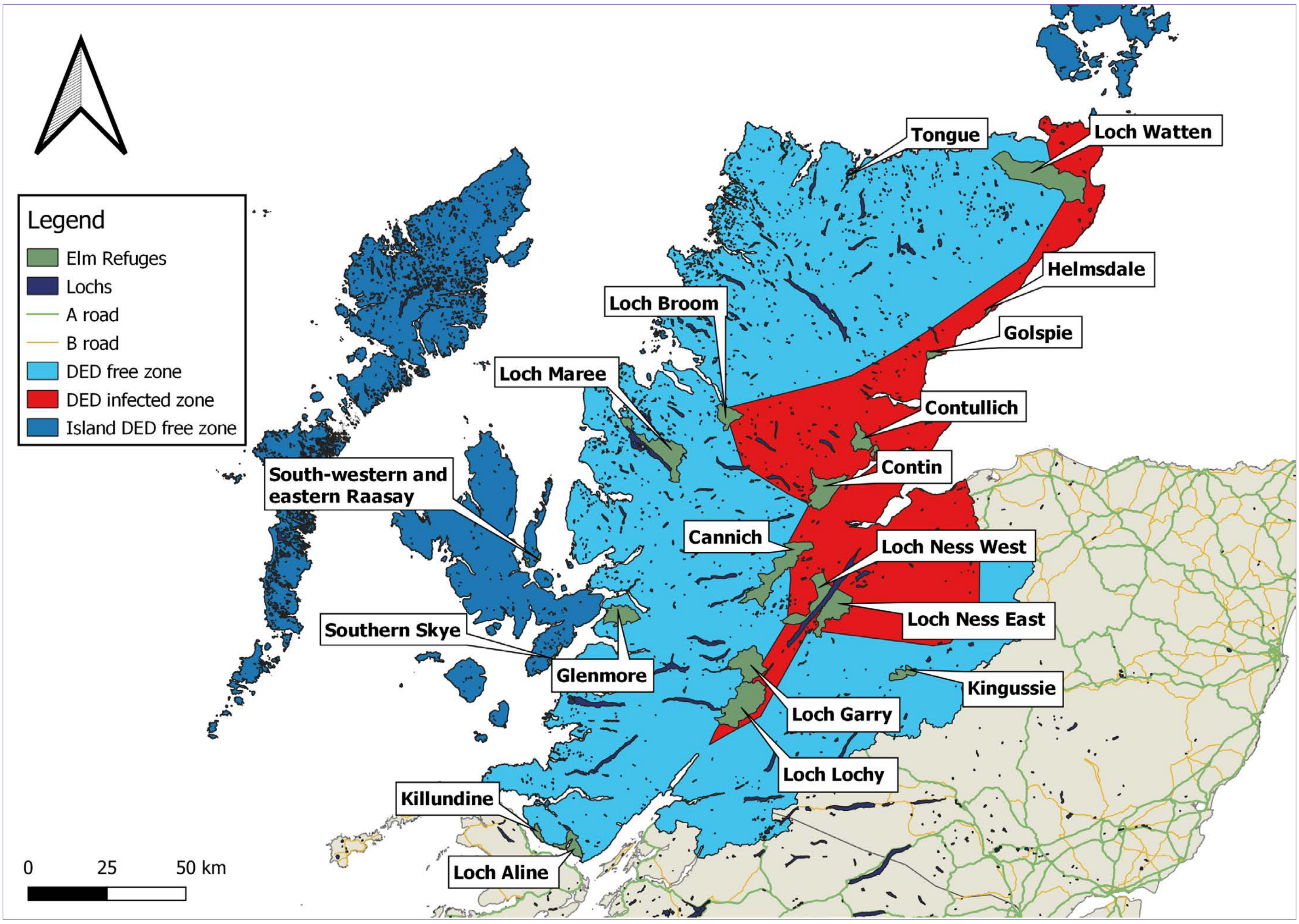

Figure 8. Map of proposed elm refuges and extent of DED spread in the Highlands and Islands. Further DED spread has occurred since the Bowditch and Macdonald (2016) report.

be able to meet high demand if market supply increased. A renewed interest in elm has been stimulated by the work of a number of individuals and organisations around the UK, and by advances in breeding and genomic techniques and technology. Now seems to be the time when elm may be brought to the forefront of tree health concerns.

Elm refuges

One possible conservation strategy that has been proposed is the establishment of elm refuges in the Highlands and Islands to protect, conserve and study the remaining healthy elm populations (Bowditch and Macdonald, 2016). **Figure 8** shows the geographical spread of proposed refuges, based on local hydrological units and areas of connected forests within which healthy elms persist. Twenty-one refuges were proposed, spanning the entire Highlands and Islands region, including Skye, Raasay and some of the most northerly areas of Scotland. Other refuges that were in and on the boundary of infected areas were included for more constructive monitoring of healthy/ resistant trees within an infected zone.

The creation of monitored conservation areas within the most densely infected areas could be used to identify individuals that may have resistant traits which could be used in a breeding programme to help local restoration efforts. These efforts should extend into central and south Scotland where the disease has been present longer and the disease transmission rate has been more intensive, offering the greatest possibility for identifying resilient trees. The overarching goal would be to create a network of refuges in the Highlands of Scotland, perhaps even nationwide, as long-term monitoring areas. Additionally, a network of healthy elms could be collated across multiple regions and islands in Scotland for both breeding and genetic testing, creating germplasm collections of living elms at safe sites for genetic conservation and research. These would be supported through a combination of remote technology, citizen science, landowners, research bodies and national agencies. This approach could also be extended to both wych and field elm in England.

The core aim of refuges is to capture new knowledge about species composition, as well as the management actions and control measures put in place to preserve, restore and enhance a species, so they might be replicated elsewhere (Reside et al., 2019). Selwood and Zimmer (2020) identify that few refuges describe environmental characteristics, therefore recording this detail of information (e.g. NVC data combined with localised characteristics) would make the application of research findings relevant beyond the individual sites and contribute to wider evidence-based conservation management. In elm refuges, the species composition could be an important factor, which could be recorded through a combination of observation and eDNA analysis.

Elm refuges would adopt an ecosystem approach to identify environmental factors that would influence resistance of elms to DED, but also identify woodland structures that may prove resilient and act as buffers. A recent paper by Grosdidier et al. (2020) identified that landscape characteristics significantly influence the development and spread of ash dieback. The disease is found to be less prevalent at low densities of ash and in open areas, such as hedgerows and isolated trees. This finding supports the establishment of refuges for elm where the spread of DED appears to be reduced in smaller and isolated populations with less connectivity to major vectors, such as thoroughfares for transport across the landscape. Islands along the west coast of Scotland, from Lewis down to Arran, might be the easiest populations to protect.

Genomics approach

The science of genomics may offer an alternative means of conserving wych elm, by enabling genetic markers for disease-resistance traits to be identified and selected in breeding programmes. The wych elm genome is currently being sequenced by the Darwin Tree of Life project.

Through the Darwin Project, the giant and coastal redwoods (*Sequioadendron giganteum/sempervirens*) genomes were mapped, proving incredibly complex at 8 billion and 27 billion DNA base pairs (Save the Redwoods League, 2020).

Recently, more relevant to the UK, the European ash (*Fraxinus excelsior*) genome was mapped, as part of an urgent response to the impact of ash dieback (Sollars et al., 2017).

The elm genome is larger than birch, oak and ash: the 28 species measured with cytometry have between 1.5 and 2.1 billion base pairs (Whittemore and Xia, 2017; Russel & Buggs, 2020). This makes the prospect of sequencing *Ulmus glabra* and *minor* genomes relatively straightforward compared to the redwoods and most conifer species (Russel & Buggs, 2020).

Sequencing a single *Ulmus* species will not be sufficient to gain a true insight into adaptability and genetic differences that lead to resistance in elm species in Europe; North American and Asian species should also be sequenced to identify the variants of adaptation across the genus. A first step from the UK's perspective would be to sequence the genomes of *Ulmus glabra, U. minor and U. laevis* and proceed with a genome-wide landscape study of elm species surviving in infected populations, those surviving remotely and those that are susceptible to the disease. In the Highlands and Islands such a study could be informed by Bowditch and Macdonald (2016), including a study of island elms, west-coast elms, small-scale woodland elms and the elms around the Beauly, Moray and Cromarty firths (the greatest concentration of population and infection).

In the early 2000s, genetically modified *U. minor* trees were developed through biolistic transfer (high-speed particle bombardment) of putative DED resistance genes to saplings (Gartland et al., 2000). However, these promising approaches were halted before any wider trials were sanctioned, due to the political climate around Genetically Modified Organisms at the time. A landscape genetics approach and subsequent breeding programmes would therefore appear to be the most promising and socially-acceptable way forward.

Future for elms and forest health

Elm species in Europe have been reduced from a consistent part of native broadleaved woodlands to a fringe species that is on the IUCN Red List and in some cases has been close to the brink of local extinction. *Ulmus glabra* is classified as vulnerable on a European scale (Rivers, 2017). Despite the devastation of multiple DED pandemics, elm appears to maintain a high level of genetic diversity due to natural regeneration and the healthy populations that persist in small areas across a wide geographical range. Over the years, a compendium of work has been conducted on elm's relationship with DED across the world, but technology and techniques, as well as accessibility to that technology, have had to catch up with researchers' and managers' aspirations.

The political environment has increasingly recognised the importance of the green economy, natural capital and ecosystem services to the future of human development, signifying that investment and funds are released more quickly than previously in the face of a critical threat (such as the response to the ash dieback). Some type of resistance clearly exists within elm populations, as healthy trees have been observed to grow next to or within infected woodlands for decades, why and how are key questions to be answered.

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