‘Where we are with Elm’

A review of the ‘state of play’ with elm in the U.K.

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Summary

Elms have long been valued as landscape, hedgerow and woodland trees. They are also environmentally tolerant, beautiful and valuable timber trees (Richens, 1983), which host 80 species of invertebrates. In Great Britain, the only truly native species is the Wych elm (*Ulmus glabra*) which has a more northerly and westerly distribution. The Field elm (*U. minor*), found in mainly in central and southern England, was introduced in prehistoric times by man (Richens, 1983). The latter includes clones such as English elm (*U. minor* ‘Atinia’, previously known as *U. procera* and typically sterile) and Plot Elm (*U. minor* ‘Plotii’). Both Wych elm and Field elm can hybridise easily and naturally occurring hybrids are frequent. Oliver Rackham (1980) described *Ulmus* as the most difficult critical genus in the entire British flora, adding that 'species and varieties are a distinction in the human mind rather than a measured degree of genetic variation'. During the 19th and early 20th centuries many cultivars and some exotic species were also planted as ornamental street, garden, and park trees.

Over the past century there have been two pandemics of Dutch Elm Disease (DED) caused by two entirely separate but related species of microfungi, *Ophiostoma ulmi* and *O. novo-ulmi* (Brasier, 1991, 2000). Together, these pathogens have killed many millions of elm trees resulting in the decimation of the British elm populations. Over 90% of the British elms died during the late 1960s and 1970s, estimated at over 25 million trees (Brasier 2000; Brasier & Webber 2019; Coleman, 1998). This massive impact on the countryside and society is still clearly recalled today. It can be most evidentially seen by the loss of the mature elm trees in woodland and hedgerows and their subsequent replacement by root suckers which grow up for 5 to 20 years before succumbing to disease again (Brasier & Webber, 2019). But not all has been lost.

Since the 1990s, it has been apparent that isolated, small populations and individual trees have survived and may be avoiding, tolerant or resistant to DED. With other native species such as ash and oak under increasing pest and disease pressures, there is currently much interest in re-considering elm with an objective of conserving, improving and ultimately restoring elm back into the landscape at a meaningful level.

This project had the objective to establish ‘where we are with elm’ in terms of knowledge, expertise and plant material. Through engagement with key private individuals, many who have been studying elm for decades, and a wide range of organisations, it is apparent that there is a substantial knowledge base and that much has been achieved already. Collections and adaptive trials of ‘resistant’ elm cultivars and selections from breeding programmes in France, Spain, Italy and the United States, plus some surviving British mature elms have been established. A start has been made to assess resistance to DED in some of this material plus novel seedling progenies - potentially promising individuals have been tentatively identified.

Further work identified includes the requirement to characterise plant material in terms of avoidance, tolerance or resistance to DED as well as morphologically, phenotypically, genetically. In addition, in the case of trees suitable for timber production, timber characterisation is required. There is also the need to further promote understanding of the complex relationships between the bark beetle vectors (*Scolytus* spp.) which transmit the pathogens, the fungal pathogens and elm. Plus the need to understand the genetic and physiological basis of disease resistance, the current evolutionary changes occurring in the pathogens, and whether deployment of resistant elms may select for increased pathogen aggressiveness.

Specialist support is required to address intellectual property matters relating to access to breeding material for commercial use as well as research. It would also be beneficial to standardise best practices and selection criteria as far as possible, improve propagation techniques and to consolidate existing material both in terms of information and security of plant collections. In addition, it is necessary to identify and collect more mature trees of interest, establish a central database for the plant material and set up replicated adaption trials.

Finally, to maximise the potential of genomic research, studies of elm progenies are required. Some exist but the number of seedlings per progeny would need to be increased substantially.

The project has also reviewed the prospects for genomic research on elm resistance to DED. Thus far, genetic work on elms has studied only a tiny portion of the elm genome. This has provided useful information about patterns of variation in elm populations, and allows identification of species and clones. In the future, whole genome sequencing (e.g. via the Darwin Tree of Life project) and analysis would give us a better understanding of the evolution of the elm genus, and the pedigree of resistant clones. Implemented on a large scale, whole genome analysis could identify genetic variants that contribute to DED resistance. This information could be used to accelerate breeding programmes, and help us understand the mechanisms by which elm trees resist DED.

The 2016 International Elm Conference hosted by the Lees Court Estate, Kent in association with the Conservation Foundation, united breeders, nurserymen and foresters across Europe. This project has built on those foundations. It has further facilitated the networking of interested individuals and organisations in elm and also provided a means for essential outline information to be gathered and for DNA samples to be collected for future research. Detailed information on plant material and sites still resides with individuals and organisations. However what is abundantly clear is the willingness to work together to, in time, provide resilient elm for conservation, amenity and forestry plantings. This warrants further work via, for example, an elm workshop and facilitated small group discussions, to agree priorities and approaches for a large project and/or series of smaller complementary projects.

To quote Max Coleman, author of Elm – The Forgotten Tree (1998) – ‘Elms have demonstrated a tenacious ability to survive; it is about time we gave them a helping hand’.

Introduction

Before Dutch Elm Disease (DED) decimated the British elm populations in the last century, elm was the second most important broadleaf timber tree in Britain, second only to oak. Like oak, it was also of great landscape importance and formed an important component of our native woodland supporting a wide range of flora and fauna. Their aesthetic appeal and beauty has been captured by many artists including John Constable.

The only truly native species in Britain is Wych elm (*U. glabra*). Field elm (*U. minor*) is highly morphologically and genetically variable (Richens 1983; Coleman et al., 2000). Its cultivars such as the English elm (*U. minor* 'Atinia'), Cornish elm (*U. minor* 'Cornubiensis') and Plot elm (*U. minor* 'Plotii') are regarded as 'archaeophytes'. Wych elm, whilst found across Britain is more frequent in the north and west where it is also known as the Mountain or Scots elm. The species are distinct but intermediate and hybrid forms are common. Field elm produces viable seed. It also freely propagates via suckers - its clones are common and can be widespread. Such clones can be naturally occurring or propagated and planted by man. It is interesting to note that in the past the cultivation of elm has been in the care of the farmer not forester (Edlin, 1944). The Wych elm is not clonal, it grows from seed and coppices. A wide range of other species, cultivars and varieties has been introduced into Britain over the past few centuries and used widely as ornamental trees in urban and rural amenity plantings. One such species is the European White elm, *U. laevis*, an introduced riparian species.

Taxonomy of the genus *Ulmus* has historically been complex. This is in particular owing to *U. minor* occurring in a wide range of forms and the occurrence of natural hybrids, cultivars and clones. Oliver Rackham (1980) described *Ulmus* as the most difficult critical genus in the entire British flora, adding that 'species and varieties are a distinction in the human mind rather than a measured degree of genetic variation'. Studies using molecular markers (Gil *et al*, 2004) have revealed that essentially there are two native species in Britain as stated above and, in Europe, the White elm (*U. laevis*). Although clonal material is often criticised for lack of diversity, in Britain the widespread disease-susceptible *U. minor* in the form of English elm and other historical species and varieties are now recognised as a series of clones that spread vegetatively. Deployment of many additional resistant clones of *U. minor* could therefore augment the current population structure (Webber, 2019).

Field elms show rapid growth and trees have the potential to reach over 40m in 100 years. Some cultivars such as the Plot's elm have naturally erect growth even when open grown. Wych elms tend to have a more open spreading habit and as a result don't reach such heights. The timber of Field elm is known as red elm reflecting its rosy-brown colour, whilst the timber of Wych elm is lighter in colour and known as white elm. The timber from intermediates is referred to as Dutch elm. All these elms produce attractive, tough timber which is durable if kept dry or continuously wet; historically it was used for water pipes. It is a very versatile timber used in furniture, turnery, woodware, coffins, cladding, flooring etc. In larger dimensions, it can be used as a structural timber for vernacular buildings, and for underwater works in harbours, docks and in the construction of wooden vessels. The keel of the *Mary Rose* (1512) was made from a massive elm timber. Not all elm timber came from woodland trees as much was sourced from non-woodland sources especially in the form of mature hedgerow trees. Elm can make excellent firewood, but as it is difficult to split and process, other species are often favoured instead.

Wych elm, along with oak and alder, started to appear in the composition of native woodland some 8000 years ago, arriving after hazel, birch and pine which had colonised rapidly after the last glaciation period. Relicts of Elm-hazel wildwoods can be found in South Wales. Elm forms a component of four out of the 18 main woodland communities: W7, W8, W9 & W10 as described by the National Vegetation Classification system (Hall et al, 2004). These represent oak dominated or mixed deciduous woodland. In Scotland, W4, 8, 9, 10 & 16 NVC habitats are the main habitats associated with elm species (NWSS, 2014).

The main associated species are birch, ash, alder, hazel and oak respectively. Rackham (2006) describes elmwoods as forming two types: Suckering elmwoods and Non-suckering elmwoods. Suckering elmwoods comprise of field elm or Dutch elm. Clones may be present and these elmwoods are often associated with deserted settlements. The Non- suckering elmwoods are of wych elm which is also a constituent of many ashwoods especially on limestone soils. Some can have a particularly rich mixture of herbaceous plants.

Elms support a wide range of flora and fauna. In the spring, its early pollen is sought after by many insects including honey bees. It hosts 80 species of invertebrate, notably the rare White-letter Hairstreak butterfly, and many moth species including the peppered, light emerald and white spotted pinion moths. As elm seeds develop long before most other seeds are available, they are an important food source for songbirds, game birds and squirrels. Elms also provide important habitats for lichens including two species unique to the genus. They are also host to bark beetles, notably the elm bark beetles (*Scolytus* spp.), which act as vectors for Dutch Elm Disease. Thus the continued loss of elm impacts British woodland diversity as well as structure.

Elm bark beetles (principally *Scolytus scolytus* and *S. multistriatus*) are the vectors for DED with infection occurring via beetle feeding wounds cut in elm twig crotches. The beetles then breed in the bark of the dying elms. Around 1000 spores are needed to infect an English elm (Webber, 1987). *S. scolytus* is a much more effective vector under British conditions, carrying far larger numbers of spores (Webber, 2000). During the main epidemic period in the 1970s-80s, the larger beetle, *S. scolytus*, was the principal vector but as large elms became scarce, its numbers fell and the smaller beetle, *S. multistriatus,* adapted to breed in bark of smaller stems such as those of recruitment elms (small trees arising from suckers or seedlings), increased (Brasier,1983). The disease can also be passed from diseased to healthy trees via interconnected root systems. With the successive outbreaks of DED, the substantial populations of recruitment elms are failing to reach maturity. In 2008 it was estimated that there were 100–300 million recruitment elms in Britain, including overgrown hedgerows, with c. 1–3 million dying annually (Brasier, 2008). It is this reoccurring cycle of small, young elms dying that is most evident today (Brasier & Webber, 2019).

Dutch Elm Disease (DED) is one of the most devastating tree diseases of the 20th century, affecting many elm species in Europe, North America and Asia. It continues to be hugely damaging in Britain. DED is a vascular wilt disease of the xylem caused by the introduction from Asia of two ancient but related species of microfungi, *Ophiostoma ulmi* and *O. novo-ulmi* (Brasier, 1991, 2000). The first pandemic of DED in Europe and North America caused by the introduced *Ophiostoma ulmi*, began in the early 1900s but declined unexpectedly in Europe from the 1930s onwards after killing 30 to 40% of the elms (Peace, 1960).

Later a second pandemic caused by the much more aggressive *Ophiostoma novo-ulmi* spread across the same areas and by 1990 most of Britain's c. 30 million mature elms had died. During the second pandemic*, O. novo ulmi* acquired debilitating viruses and changed from being largely clonal to highly genetically variable, through interspecific acquisition of novel, sometimes deleterious, genes from *O. ulmi* (Brasier, 2001). There is no evidence of attenuation (weakening) of the pathogens aggressiveness in the current, second epidemic comparable to that in the 1930s with *O. ulmi* (Brasier & Webber, 2019). Also, in Europe two distinct subspecies of *O. novo ulmi* were introduced, including into Ireland. These subspecies have been freely hybridising since the 1980s, with the result that novel genetic and morphological forms of *O. novo umli* are emerging: *O. novo ulmi* is essentially reinventing itself in Europe (Brasier & Kirk, 2010).

Wych elm is significantly more susceptible to *O. novo-ulmi* than English elm when xylem inoculated, (Brasier, 1977). White elm (*U. laevis*) is more susceptible than English elm (Brasier & Gibbs, 1976). However, host feeding preferences of the *Scolytus* beetles also affects infection on different elms. *S. scolytus* markedly prefers to feed on English elm when given a choice between English elm and Wych elm; or between English elm and White elm

(Webber, 2000). On White elm the vectors are apparently discouraged by the presence of an antifeeding triterpene in the bark, alnulin, (Martín-Benito et al., 2005). Further, there is evidence that differential resistance of elms to *O. novo-ulmi* infection occurs via the beetle feeding wound. In the moderately disease susceptible Commelin elm (*U. x glabra*) entry of *O. novo-ulmi* to the xylem via the feeding wound is strongly restricted. In the highly resistant Siberian elm (*U. pumila*), however, entry occurs readily, as it does also in English elm. Commelin elm may therefore have active resistance to entry in its bark, possibly because of its *U. glabra* parentage (Webber & Brasier, 1994).

Ecologically, and from a research and disease control perspective, the transmission of Dutch Elm Disease is best understood not a spasmodic event centred on beetle crotch feeding but as a continuum of highly dynamic ecological processes occurring between late summer one year and mid-summer the next (Webber & Brasier, 1984). Similarly DED is itself best viewed as a 'multiple host- vector- pathogen- fungal virus- microbial antagonist and environment' system in which all the various components and their interactions can be subject to many critical thresholds, any one of which might alter the balance from an intense and explosive epidemic to a sporadic level of disease (Brasier, 1986; Webber & Brasier, 2019).

Indeed the more intense epidemic caused by *O. novo-ulmi* allowed the disease to move further north than before. However significant populations of mature elm remain in the few areas of Britain where DED has yet to arrive, notably parts of North & West Scotland (Bowditch & Macdonald, 2016). Nonetheless, the disease is now reported to be migrating south and west from Inverness via the Great Glen. The study by Bowditch & Macdonald, 2016 and commissioned by Forestry Commission Scotland, has examined the current status of elm trees and Dutch elm disease (DED) in the Scottish Highlands. It identified potential refuge and options for active management. It also reported that both seed and planting stock sales of elm have increased significantly in the last three years, possibly as a reaction to the threat of *Chalara* dieback of ash.

Elms were included in a report commissioned by the Woodland Trust in 2015, to identify domestic sources of seed and production strategies for 15 broadleaf species and Yew in Britain. The initial ranking of the species according to seed demand, conservation and industry interest was low to medium priority for Wych elm and very low priority for English elm (Russell, 2015) reflecting the low planting interest at that time.

There are areas such as the Isle of Man, Edinburgh[3] and Brighton & Hove where mature elm survives as a result of sanitization programmes (Brighton & Hove City Council, 2015; Coleman, 2009; Isle of Man Government, 2015) whereby trees succumbing to DED are immediately felled and burnt. However, occasional, mature trees still survive, as isolated trees or in small groups, within DED affected areas in Britain. These trees are known to interested individuals/organisations and have, in some cases, been propagated. A small number of these selections (c.10) were tested for susceptibility to *O. novo-ulmi* by xylem inoculation in the 1990s by Forest Research and found to be susceptible. Many have not yet tested for their ability to avoid or resist DED. Trees which can avoid infection and which can resist infection are both of interest. Whilst the mechanisms operating will be different, in terms of resilience capturing and using this genetic diversity is essential.

Elm breeding for resistance to DED started in the Netherlands in 1928, the United States in 1937 and Italy in 1978. Considerable progress was made regarding the development of elms for amenity plantings, using resistant Asiatic elm species, notably Siberian elm (*U. pumila* L.), Japanese elm (*U. davidiana* var *japonica* Rehder.) and Himalayan elm (*U. wallichiana* Planch.) as sources of DED-resistance genes (Mittempergher & Santini, 2004). In recent decades,

[3] https://stories.rbge.org.uk/archives/24774

support for traditional elm breeding programmes has largely stopped, except in Spain where the Universidad Politecnica Madrid has raised resistant field elms for use in forestry (Martin *et al*. 2019). Meanwhile an extensive selection programme, started in France in 1987, using only native elms failed to find any native elms with a resistance to DED approaching that of the hybrid cultivars in commerce (Pinon et al, 2005). However, useful variation in tolerance was found which could potentially be used in further breeding work.

The appearance of some hybrid elms can be somewhat different to the European species, often with uncharacteristic foliage and thus are better suited as ornamentals for urban streets and parks. However, few of these have forms suitable for timber production. Some varieties develop a more rounded canopy with age. In the UK, Hillier Nurseries approached Eisele in Germany to obtain disease-resistant varieties, marketed under the moniker 'Resista', notably 'New Horizon', promoted this year as part of their campaign called 'Re-elming the British Countryside' to, by planting, expand the presence of elms throughout Great Britain.

In the absence of a government funded elm breeding programme in Britain, private individuals have sought and amassed considerable knowledge and expertise on elm. Much effort has gone into identifying, assessing and propagating mature trees which have survived the DED pandemics by avoiding infection. However, it should be noted that only a very few European elms are likely only to have useful tolerance not resistance to DED. Links were forged with research programmes in France, Italy, Spain and the United States. Plant material (native species, hybrids and timber selections) has been imported into the Britain and propagated for adaptive trials, testing for DED resistance and breeding.

Key people include: **Dr David Herling** who is interested in identifying hybrid material and mature native trees with DED tolerance which are suitable for growing in Britain (see www.ResistantElms.co.uk for further information). David has established nine adaptive trials with urban and rural locations. He has also, by backcrossing hyper resistant hybrid elms with superior Kent field elms, created a range of promising progenies; **Alex Gunner**, who has been identifying, propagating and assessing surviving native mature trees of *Ulmus minor* and its hybrids; **Matthew Ellis**, founder and curator of the Grange Farm Arboretum in Lincolnshire which holds the widest range of elm species and hybrids in Britain; **Peter Bourne**, an elm enthusiast involved in the characterisation of the National Elm Collection in Brighton and **Robert Somerville**, a designer and traditional timber framer building with elm and oak from local woods.

Some of the key organisations which have interests in elm include: **The Conservation Foundation** involved in supporting elm for 40 years this year, via a series of projects. A recent project is the Great British Elm Search, recording mature elm trees across the UK to build an accessible, public database that records the state of the elm population and potentially disease-resistant trees; **Forest Research** with particular expertise in the pathogens and vectors of DED; **Butterfly Conservation** in the assessing different elm cultivars' adaptability to growing conditions in England and their ability to support the White-letter Hairstreak Butterfly; **Royal Botanic Gardens Kew** in terms of seed and plant collections, characterisation and propagation; **Woodland Trust** in relation to conservation, seed supply and tree planting; plus members of the **Country Landowners Association** who have provided trial sites (Symes, 2018).

Together, these private individuals, organisations and others have ensured that elm hasn't been forgotten. Indeed they have, with typically very limited resources but great perseverance, been working in various ways to safeguard and aid the return of elm to the British landscape by securing plant material and developing a network of knowledge and expertise. By engaging sensitively with these enthusiasts and experts, this small project sought to gather information to provide a snap shot of 'where we are with elm now' which would also include a review of the current genomic elm research.

Overall Objective

To provide a snap shot of ‘where we are with elm’ by engaging with individuals and organisations to identify constraints and opportunities to further work on elm and determine whether there is sufficient interest in developing collaborative projects on elm.

Tasks (as originally set out)

1. Meetings with the interested individuals to understand their interests and objectives, identify gaps and how they’d like to engage with a wider project on elm

2. Discussions with the Conservation Foundation, Woodland Trust, Royal Botanic Gardens Kew and Forest Research to determine interests, strengths and opportunities for collaboration

3. A snapshot evaluation of the status of genetic research on elm, particularly relating to the Dutch Elm Disease to identify constraints and research opportunities

4. Summary of findings and recommendations to inform whether developing a large project on elm is warranted

Approach

For Tasks 1 and 2, information was gathered by Karen Russell via a combination of one to one meetings, telephone calls and email exchanges with individuals and organisations, predominately located in England, who kindly agreed to contribute to this project. This information is summarised below in Table 1. For Task 4, information was reviewed to provide the overview summary of key findings and recommendations. For Task 3, Prof. Richard Buggs undertook a literature review and prepared ‘Prospects for genomic research on Elm resistance to Dutch Elm Disease.’

Results

Over 20 individuals / organisations were contacted in relation to Tasks 1 and 2 of this project. These are listed alphabetically in Table 1 which notes their interests in elm and in some cases, key constraints. However, note it should not be taken as a complete list of those with interests in elm. Had further resources been available, then other individuals and organisations involved in hosting trials and collections certainly would have been contacted.

Task 1: Meetings with the interested individuals to understand their interests and objectives, identify gaps and how they’d like to engage with a wider project on elm

Meetings were held with Matthew Ellis, David Herling and Fergus Poncia, Alex Gunner, Peter Bourne and Robert Somerville – all private individuals who have been involved with work on elm for decades. Interests range from identifying, characterising and propagating mature surviving elms to establishing collections to trialling and breeding novel seedling selections, to growing timber trees and using elm for timber framed buildings, to the provision of informative websites on elm. In addition, Edmond Harris was contacted in relation to *Ulmus laevis* and his work in identifying specimen trees and trialling of seedlings. What unites them is a desire to identify elms with tolerance/resistance to DED, whether for amenity, landscape or forestry purposes.

Between them, the depth and breathe of knowledge of elm species, varieties including hybrids, uses, breeding and experience of DED is very considerable. They hold (or know the location of) most of the key plant genetic resources required for tree improvement and genetic studies. The selections and varieties come from France, Italy, Spain, Netherlands, Russia, USA and Asia as well as Britain. They have established strong international links with nurseries and research centres. Given that the vast majority of work undertaken has been self-funded, the co-operation and their achievements are very substantial indeed. All have expressed interest and willingness to participate openly on continuing and new collaborative work on elm.

Key achievements (person(s) responsible in brackets)

1. Establishment of the most diverse *Ulmus* arboretum in Britain with 165 accessions including many rare Asiatic species as well as hybrids and varieties. Performance, appearance and DED tolerance is being observed in the collection. (Matthew Ellis)

2. Establishment of adaptive trials of DED tolerant field elm selections from Spain (‘Ademuz’, ‘Dehesa de Amaniel’, ‘Retiro’) and hybrids from Italy, France and USA (Eisele clones A1 & E2, ‘Fiorente’, FL462, FL493, FL506, LUTUCE[4], ‘Morfeo’, ‘New Horizon’, ‘Patriot’, ‘Rebona’, ‘San Zanobi’) from plus *U. laevis*. The objective is to test how suited these elms are to British soils and climates, and to observe how much they resemble our native elms (David Herling)

   The adaptation trial at the Lees Court Estate, Kent was established in 2016. It contains ‘Fiorente’, ‘New Horizon’, ‘Rebona’, ‘Ademuz’, *U. laevis* and Eisele clones A1 and H1 plus FL462, FL 493, FL 506, ‘Dehesa de Amaniel’, ‘Retiro’, ‘Morfeo’ and ‘Nanguen’. It was planted at 5m x 5m and has 6 replicates of each variety/selection. The other smaller 8 trials, planted in 2018, have three replicates each of ‘Fiorente’, ‘New Horizon’, ‘Rebona’, ‘Ademuz’, Eisele clones A1 and H1, and *U. laevis*.

   These were established at a range of rural and urban sites: Royal Botanic Gardens Kew and Edinburgh; Harcourt Arboretum, Oxfordshire; Harrow School, London; Highgrove, Gloucestershire; Sheffield & Rotherham Wildlife Trust site in Sheffield, with the Trees Please nursery, Northumberland, and on private estates belonging to Sir Henry Studholme, chairman of the Forestry Commission, and Ross Murray, formerly head of the Country Landowners' Association in Devon and Monmouthshire respectively. (David Herling)

3. Establishment of a timber trial of hybrid elms, Fiorente and VADA, on a restock woodland site at the Lees Court Estate, Kent. (David Herling)

4. Created and raised seedling progenies specifically to incorporate DED tolerance with the appearance of British elms by undertaking a controlled breeding programme of DED resistant elm hybrids with outstanding mature British elms that have tolerated DED for several decades. The first breeding work in Britain for many years. (David Herling)

5. Seven progenies from two elm breeding programmes have been established, in a field trial near Wateringbury in Kent for DED testing (David Herling & Fergus Poncia)

[4] ‘Nanguen’, ‘Wanoux’ and ‘Morton’ are cultivars also accorded selling names LUTUCE, VADA and ACCOLADE respectively.

and at Butterfly Conservation's main trial site at Great Fontley Farm, in Hampshire. (Andrew Brookes)

a. FL 493 x U. minor 'Tonge Mill' - 76 seedlings, this is the largest progeny
b. FL 493 x 'Patriot' – 50 seedlings
c. FL492 x 'Patriot' – 5 seedlings
d. 'Morfeo' x 'Sapporo Autumn Gold' – 2 seedlings
e. 'Columella' open pollinated – 4 seedlings
f. 'Morfeo' open pollinated – 3 seedlings
g. 'San Zanobi' open pollinated – 4 seedlings

For reference, the trial also contains 'Ademuz', 'Dehesa de Amaniel', 'Retiro', VADA, *U. pumila* "Aurescens" and *U. davidiana* var. *japonica* ACCOLADE.

6. In 2019, field inoculations of the seedling progenies and controls with an aggressive strain of *Ophiostoma novo-ulmi* provided by Clive Brasier of Forest Research, were undertaken to test for DED tolerance. English elm suckers present in nearby hedges were also inoculated.

   After twelve weeks after inoculation, four seedling selections (6.13, 6.21, 6.22, 6.23) of FL 493 x *U. minor* 'Tonge Mill' were either asymptomatic or had 2% or less of wilting/damage. **This is a very significant result as it means British-bred elm seedlings with very high tolerance / resistance have for the first time been identified.** (David Herling & Fergus Poncia)

7. The FL 493 x *U. minor* 'Tonge Mill' progeny has been identified for potential genetic mapping studies. Leaf samples were collected for DNA analysis from the inoculated seedlings. (David Herling & Richard Buggs)

8. Identification, characterisation and propagation by softwood cuttings of mature surviving elms with DED tolerance in East Anglia, and establishment a small private collection which also includes a range of varieties from breeding programmes. (Alec Gunner)

9. Characterisation, protection and promotion of the National Elm Collection which includes over 17,000 elm trees. (Peter Bourne with Rob Greenland of Brighton & Hove City Council)

10. Designs buildings, identifies and uses green timber from British elm trees to construct elm timber framed barns using traditional techniques. Promotes the knowledge and use of elm through training courses, volunteers' involvement in the buildings and construction. (Robert Somerville)

11. Identification of mature surviving elms with DED tolerance in Hertfordshire and elsewhere, especially trees of good timber quality. Propagation of some 25 mature trees by root cuttings and creation of a small collection. (Robert Somerville)

12. Identification of specimen trees of European white elm (*U. laevis*) from over 20 British locations. Distribution of nearly 1000 seedlings from the Harewood trees for trial and monitoring. (Esmond Harris)

13. Promotion of elm trees and interests through the media and via specialist websites. (All)

Task 2: Discussions with the Conservation Foundation, Woodland Trust, Royal Botanic Gardens Kew and Forest Research to determine interests, strengths and opportunities for collaboration

Over the summer of 2019, discussions were held with individuals from The Conservation Foundation, Woodland Trust, Royal Botanic Gardens Kew (Wakehurst Place, West Sussex) and Forest Research (Alice Holt, Surrey) – all have existing and often long standing interests in elm. In addition, to facilitate information exchange and networking across the project and to help safeguard key genetic resources, discussions were also held with individuals from Alba Trees Plc, Butterfly Conservation, Duchy of Cornwall, East Malling Research (NIAB-EMR), Forestart Ltd and the University of the Highlands.

Together these organisations represent academic research centres and organisations, conservation charities and those involved in the seed collection, propagation and growing of plants. Their interests cover the full potential remit of elms - from landscape to amenity to conservation to forestry interests including pest and diseases. A common strength is that the organisations have established resources (e.g. expert staff and facilities) which can be directed to support work on elm. However, a common weakness is that the level of work is frequently determined by funding availability and/or commercial interest in elms. Another is the archiving of plant material and data may be incomplete when projects end.

There is a real and strong desire for building on existing initiatives and developing new ones on elm which would involve many organisations and private individuals. Areas of interest vary from research to:

- understand the complex relationships between the pathogens, vectors and the trees
- locating further mature trees and populations which have avoided, tolerated or resisted DED
- assessment of plant volatiles in relation to beetles locating and feeding on elms
- developing conservation strategies
- characterising collections (genetic and physical)
- trialling and assessing the adaptiveness and landscape appeal of hybrids
- developing and screening varieties with DED resistance
- applying genomic technologies to advance the understanding of DED
- identifying genes for resistance,
- improving propagation and reducing the cost of elm varieties with DED tolerance

Key achievements (organisation / person responsible in brackets)

1. Establishment of adaptive trials at four contrasting sites in Hampshire in 2000. Trials comprise of 19 varieties including a wide range of hybrids selected for high DED tolerance plus accessions of nine species. Their performance has been assessed and planting recommendations made. Breeding of the White-letter Hairstreak Butterfly on LUTECE, 'New Horizon' and 'Sapporo Autumn Gold' has been recorded at other sites in England. (Butterfly Conservation, Andrew Brookes[5])

[5] Also note Andrew Brookes contribution under Task 1, key achievement 5.

2. Promotion of elm and creation of an extensive database of elm locations, tree details and contacts plus propagation of a subset of mature trees derived from a number of past and on-going elm projects. (The Conservation Foundation, David Shreeve)

3. Assessment of the current status of elm in the Scottish Highlands and outline of a range of DED management strategies completed. A short-term scoping project to establish pilot elm refuges, with the aim to monitor and conserve elm populations in those areas, plus a parallel study to develop DNA extraction techniques and markers to characterise elm diversify, are planned in partnership with the Woodland Trust Scotland. (University of the Highlands & Islands, Euan Bowditch)

4. Review of national elm datasets and development of outline strategies to create/secure seed resources, as part of wider work to develop sustainable seed sources for minor broadleaf trees species. (Woodland Trust & Future Trees Trust/John Tucker & Karen Russell)

5. As part of the UK National Tree Seed Project, establishment of a British Wych elm seed bank collection of 296,691 seeds from 370 mother trees from 23 native seed zones. (Royal Botanical Gardens Kew – Wakehurst Place, Alice Hudson & Ian Willey)

6. Isolation and characterisation of the different strains of *Ophiostoma ulmi* and *O. novo-ulmi*, monitoring of *Scolytus* elm bark beetles and elm populations, on-going understanding of how these different species are interacting and evolving. Small elm collection. Provision of *O. novo-ulmi* inoculum for DED field trial. (Joan Webber & Clive Brasier, Forest Research)

Task 3: A snapshot evaluation of the status of genetic research on elm, particularly relating to the Dutch Elm Disease to identify constraints and research opportunities

This is presented as: '**Prospects for genomic research on Elm resistance to Dutch Elm Disease'.**

Lay Summary

Thus far genetic work on elms has studied only a tiny portion of the elm genome. This has provided useful information about patterns of variation in elm populations and allows identification of species and clones. In future, whole genome sequencing and analysis would give us a better understanding of the evolution of the elm genus, and the pedigree of resistant clones. Implemented on a large scale, whole genome analysis could identify genetic variants that contribute to Dutch Elm Disease (DED) resistance. This information could accelerate breeding programmes, and help us understand the mechanisms by which elm trees resist DED.

Introduction

For almost a century, attempts have been made to breed elm trees with resistance to Dutch Elm Disease (DED). Natural resistance of mature elms to DED is limited in European and North American elm species, largely prohibiting breeding programmes that rely exclusively on genetic variation found within these species. However, several Asiatic elm species seem to have natural resistance to DED and have been hybridised with European and North American elm species as a starting point for promising breeding programmes.

Attempts have also been made to develop DED-resistant elms through the introduction of anti-fungal genes from other plant families by genetic modification. An excellent review of research on Dutch Elm Disease (DED) resistance in Elms has recently been published by Martín *et al*.,

2019. Rather than recapitulate this material here, it is taken as the starting point. Areas are highlighted where genomics could contribute to future research on DED resistance.

Whole genome sequencing

No genome assembly for an elm species has been published. Nor is there any known, ongoing project to sequence an elm genome. However, through the launch of the Darwin Tree of Life Project[6], it is hoped the sequencing of wych elm and field elm could be prioritized. The sequencing and assembly of an elm genome would be a foundational resource that would facilitate the exploration of the genetic basis of DED-resistance.

The genome sizes of 28 species of elm have been measured using flow cytometry (Whittemore & Xia, 2017), showing that the majority of species are diploid with 2C genome sizes of 3.0 - 4.2 pg (haploid genome size of 1.5-2.1 Gbp). All accessions of *U. minor* measured had a 2C genome size of 4.04-4.10 pg (haploid genome size of 2.0 Gbp). This is larger than the genome sizes of birch, ash and oak, but much smaller than the genome sizes of coniferous trees. The sequencing and assembly of its genome should therefore be relatively straightforward.

Diploid elms tend to have a 2n chromosome number of 28 (Santamour & Ware, 1997; Santamour, 1969). On the basis of isozyme evidence it was suggested that European elms with 28 chromosomes (2n=28) are segmental allopolyploids (Machon *et al*., 1997; Machon *et al*., 1995). If this were the case it would make genomic work on them harder than if they were diploids. However, Hollingsworth *et al*., (2000) argued that the isozyme evidence is not conclusive. This issue could be resolved using kmer analysis of whole genome shotgun read data which are generated in the first stage of sequencing a genome.

The chloroplast genomes of five Chinese *Ulmus* species have been assembled (Zuo *et al*., 2017). These are a useful resource for phylogenetic studies but it is unlikely that the chloroplast genome plays a major role in DED resistance.

A handful of transcriptomic studies have sequenced genes expressed in elm under various conditions. The transcriptomes of three genotypes of *U. minor* growing under various biotic and abiotic conditions have been sequenced (Perdiguero *et al.*, 2015). The transcriptomes of *U. minor* leaves damaged by larval feeding have been sequenced, with and without prior egg deposition (Altmann *et al.*, 2018). Transcript levels during a time-course of DED invasion have been measured in *U. minor* using microarrays (Perdiguero *et al.,* 2018). Together, these studies have generated hypotheses about the gene expression changes involved in the development of DED in *U. minor*, but by themselves they do not identify variants that can be used as markers to predict DED-resistance in breeding programmes.

Phylogenomics of the genus *Ulmus*

The main sources of heritable resistance to DED used thus far in breeding programmes are Asiatic elms species with natural resistance to DED (Smalley & Guries, 2000). A thorough understanding of relationships among species of the Elm genus may improve our ability to understand DED-resistance and design crosses with good potential for DED-resistance breeding. The phylogeny of *Ulmus* was investigated in the 1990s using chloroplast restriction site variation (Wiegrefe *et al.*, 1994) and morphology (Zavada & Kim, 1996). Alan Whittemore and Andrew Hipp are currently working on a phylogeny for *Ulmus* based on genome-wide RAD-seq SNP markers; early results suggest that this phylogeny will differ from previous treatments (Whittemore & Hipp, 2016).

[6] https://www.sanger.ac.uk/news/view/genetic-code-60000-uk-species-be-sequenced

A phylogenomic approach where hundreds of genes are sequenced per elm species, and analysed individually and together would have several benefits. It would give us a more reliable phylogeny than has been possible previously. It would help us to understand how much hybridisation has occurred among species in the genus in the past. We could seek answers to questions such as: Is DED-resistance an ancestral state in the genus *Ulmus*, or has it evolved since the origin of the genus? If the latter, has it evolved once or many times? A robust phylogeny may allow us to select pairs of species that are likely to be able to hybridise. A phylogenomic study of genes showing convergence among resistant species may also help in the identification of candidate genes involved in resistance.

Genetic diversity within Elm species

In the 1990s and 2000s, many studies were published that analysed genetic diversity in various elm species at a small number of genetic loci. In general these studies showed good levels of genetic diversity in the European (e.g. Machon *et al.*, 1995; Čurn *et al.,* 2014), American (Wiegrefe *et al.*, 1993) and Asian (e.g. Zalapa *et al.*, 2008) elm populations studied. They also revealed the widespread planting of clones in Europe. The application of RAPD markers to UK elms showed that within the *U. minor* complex there are widely dispersed clones, one of which has been named *U. minor* 'Plotii' (Coleman, 2002, Coleman *et al.*, 2002, Hollingsworth *et al.*, 2000).

Chloroplast variation within European populations of *U. glabra* and *U. minor* were studied by Gil *et al.,* (2004), who used this information, together with AFLP and microsatellite marker data, to show that the "English elm", sometimes referred to as *U. procera*, is a widespread clone of *U. minor*. Buiteveld *et al*., (2016) studied nuclear microsatellites in *U. minor* populations of the Netherlands, France and Belgium and also found evidence for widespread clones. Whilst it may be that the widespread planting of clones may have made European elm populations more susceptible to DED, it should be borne in mind that American populations have also succumbed rapidly to DED even though they do not have a history of widespread clonal planting.

Studies based on a small number of variable loci are perfectly adequate for elucidating the basic population genetic structure of elm populations, and the detection of clones. Further understanding could be gained by using larger sample sizes in wider geographic areas. A small number of variable loci are also likely to be adequate to: Describe variation in gene banks and collections, detect hybrids, detect potential mis-identifications and synonyms, and 'fingerprint' material of interest in terms of e.g. Plant Breeders Rights. Where the exact pedigree of the progeny of several generations of crossing among different species has been forgotten, larger numbers of loci may be needed to reconstruct its pedigree.

Discovery of candidate genes for DED-resistance

Little is currently understood about the genetic basis for natural resistance to DED in elms. Thus far the only information we have is from studies of gene expression differences between susceptible and non-susceptible species, and studies of gene expression changes under DED infection (Perdiguero *et al.*, 2018, 2015; Altmann *et al.*, 2018). Such studies provide useful clues about the processes involved in resistance, but they do not identify the genetic differences that cause differences in resistance. It may be found that a certain gene is expressed at higher levels in resistant species, and is also up-regulated when trees are inoculated with DED. However, the genetic difference that causes the higher expression of this gene in the resistant species may not lie within the gene itself; it may lie in another gene or in a non-coding part of the genome.

Identifying variants that actually cause differences in resistance, and are therefore useful in breeding programmes, requires genome-wide studies of variation in large numbers of trees. There are two classes of approach possible: (1) Genome-wide association studies, which analyse a large number of individuals of unknown relatedness, and seek variants that are statistically associated with resistant versus susceptible trees (e.g. Stocks et al., 2019); (2) Family studies where the susceptible versus resistant progenies of hybrids from a cross between a resistant and a susceptible individual are analysed (e.g. Santos et al., 2017; Brewer et al., 2018). Generally, approach (1) is quicker but more expensive than approach (2). Given the lack of natural resistance to DED in European and American elm populations, and given the existence of advanced hybrid breeding programmes, approach (2) is likely to be the most feasible and effective.

Predicting the DED-resistance of elm seedlings

Genomic knowledge can accelerate a breeding programme if it allows us to predict the level of resistance encoded in the genome of a young seedling. This means that from a multitude of progeny from a cross, a subset of the most promising seedlings can be selected for growing on for eventual inoculation testing. This saves time, space and effort. There are two ways of doing this. (1) Marker-assisted breeding: This uses candidate genes for resistance identified in a genome-wide association study or a family study, and selects progeny from crosses based on the presence/absence of variants in them. (2) Genomic prediction: A statistical model is trained on thousands of genetic loci in a large number of individuals of known susceptibility or resistance to DED, estimating the contribution of every locus to DED resistance; this allows the prediction of the susceptibility or resistance of other individuals for whom only genetic information is available.

Understanding mechanisms of DED-resistance

Classical approaches have thus far not identified the mechanisms by which elm trees resist the DED fungus with any certainty (Guries & Smalley, 2000; Martín *et al.*, 2019). While much evidence has been accumulated, this is mainly correlative, and different studies have conflicted in their results. Some resistant elms have been observed to form a “barrier zone” between infected and uninfected tissues, which seems to hinder fungal growth *(Bonsen, et al.*, 1985; Shigo & Tippett, 1981). There is also evidence that resistance to pathogen entry via the beetle feeding wounds in the bark is a different process from resistance to spread of the pathogen within the xylem (Webber & Brasier, 1994).

Variation in the length and diameter of xylem vessels in elms has also been implicated in resistance (Elgersma, 1970; McNabb *et al.*, 1970; Banfield 1938). But other studies do not support this (Gkinis, 1978; Solla & Gil, 2002a) or suggest that the timing of formation of vessels of different size may be important (Solla et al., 2005). Rapid tylose formation after infection, blocking xylem vessels, may also be involved in DED resistance (Elgersma & Miller, 1977; Elgersma, 1973), but this also damages the tree if done in excess.

Phytoalexin mansonones accumulate under infection by DED in *U. pumila* (Duchesne *et al*., 1986) and *U. americana* (Dumas *et al.*, 1983; Jeng *et al.*, 1983); these appear to have cytotoxic effects (Wang *et al.*, 2004; Wu *et al.*, 1989). The role of secondary metabolites such as lignin and suberin in DED-resistance is suggested by infrared spectral differences between susceptible and resistant elms (Martín *et al.*, 2005). Differing levels of various amino acids, ammonia, γ-amino-n-butyric acid and sugars were found in xylem sap of elm species with different levels of resistance to DED (Singh & Smalley, 1969).

Induced host resistance has also been investigated (Hubbes, 2004; Sutherland *et al.*, 1995). Environmental conditions also seem to affect DED resistance: Mean air temperature and mean number of sunshine hours appear to affect the amount of defoliation of elm infected with DED (Sutherland *et al.*, 1997) and water stress may also play a role (Solla and Gil, 2002b).

Elm trees may avoid DED via traits that reduce damage by the elm bark beetles vectors of the fungus (Santini & Faccoli, 2015; Webber, 2000). However, there has been little research in this area (Santini & Faccoli, 2015). It has been suggested that damage by bark beetles may be avoided via an asynchrony of the growth and life-cycles of the trees and beetles (Ghelardini

& Santini, 2009). Other promising areas for research may be the chemical signals that lead elm bark beetles to trees infected by the DED fungus, the nutritional quality of elms, and tree defences against bark beetles (Santini & Faccoli, 2015).

This accumulation of data suggests that several different mechanisms may be involved in DED-resistance, and therefore the trait is likely to involve a large number of genetic loci. The discovery of candidate genes for DED-resistance will provide further information about the mechanisms by which DED-resistance works.

Trans-genetics

Despite a lack of understanding of how elms naturally resist DED, trans-genetic elms can be produced via transformation with anti-fungal genes from other sources. Four *Ulmus americana* clones transformed with a synthetic antimicrobial gene appear to have some resistance to DED (Newhouse *et al.*, 2007). Transgenic *U. minor* clones have also been produced (Gartland *et al*., 2000).

Thus far social and political concerns seem to have inhibited the use of transgenic elms. Discovery of genetic variants that naturally confer DED-resistance within elm species will open up the possibility of cis-genetics (the movement of genes between species of the same genus) or gene editing (the directed change of a DNA sequence). These approaches would be less invasive than previous genetic engineering on elm, and may be more socially and politically acceptable.

Conclusion

The most appropriate way forward would be the whole genome sequencing of a widespread *U. minor* clone and the mapping of resistance-associated loci in a family derived from a cross between this clone and a resistant Asiatic species. This would build on decades of hybrid breeding programmes. If genes are mapped that have been functionally characterised in other plant species, this will help us to understand the mechanisms involved in DED resistance in these families.

This understanding of the genetic and mechanistic basis of DED-resistance would make a practical contribution to the development of DED-resistant elm trees if it were used to inform selections for breeding programmes, or to inform cis-genetic modifications of elm.

A phylogenomic study of the genus *Ulmus*, involving sequencing the genome or a substantial number of genetic loci in every species, would build our understanding of which species might be the most usable repositories of resistance genes, and could be another approach to identify resistance genes.

Task 4: Summary of findings and recommendations to inform whether developing a large project on elm is warranted

This project has provided an opportunity to review 'where we are with elm'. In doing so, it has established, with no doubt, that there is very considerable interest, expertise and willingness to work together:

a) to review, consolidate and archive existing key data and plant material;
b) to further identify, conserve, characterise and test mature elms for DED tolerance;
c) to further assess adaptiveness of elm including hybrid elms;
d) to further develop British elm varieties, particularly those with DED tolerance;
e) to promote the use of elm for planting and timber;

f) to engage with the scientific community to develop and apply scientific ‘tools’ which would advance knowledge, provide robust data and increase confidence in the planting of elm.

The common goal is to provide resilient, British grown elms for conservation, amenity and forestry plantings. Key to this is identifying elms with high tolerance/resistance to DED. It is also necessary to determine whether there is sufficient commercial demand to move elm from its current niche as a very minor nursery tree crop to more of a mainstream species. Whilst this is not yet known, it is promising that there are nurseries who are potentially interested.

What is known is that through the determination, dedication and passion of those involved in elm and their work over the past decades, the timing for elm to make a comeback has never been better.

Much of the required plant material from European and American breeding programmes is established in various plantings and is undergoing assessments. Novel British seedlings which combine the appearance of native elms with DED tolerance have been putatively identified in the first field screening test using an inoculum of an aggressive strain of *O. novo-ulmi*. Leaf samples for DNA analysis were collected from the main seedling progeny to safeguard this key resource for future genomic research.

Whilst detailed information on plant material and sites still resides with individuals and organisations, much outline information has been captured in this project.

There are strong, typically informal, relationships between many of the private individuals and organisations. One output of this project has been the development of this by Karen Russell, especially in propagation (e.g. by introducing Alba Trees and East Malling Research to private individuals) and genetic research (e.g. introducing Prof. Richard Buggs to David Herling).

Another has been to obtain an overview of the various elm interests and the parties involved. Efforts are frequently focussed understandably on the participants’ key interests, e.g. conservation, amenity or forestry but there is considerable crossover in terms of application of knowledge and technology which could be better coordinated and exploited.

To date, international genetic work on elms has studied only a tiny portion of the elm genome. This has provided useful information about patterns of variation in elm populations, and allows identification of species and clones. In the future, whole genome sequencing and analysis would give us a better understanding of the evolution of the elm genus, and the pedigree of resistant clones. Implemented on a large scale, whole genome analysis could identify genetic variants that contribute to DED resistance. This information could be used to accelerate breeding programmes, and help us understand the mechanisms by which elm trees resist DED.

There are many possible areas of further work which require additional review and prioritisation. Most link to points ‘a’ to ‘e’ above and are dealt with under recommendations. However what is abundantly clear is the willingness to work together to provide resilient elm for conservation, amenity and forestry plantings.

Much can and has been achieved through informal discussion and collaboration. **However, there is now the need for greater support and coordination to agree priorities, develop approaches and to harness support via e.g. facilitated small group discussions, an elm workshop and targeted publicity. This ideally requires a dedicated and funded elm facilitator who could help coordinate and develop smaller complementary initiatives**

and provide input into larger scale projects incorporating novel and existing science elements.

To quote Max Coleman, author of Elm – The Forgotten Tree (1998) – 'Elms have demonstrated a tenacious ability to survive; it is about time we gave them a helping hand'.

Recommendations

In undertaking this project, it has become apparent that key elm resources are held by various individuals and by different organisations. To secure and safeguard these resources for future reference, research and development, it is critical that these are properly documented to establish a national elm resource. In the case of plant material, important rare individuals should be replicated and planted on secondary secure sites.

a) Review, consolidate existing key data and plant material, and archive when appropriate

Data sets to be compiled can be broadly split into:

1) Information on mature elms trees *in situ* and contact persons
2) Collections and trials of species, varieties, selections propagated from mature DED tolerant trees plus seedlings including formal and informal sites

In reviewing the plant material held in collections and trials, material at risk of being lost, i.e. only present at one site, if considered of interest should be prioritised for propagation and planting at a second site.

b) Identify, conserve, characterise and test mature elms for DED tolerance

In addition to point 'a' above, there is existing additional knowledge in the wider 'tree' sectors, interested landowning and general public which needs harnessing to complement and extend the collection of British mature trees for further study. A collection of mature trees with timber potential should be created to form the basis of a future seed orchard.

c) Assess adaptiveness of elms including hybrids

The network of existing adaptive trial sites provides highly valuable information on the performance and suitability of elm varieties including hybrids and species to different soils and climates, and their ability to support biodiversity, notably the White-letter Hair Streak butterfly.

It is essential that these trials are maintained and monitored. It is also essential that new, replicated trials are established which include new material and reference material.

d) Develop British elm varieties, particularly those with DED tolerance

Via the backcrossing of hybrid elm with outstanding mature examples of British elm, novel DED tolerant offspring have been identified. These need to be propagated and trialled to assess performance included DED tolerance under different site conditions.

In addition, further progenies should be generated to increase the diversity of British elms varieties. The use of elm species such as European white elm (*Ulmus laevis*) which avoid DED should be considered as potential breeding with British as well as species which have resistance.

e) Promote the use of elm for planting and timber

Strategies to adopt the planting of elm which cater for different planting objectives need to be developed and promoted. The 'buy in' of the conservation bodies and administrative bodies as well as the amenity and forestry sectors needs to be secured. Support of the nursery sector to invest in elm should be a priority. A key priority for support is to facilitate the acquisition of Plant Breeders Rights for the propagation of existing resistant clones that have proven to be adapted to UK growing conditions. This links to and enables the planting of resistance elms arising from items c & d.

There is a substantial resource of small to medium dimension elm timber being under-utilised in Britain which is suitable for structural and decorative uses. This is in part because of the lack of awareness of potential markets and uses. Utilising such timber would not only help meet the sustainability and climate change agendas but also would reduce the availability of declining elm as a breeding resource for the elm bark beetles. Thus investment is required to promote and develop the elm timber chain.

f) Engage with the scientific community to develop and apply scientific 'tools' which would advance knowledge, provide robust data and increase confidence in the planting and use of elm

There is work required to build elm partnerships involving private, industry and research parties on a national and European level. This would promote the exchange of knowledge and aid the development of research projects and best practice.

In addition to items 'a' to 'e' above, suggested areas which require further research include:

- understanding of the complex relationships between the bark beetle vectors (*Scolytus* spp.) which transmit the disease, the fungal pathogens and elm to identify the mechanisms of avoidance and resistance

- testing and characterisation of plant material (varieties, mature trees and seedling selections) for DED resistance using conventional inoculation and screening

- understanding the mechanisms by which elm trees resist the DED fungus using genomic approaches

- use of genetic markers to describe genetic variation in gene banks and collections, detect hybrids, detect potential mis-identifications and synonyms, and 'fingerprint' material of interest in terms of e.g. Plant Breeders Rights

- assessment of the basic population genetic structure of elm populations, and the detection of hybrids and clones

- identification of candidate genes for DED resistance in elms by analysis of an interspecific mapping progeny segregating for susceptibility versus resistance. Note: David Herling's FL 493 x *U. minor* 'Tonge Mill' progeny if increased in size could be suitable

- promotion of DED control measures including development an elm app on Tree Alert or similar

- improvement of propagation techniques especially use of vegetative cuttings

- provision of specialist support to address intellectual property matters relating to access to breeding material for commercial use as well as research

K Russell & R Buggs

On behalf of Future Trees Trust
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Table 1: Individuals and Organisations who contributed to information on elm and their key interests.

Name	Organisation	Interest Areas (xx indicates key interest): Native mature trees with DED tolerance	Landscape	Amenity	Conservation	Timber production &/or use	Seed supply/ propagation	Trials & DED testing	Collections	Breeding & Genetics	Research & Development	Comments
Peter Bourne	National Elm Collection and private individual	xx	x	x	xx		x		xx		x	National Elm Collection Volunteer Curator for Plant Heritage, collaborating with Rob Greenland, Arboricultural Tree Officer, of Brighton & Hove City Council. The City Council is internationally renowned for its expertise in the field of disease management - based on a policy of sanitation essentially involving the removal of moribund elms to prevent them becoming a source of breeding material for elm bark beetles. Peter has expert knowledge of the elms in the city; over 17,000 trees listed on the ArbTrack system representing more than 120 species, varieties and types. Over 30 years, Peter has helped identify, characterise and promote the collection. He is also involved in open space forums and park friendship groups which plant elms in the city. He has a large photograph collection, data sets and private herbarium of rare species. He contributed data to help secure its National Collection status. Peter is active in the Wikipedia Elm Research Group which involves researchers and experts across Europe and beyond. Key constraints: Public awareness about risk elm timber and firewood poses as source of DED infection, propagation of elms at risk of being lost, securing and compiling datasets.
Euan Bowditch	University of the Highlands & Islands (UHI), Inverness College	x	xx	x	xx	x				x	xx	Background in forest management and community engagement. Co-authored 'Elm in the Highland: Current studies and potential management responses to Dutch elm disease' in 2016. Data provided on the environmental, social and economic importance of elm, spatial analyses of elm populations and occurrence of DED. Elm refuges identified, management strategies proposed and potential planting stock including resistant elms of non-native origin reviewed. Currently in partnership with Woodland Trust Scotland, Euan is undertaking a scoping project that will establish pilot elm refuges with the aim to monitor and conserve elm populations in those areas. Also at UHI, a small genomics study will be piloted to determine the best DNA extraction technique for elm. The aim is to analyse potential resistant markers to DED in a follow-up project using a population genetics approach, sampling DNA from both infected and healthy trees all over Scotland. Key constraints: limited genetic conservation studies, identification of DED resistant genes, repository for information and samples, lack of integrated forest management systems and early warning system of DED (via leaf assay). Linking with elm partnerships nationally and at European level as would be development of an elm app on Tree Alert.
Andrew Brookes	Butterfly Conservation, Hants & IoW Branch	x		x	xx	x		xx	xx		x	Main interest is elm conservation particularly in relation to the White-letter Hairstreak Butterfly (WLH). In 2000, adaptive trials of varying size, were set up on four contrasting sites in southern Hampshire and including a maximum of 102 varieties & species including hybrids (at the Great Fontley site). The trials concentrated on the growth and appearance of the trees, together with their tolerance of environmental stresses such as exposure, drought, and waterlogging. Recorded WLH breeding successfully on hybrid elm cultivars LUTECE and 'Sapporo Autumn Gold' in 2015. See reference Brookes, 2019. In addition, open pollinated seedlings from the hybrid varieties 'Morfeo' and 'San Zanobi' are available. Key constraints - difficulty in obtaining affordable plants due to import, IPR restrictions and lack of British propagators.
Emma Easton	East Malling Research (NIAB EMR)						xx				x	Manages glasshouses and propagation units for perennial plant research including top fruit and soft fruit. Has propagated a wide range of broadleaf trees species and would be interested to try to propagate elms via cuttings and grafting.
Matthew Ellis	private individual	x		x	xx		x	xx	xx	x	x	Established and manages Britain's most diverse *Ulmus* collection of species and varieties - 165 accessions including many rare Asiatic species. Has links with researchers, collectors and breeders around the world. Interested in the further accessions and characterisation of the collection - morphologically, genetically and for DED resistance. The collection forms part of a small, private Arboretum: https://en.wikipedia.org/wiki/Grange_Farm_Arboretum. Key constraints: Release of elms which are not DED tolerant/resistant, lack of testing and education, IPR restrictions on use.
Alex Gunner	private individual	xx	xx	x	x	xx	x	xx	xx		xx	Interested in locating, characterising and understanding surviving strains of mature and veteran *U.minor* trees and its hybrids which show high tolerance to DED. Has identified mature, surviving trees in South Cambridgeshire, South Suffolk and North Essex. Trees with good form for timber production have been propagated from softwood cuttings to assess their suitability for propagation as well as provide material for a future inoculation trial. Alec also has 6 of the 7 Spanish hybrids. He highlights that amenity vs forestry uses require different improvement approaches and types of communication. Key constraints: Characterisation of material including timber properties and trialling, standardisation of best practice, maintaining and building research links overseas.
Esmond Harris	private individual	xx		x	x	xx	x		x			Main interest is White elm, *U. laevis* , as an introduced, riparian species which tends to avoid DED as the bark beetles are discouraged from feeding by the presence of a triterpene (alnulin) in the bark. Esmond has propagated and distributed seed widely from specimen trees to encourage the amenity use of white elm (not forestry as timber quality is poor). He has also compiled an list of White elm locations in Britain.
David Herling	private individual	xx	x	x	x	xx	x	xx	xx	xx	xx	Interested in native elms for landscape and timber production, especially English elm. In 2000, David set up, funded and oversaw the Forest Research-approved Kentish Elm Conservation Programme, which had as its objectives the identification, mapping, and practical conservation of surviving mature elms in East and North Kent. In 2015, he started to establish 9 trials to assess form, performance and adaptability of native, introduced and hybrid elms from European and US breeding programmes. David has undertaken the first elm breeding work in Britain by backcrossing hyper-resistant hybrid elms with those "native" survivors which show some disease resistance plus optimal landscape character. The resulting seedling progenies are 7/8th European elms in terms of inheritance and look the same in appearance as native hedgerow elms. The seedlings were planted out in trial in 2016. In summer 2019, the larger seedlings were artificially inoculated with an aggressive strain of DED - four appear to be highly tolerant/ resistant. Further information is available at www.ResistantElms.co.uk Key constraints: Propagation, seed viability, lack of British propagators, IPR issues relating to the commercial use of varieties, lack of informed promotion and education relating to hybrids, trialling and testing for DED tolerance.

Name	Organisation	Interest Areas (xx indicates key interest)										Comments
		Native mature trees with DED tolerance	Landscape	Amenity	Conservation	Timber production &/or use	Seed supply/ propagation	Trials & DED testing	Collections	Breeding & Genetics	Research & Development	
Alice Hudson and Ian Willey	Royal Botanic Gardens (RBG) - Wakehurst Place	x			xx		xx		x		xx	Wych elm is included in their UK National Tree Seed Project: 296,691 seeds from 370 mother trees have been banked from 23 native seed zones, most below 300m altitude. Their flora project has very small quantities of *U. minor* including plotii, *U. laevis* and *U. x hollandii,* plus they hold a historic collection of *U. procera*. RBG Kew's arboriculture department have been trying propagate cuttings of *U. glabra* and *U. x hollandica* 'Wentworthii'. Key constraints: Further information on other elms species and seed management.
Robert Lee	Forestart Ltd		x	x	x	x	xx		xx	x	x	Main interest is the collection and supply of Wych elm seed as demand for other elm species is either negligible or absent. Seed demand per annum is in the upper 10,000s. It is collected from seed zones 108, 201, 204 and 403. Annual plant production is about 30,000. Forestart do not have difficulty in obtaining the quantity of seed they require and have sufficient seed in store for 3 years, despite 2019 being a no crop year. Seed viability normally increases the further north you go.
Fergus Poncia	private individual	x	x			xx		xx	x		x	Private landowner and associate of David Herling's who has planted a range of elm varieties on his own land. Involved in the establishing and maintaining the DED inoculation trial in Kent which is hosted by Southern Water. With David, he undertook the inoculation of the trial and subsequent assessment of disease symptoms in 2019.
Geraint Richards	Duchy of Cornwall	xx	x	x	x	xx	x	xx	x	x	x	Interested in elms generally, but especially for timber production and landscape uses. One of the nine adaptive trials of elms established by David Herling is hosted at Highgrove. It includes some field elms which have been rigorously selected for high disease tolerance to DED as well as elm hybrids. Other elm species and varieties are planted on Duchy ground. Geraint has been involved in arranging the propagation of some important elm specimens with Kew. He is supportive of work to identify mature trees with high tolerance to DED and to see such elms used, if suitable, for timber production.
Rodney Shearer	Alba Trees		x	x	x	x	xx			x	x	Main interest is in the potential propagation and growing of high quality elm seedlings and possibly selections (under licence) for use in forestry, conservation and amenity plantings. As minor species, elms have a niche market - wych elm is main species at present. Main constraints: Low demand for plants compared to other species, DED concerns.
Robert Somerville	Robert Somerville	xx	x		x	xx		xx	xx		x	Main interest is in the use of elm in timber framed buildings. Robert has constructed an elm barn in Hertfordshire. As a carpenter and framer, Robert has found green elm very easy to work with, similar to oak (though very tough and difficult when dry). It is also more stable than oak and less prone to shakes in large sections in a finished frame. With elm, small diameter trees (150 to 400mm DBH) as well as dead standing trees can be used which enables use of some DED affected stock locally. The elm sapwood is fully incorporated in the frame. Elm has half the amount of milling waste that oak does (given similar quality of butts). For structural frames, Robert thinks elm exceeds oak as a suitable tree. Also interested in the growing of elm for high quality timber. Robert has identified and propagated by root cuttings some 25 individual, mature trees (over 100 years of age) and established these in a small trial. He also provides training courses in timber framing using elm, oak and sweet chestnut. Main constraints: Knowledge of and availability of elm timber in the wider timber framer sector - links between growers/landowners/woodland managers and end users need to be developed.
David Shreeve	Conservation Foundation	xx	x	x	xx			x	x		xx	Co-founder of the Conservation Foundation (CF) which has been involved in elm projects since 1978. The Great British Elm projects include trying to unlock the mystery of why some trees survived Dutch elm disease, the Ulmus Maritime project to help protect the elms, regenerate the population and raise awareness of this exceptional feature of the Sussex landscape, and the Great British Elm Hunt to locate mature trees. CF have propagated mature trees but not tested them for DED tolerance. 1000s of trees reported but not all information collated and verified. Interested to work with others to draw together elm information and contacts. CF wish to combat the view that 'Elms have had it!' and see elm return to the landscape. https://conservationfoundation.co.uk/projects/the-great-british-elm-experiment/
Harry Studholme	Forestry Commission and private individual	x	xx	xx	x	xx	x	xx		x	x	Interested in the possibility of elm returning to the British landscape, including urban settings, in a meaningful way. As a private individual, Sir Harry hosts one of the nine adaptive trials. Recognises the difficulties (high cost, limited availability) in obtaining DED tolerant young elms for planting. Supports the breeding and selection of DED elms including non native species where appropriate.
Christine Tansey & John Tucker	Woodland Trust	xx	x	x	x	xx	xx			x	xx	Supporting research at UHI to provide information on Wych elm populations in Scotland to inform management approaches. Interested in further work to conserve and utilise elm, to identify mature trees, understand genetic diversity, adaptability, ability of hybrid elms to fulfil the same ecological roles as native species and enabling British propagation and growing of elm. Strategies for conservation and timber production would differ. There is interest in potential inclusion in planting mixtures. Also interested to explored whether lessons learnt from elm and the impact of DED could be applied to ash.
Joan Webber & Clive Brazier	Forest Research	x	x	x	x	x		xx		x	xx	Involved in key pathology and entomology research on DED for many years including post epidemic attenuation studies. Interested in the complex relationships between the fungal pathogens, beetle vectors and the elms themselves. Also in understanding the genetic diversity of wych elm and field elm, beetle feeding behaviour and epidemiology. Provided the inoculum for the DED testing undertaken by David Herling and Fergus Poncia in 2019.