Forest Resilience in British Forests, Woods & Plantations

3. Past and Future Forests in Britain

In a further part of his series on resilience in forestry, **Jonathan Spencer** looks at forest composition in the distant past and the likely possible near future.

The hot summer of 2018 brought home to us one of the key characteristics of recent climate change predictions; extremes of heat and drought, with the fires on Salisbury Plain and Saddleworth Moor emphasising the more dramatic consequences. Increased extremes in the weather have long been predicted, but the science also points out that we can only avert the worst if we act boldly and act soon. Recent reassessment by the Intergovernmental Panel on Climate Change (IPCC, 2018) makes it very clear that to keep within 1.5°C of pre-industrial levels of greenhouse gases in the atmosphere we have to make major adjustments to the structure of the world economy and that we have only some 10 to 15 years to do so. Dramatic changes to the environment within which the next generation of our trees will be maturing thus appear inevitable. Even if we stop pumping carbon dioxide into the atmosphere and limit global warming to 2°C, a cascade of tipping points may result in a warming of 4 or 5°C or more; an environment not seen since the mid Tertiary some 20 million years ago. In planning for future forest resilience, we face climatic uncertainty, with potential conditions last seen in a distant sub-tropical past or the climate of a very warm interglacial if we manage to exert some control over carbon emissions.

In the Forestry Commissions centenary year, looking ahead to the challenges of the coming century would seem appropriate. For forest managers these challenges include tree establishment and silviculture having to accommodate conditions not anticipated at all a century ago. The case for resilient forests and the management implications of doing so have already been considered (Spencer, 2018a and 2018b). In this article consideration is given to why tree species diversity, especially those valued for timber production, is so limited in north western Europe, and why forest timber tree species from north-west America are so strongly favoured in northern and western Britain. Comment is also made on the lost native trees from the Tertiary and from earlier Pleistocene interglacials. Foresters and the forest industry tend to see the future in terms of alternative tree species. Forest ecologists tend to see the future in terms of forest tree communities and species diversity imparting forest resilience. Given that forest resilience is so bound up with the establishment of tree species diversity and genetic variation, but forestry and forest production in the performance of particular tree species, this review is presented largely in terms of the key timber-yielding species present in our past forests. The continuing role of forests in the provision of timber, fuel and fibre as society moves towards the establishment of a low carbon economy in the 21st century will remain extremely important. This commentary is intended to provide some insight into the potentially more radical choices that may need to be considered in the likely event of unprecedented climate change.

Past climates and past forests

For most of the past 50 million years, before the onset of the ice ages some two and a half million years ago, much of the earth has been much hotter than today, with few frosts and hot summers (see Figure 1). Rather more recently, the

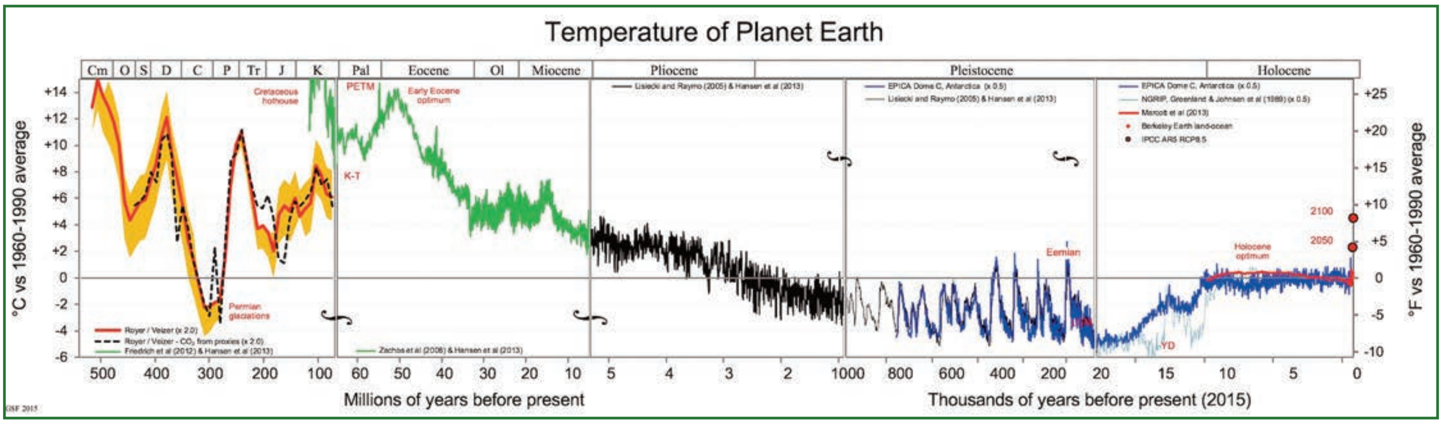


Figure1 Past average temperature across prehistory. For full detail and references, see http://gergs.net/2015/06/updating-the-geological-temperature-plot/all_palaeotemps/ (By Glen Fergus - Own work; data sources are cited below, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1240577)

interminably long glacial periods were interspersed in the UK with periods of milder interglacials of varying length and character, when conditions improved and forests returned. These past interludes provide important insights into the nature of our forests in the past and provide plausible models for forests of the future. A sound appreciation of the diversity and character of the forest communities that prevailed under the different climate conditions of the past could inform both future policy and practice.

Forests before the ice…

The ancient forests of Northern Europe were full of familiar species, although in assemblages that appear strange and unexpected today. We can look back at forest composition throughout the Tertiary and consider forests at a time when the climate was similar to that we may well be experiencing soon; with average temperatures reaching several degrees higher than at present and with little or no ice or frost. The Tertiary period started about 65 million years ago and lasted until the onset of the ice ages some 2 million years ago. The early Tertiary forests were essentially tropical in character; the later Oligocene and Miocene forests were more familiar temperate forests with average temperatures some 4 to 10°C or so above those of today.

Late Tertiary forests in Europe shared many characteristic species with forests worldwide at the time. They were dominated by frost-sensitive conifers and large leaved broadleaves. Although the trees were from familiar genera, the species were clearly rather different. ‘Timber’-bearing species included *Sequoia* spp, *Metasequoia* spp, *Abies* firs, *Picea* spruces, pines, *Tsugas*, *Taxodium* (swamp cypresses), *Fagus* spp. *Cryptomeria*, *Carpinus* spp, *Pterocarya* (wingnuts), chestnuts, yews, *Liquidambar*, elms, oaks, *Acers* and *Platanus* (planes), limes, magnolias and *Liriodendron* spp (tulip trees), with laurels, hazels and palms in the understory (Ingrouille, 1995). The far drier and cooler Pliocene started about 7 million years ago and led to significant changes in the tree flora of Europe, and a shift towards broadleaves. Horse chestnut, walnut and elm seem to have retreated to the Caucasus at this time, to reappear in southeastern Europe with the improving climate at the end of the Tertiary. These forests occurred across northern Europe, Eurasia and North America and were the precursors of forests that lived through, were destroyed by, or responded to, the glacial and interglacial periods that shaped the forests of Europe and North America as we now know them today.

Tree species diversity in British Quaternary interglacials

These extraordinary forests were all rapidly swept away, geologically speaking, with the arrival of the prolonged glacial ‘ice ages’. Towards the end of the Tertiary repeated cycles of warm and cooler climates became established, each lasting about 100,000 years. These became more pronounced, the cooler periods became much colder and glacial ice spread out from the higher and more northern areas to eventually form continent-wide ice sheets. Seventeen cycles of cold and temperate climates can be recognised in Britain over the past two million years, with ten in the last million. However, in the last 300,000 years things became very cold indeed with three episodes of glaciation covering large parts of Britain. These oscillating advances and retreats eventually swept away all the frost sensitive Tertiary forest trees. With each advance and retreat the forest composition of Europe was reduced in species diversity. Sometimes the recovering forests were of markedly different composition, clearly demonstrating that plant communities are contingent entities and not independent of geographical chance. Some species, such as the Caucasian wingnut *Pterocarya fraxinifolia*, were present in diminishing abundance in early warm periods but disappeared with the arrival of severe cold dry periods; others such as Norway spruce and silver fir appear in some interglacials but not in others, suggesting a degree of chance as to their presence or absence across Britain. The relict *Picea omorika*, the Serbian spruce, was once widespread across Europe but is now confined to one valley in Bosnia. The hemlock, lost to Europe in the early Pleistocene, was one of the last survivors of the Tertiary forests in Europe (*Tsuga caroliniana/ canadensis*, not the *Tsuga heterophylla* from the west coast of North America, though ecologically very similar). The signal is clear; what constitutes the composition of British forests throughout this period of early climate chaos was the result of a combination of ecological necessity (the species that could thrive under the prevailing ecological conditions) and geographical chance (those that perchance were in a position to recover and respond when conditions allowed). Throughout, though, a core suite of familiar native trees responded and returned, demonstrating an inherently high degree of resilience and adaptability that should be carefully considered in any strategy to build resilience into future forest composition. Scots pine, Norway spruce, silver fir, various oaks, limes, hazel, hornbeam, beech, rowan and birch, aspen, elm and alder; all have shown a repeated ability to respond and recover from major climatic events in the past and all are found across most of Western Europe, from Cantabria and the Pyrenees in the south to Scotland and Sweden in the North.

However, the overall diversity of species across Europe diminished considerably. Tertiary relicts were rapidly lost (though some persisted for surprising lengths of time, notably the wingnut, *Pterocarya fraxinifolia*) and most are now confined to very distant relict refugia in European enclaves in the forests of northern Turkey, the Caucasian forests of Georgia, the southern fringes of the Caspian Sea, or in fragments of evergreen forests in the Azores and the Canary Islands. The history of individual tree species is rich and complex (an accessible and full account can be found in Ingrouille, 1995). Tree species assemblages are not arbitrary, but neither are they fixed and immutable; they are the product of both prevailing conditions and the changing fortunes and opportunities driven by the vagaries of climate and biogeography.

Holocene change

The fluid nature of tree distribution and forest communities in the present, the Holocene and Anthropocene, has also been well described (see Birks and Tinner, 2016). The Holocene,

The Axel Heiburg Island Forest, North West of Greenland.

Under such mild conditions early Tertiary forests spread far to the north of the Arctic Circle. These arctic Eocene forests were warm and sub-tropical in character (similar to those of Florida today) and probably never experienced freezing, even though they experienced three months of darkness each year. They are very well understood given the survival of exquisite fossil beds on Axel Heiburg Island, north-west of Greenland (Jahren, 2007). Dating from about 45 million years ago, this polar forest is preserved as tree stumps, logs, roots, leaves, seeds and cones, and is comprised of tall dawn redwoods, *Metasequoia* spp., by far the most abundant fossil present, along with *Glyptostrobus pensilis*, the Chinese swamp cypress, *Ginkgo* spp., *Larix* spp., spruces, pines, several hemlocks (*Tsuga* spp), several hickories (*Carya* spp), a *Platanus*, *Betula* spp., *Alnus*, *Acers*, chestnut and beech, ash and elms, holly, walnut, *Liquidambar, Nyssa* and a lime (*Tilia* spp); along with the bones of alligator, turtle and an extinct rhino like herbivore… and fossil wood containing galleries of *Dendroctonus* bark beetles.

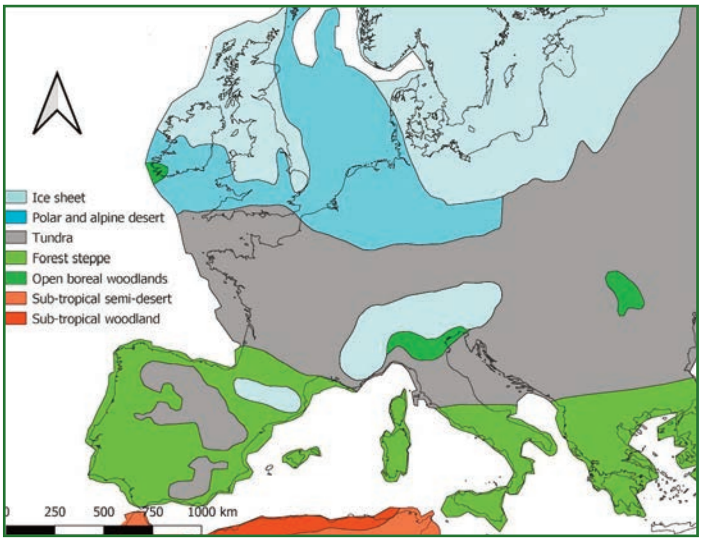
Middle Eocene fossil Metasequoia stump, Axel Heiburg Island today. (Photo: Ansgar Walk, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6416489) the span of time since the retreat of the ice some 12,000 years ago, is characterised by both prolonged climate stability (see Figure 1) and the successive and rapid arrival of tree species, subsequent fluctuations in their comparative abundance and distribution, followed by an unremitting history of forest removal and soil degradation since the late Neolithic and Bronze Age.

Few tree species were lost, but many have become localized or scarce (limes in particular have a distribution and history closely tied to past climate and human land use; see Pigott, 1991). Scots pine, *Pinus sylvestris*, persisted as a scarce component of upland northern British forests for far longer into early history than is generally appreciated, with remains of pine branches found in Roman cemeteries in York and as pollen in peaty deposits in Cumbria as late as the 13th century AD (Huntley, 2010). Recent studies of the DNA of the 14 surviving pines from Williams Cleugh, north of Bellingham in Northumberland, demonstrate a strong affinity with the genetic makeup of native pinewoods in the north of Scotland, supporting the view that Scots pine persisted throughout the Holocene, not only in Scotland but over much of northern Britain (Forest Research, 2005). Forest loss and anthropogenic changes to forests and soils alike have long determined forest composition in Britain.

Europe & North America compared

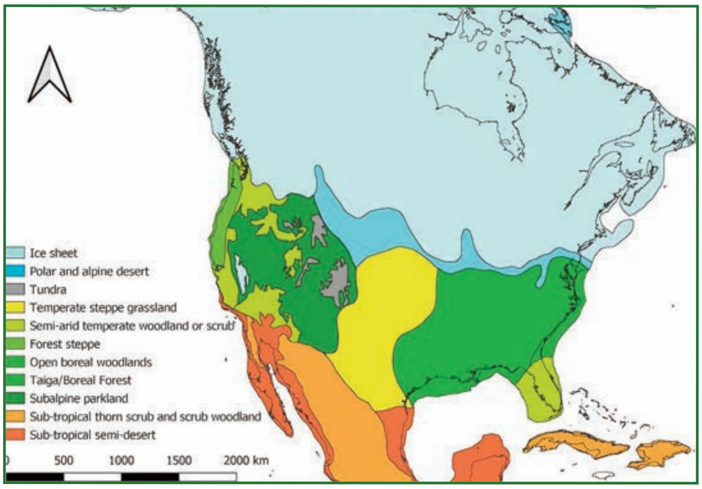
The tree flora of Europe is much impoverished as a result of the accidents of continental geography. The major geographical barriers (the Sahara, the Mediterranean Sea, the Atlas Mountains, the Pyrenees and Alps, the Channel and Irish Sea), all run east-west, across the advance of the ice from the poles. In North America the mountain ranges of the Rockies and Appalachians, the prairies of the Midwest, the peninsula of Florida, the coasts of the Pacific and Atlantic all run north-south, allowing forests to expand and contract without facing insurmountable biogeographical barriers. This has had profound implications for the character of present day forests across both continents and has determined both the paucity of timber tree species in Europe and their diversity in North America (See Maps 1 and 2).

The situation was exacerbated in Europe by the nature of the refugia within which our tree flora persisted at the time of the Late Glacial Maximum. In Europe the refugia for trees were very dry. They lay in the Iberian Peninsula and across much of the Balkans, both of which experienced continental *dry* climates. The Atlantic seaboard was *dry* and cold; the southern refugia *dry* and warm. It has been speculated that the Atlantic ecotypes of silver fir and Norway spruce both disappeared during these cold *dry* periods, robbing present day foresters of native conifers that might have thrived in cold, wet conditions (Rackham, 1980). In North America the refugia for many conifer species persisted in the western regions of the coastal pacific and in the Rockies; coast redwoods, hemlocks, spruces, cedars and cypresses all persisted here in wet and cold, but essentially mild conditions. Redwoods, spruces and other timber bearing conifers survived and spread north to create the extensive western conifer forests found today. Sitka spruce appears to have survived farther north in cold, wet coastal refuges in modern day Alaska and British Colombia. The wet rainy conditions found in the north and west of Britain today support few native tree species, but the conifers of western Canada and the north west of America thrive under such conditions.



Map 1. Europe in the Late Glacial Maximum. Trees and forests were repeatedly scraped from the face of Europe. The biogeographic barriers run east-west with forest refugia in cold dry Iberian peninsular and the warm, dry southeast of the continent. Tertiary species once found in Europe are now restricted to locations in the Caucasus, the Hyrcanian forests of the Caspian Sea, with more remote survivals in temperate China. Data modified from Ray and Adams (2001).

One encouraging consequence of forest history in Europe is that the tree species regarded as native to Britain can reliably be regarded as resilient against future climate change; they have survived and recovered from many dramatic changes over hundreds of thousands of years. They have been memorably described as the weed species that raced back with the retreat of the ice (Richard Jinks, pers comm.). Most have widespread distributions and are genetically very varied. Having coped with the wildly



Map 2. North America in the Late Glacial Maximum. The biogeographic barriers run north-south with extensive forest refugia in the cold wet pacific coast and western mountains, and warm temperate and sub tropical refugia in the South eastern states where many 'Tertiary' forest species persist to the present day. Data modified from Ray and Adams (2001)

fluctuating environmental conditions of the past two million years, they will continue to thrive under the changes anticipated by climate scientists today. If we curb emissions and restrict average temperature change to below 2°C we shall be working with forests of familiar composition and character. Should we breach these conditions then we are heading into climate territory not seen since the mid-Tertiary and our ideas for forest composition, and the timber tree components they support, will have to change accordingly.

Lessons learnt

The key lessons to be drawn from a study of past climates and forests appear to be:

- Forest composition is not arbitrary, but neither is it fixed and immutable; it is the product of both prevailing conditions and the changing fortunes and opportunities driven by the vagaries of climate and biogeography.

- Forests are resilient to both extremes of climate and rapid changes in temperature, adjusting over time as conditions prevail (though within timescales that are not well suited to human lifespans, our inherent impatience, nor the immediate needs of society for the goods and services that forests provide).

- Our native tree species demonstrate an inherent high degree of resilience and adaptability. They have shown a repeated ability to respond and recover from major climatic events in the past and all are found across most of Western Europe.

- British forests are a subset of a wider (but not much wider) range of European trees, some of which have occurred here in previous interglacial warm periods and some of which simply did not return fast enough over the past 8,000 years to become regarded as native trees.

- We nevertheless have either lost, or never had, a suite of trees adapted to the cold wet conditions and the gleyed or peaty soils of north-western Europe. To make our upland and western forests more resilient and maintain their capacity for timber production we will have to look to north-west American forest trees, chosen for their performance as timber, and find European or north-American associates that might impart resilience against changing conditions and novel pests and diseases.

- Longer term changes in our possible climate future may take us towards uncomfortable territory and the need to

Table 1. Past and present native timber trees … a brief review.

Present interglacial native British trees…	Oaks, beech, elms, ash, small-leaved and large-leaved lime, field maple, hornbeam, birches, alder, aspen, black poplar, cherry, wild service tree, rowan, Scots pine, yew, juniper. Plus sycamore and sweet chestnut as long established introductions.
Past interglacial native British tree species…	All species above plus: Silver fir, Norway spruce, Serbian spruce, hemlock (*Tsuga*), sycamore, Norway maple, Montpellier maple (*Acer monspessulanum*), hickory (*Carya*) Caucasian wingnut (*Pterocarya*), walnut (*Juglans*), tulip tree (*Liriodendron*).
Past European Tertiary natives… before the ice.	All the above plus: *Sequoias*, *Metasequoia*, *Cryptomeria*, *Cedrus* spp., *Abies* firs, *Picea* spruces, *Thuja* spp., pines, *Taxodium*, *Tsuga* spp., *Ginkgo*, *Larix* spp., *Fagus* spp., *Quercus* spp., *Liriodendron*, Magnolias, *Parrotia*, *Liquidambar*, *Acer* spp., *Platanus* spp., *Juglans* spp., *Tilia* spp., *Zelkova* spp., *Ostrya* spp., *Carya* & *Pterocarya* spp., *Betula* spp., *Alnus* spp.

consider forest species that have long since been lost to Europe as native elements.

- Many of these trees are already present in the modern landscape in parks, gardens and arboreta. These trees will no doubt respond in any event as changing climatic conditions allow for their reproduction and spread across the landscape. We should consider such species on their merits and assess our response accordingly (see Thomas, 2017).

The European forest landscape of the past was very different. Its forests were direct descendants of forests that had persisted in one form or another for many millions of years. They were extensive, complex, and comprised of a great diversity of tree species and genera. These forests stretched from North Africa to the Arctic Circle. Changes in climate are not new challenges to forests per se; forests in some form will persist and thrive. But they will be forests of species and composition unfamiliar to foresters and conservationists alike. If we wish to remain comfortably within our existing forest and nature conservation paradigms, then addressing climate change has to remain our highest priority. Change though, now appears to be inevitable. Sustaining the status quo for forestry or nature conservation alike will sadly no longer be an option.

Acknowledgements

I should like to thank Dr Mark Broadmeadow, Dominic Driver, Chris Reynolds and Andrew Stringer for their help in the preparation of this article, and to Dr Freia Bladon for help in its drafting. I would particularly like to thank Andrew Stringer for his major contribution in preparing the maps of Ice Age America and Europe. Thanks are also due to Emmanuel College Cambridge and the Derek Brewer Visiting Fellowship, and the Conservation Science Group at Cambridge University, whose support in the preparation of these articles in spring 2017 was invaluable.

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Remote Sensing Technologies for the Management of Tree Pests and Diseases

Chloe Barnes reviews the use of airbourne hyperspectral imagery and related technologies in monitoring tree health.

Pest and disease monitoring surveys are key for the management of pests and pathogens threatening the health of forests. Remote sensing technologies provide a means of obtaining information about forest environments, with precise geospatial locations, to assess canopy changes indicative of declining tree health. This article presents the application of airborne hyperspectral imagery for the classification of dieback presence in hedgerow ash (*Fraxinus* spp.) trees. The research findings are reviewed in light of the wider literature concerning the potential applications of remote sensing technologies in tree disease detection.

Introduction

The fungal pathogen *Hymenoscyphus fraxineus* is the causal agent of the large-scale dieback of European ash (*Fraxinus excelsior)* and other ash species across Europe. Following the introduction of the pathogen into the UK in 2012, ash dieback has subsequently spread across large areas of the country (Forestry Commission, 2018). This particular disease outbreak is just one of many currently causing serious concerns for the management of UK forests (British Woodland Survey, 2015). Monitoring activities that provide information regarding the location, distribution and severity of disease outbreaks form a strategic part of the management and response to tree pests and pathogens. In recent years remote sensing technologies have been increasingly citied for their capabilities in the assessment of tree health and disease detection (Lausch et al., 2016).

The term remote sensing is simply defined as “the acquisition of data regarding objects without direct contact with the specific target” (Nutter et al., 2010). With regards to forestry, remote sensing has typically been conducted via three main platforms; these include satellites, aircraft and more recently unmanned aerial vehicles (UAVs) (Huete, 2012). Whilst each platform presents its own advantages and limitations, spatial resolution requirements and the extent of the area of interest are the primary drivers for platform selection. Each platform also supports a variety of sensors. Traditionally, optical sensors have been applied to identify discolouration and defoliation associated with disease in trees (Näsi et al., 2015). However, research has also demonstrated the applications of light detection and ranging (LiDAR) for the assessment of structural changes in crown architecture associated with the defoliation of affected canopies (Barnes et al., 2017a).

This article presents research conducted to investigate the potential capabilities of airborne hyperspectral imagery for the assessment of ash dieback in a hedgerow environment in England. In comparison to traditional true-colour aerial photography, which images in three bands (blue, green and red), hyperspectral sensors image hundreds of narrow bands across the visible and infrared regions of the electromagnetic spectrum providing a higher level of spectral detail. This allows for the biochemical and biophysical characteristics of the tree canopy to be analysed and assessed in greater detail. In addition to the presented research, a wider discussion examines other examples from the scientific literature to consider the current capabilities of remote sensing technologies across all platforms to assist in the monitoring of tree pests and pathogens in the UK.

Figure 1. True-colour image (collected from aircraft) demonstrating the characteristics of the study site with a selection of surveyed ash trees highlighted by green polygons.

Case study: Ash dieback in hedgerows

Study site

The study site consisted of a roadside hedgerow bordering agricultural land (Figure 1) between the villages of Lowick and Aldwincle in Northamptonshire. The site was selected due to the variability in ash dieback severity and accessibility for ground surveying.

Data collection

A total of 52 individual trees along the hedgerow were subject to ground survey to determine species. European ash (*Fraxinus excelsior*), which accounted for the majority of trees surveyed (86%), were subject to additional assessment to determine the percentage of crown dieback (recorded in 5% intervals). This assessment was conducted by the same surveyor to ensure consistency in observations.

Airborne true-colour (0.07m resolution) and hyperspectral (0.33m resolution) imagery was acquired for the study site on the 25th August 2017. All imagery was acquired in strips using the Piper PA31 Navajo aircraft at a flight height of 300m. Following acquisition several processing steps were undertaken including georectification (mapping the image onto a co-ordinate system), atmospheric correction (removing the effect of the atmosphere on reflectance values) and photogrammetry (deriving three-dimensional models from aerial photographs) to provide analysis ready imagery and a digital surface model.

Ash dieback assessment

In order to conduct the ash dieback assessment for individual trees in the hedgerow, individual tree crowns (ITCs) were automatically identified using height information from the digital surface model derived from the aerial imagery. This stage of the process enabled the automatic generation of polygons (outlines) to represent each tree crown in the hedgerow (Barnes et al., 2017b). To assess how well individual tree crowns could be automatically detected, manual drawings were also produced using the high resolution true-colour imagery. This process of manually identifying individual tree crowns is however time consuming, so an automatic approach is preferred.

The reflectance values recorded by the hyperspectral camera were extracted for each tree using the tree crown polygons (outlines). The very detailed information captured by the camera provides the reflectance values for over 300 bands (or wavelengths) in the visible and infrared regions of the electromagnetic spectrum. This provides a lot of data for each individual ash tree in the hedgerow. One way to reduce this amount of information is to produce vegetation indices, which combine specific bands (or wavelengths) of interest for the study of vegetation. In this case 64 vegetation indices were calculated from the hyperspectral imagery and used to classify the presence of dieback in individual ash trees at the study site.

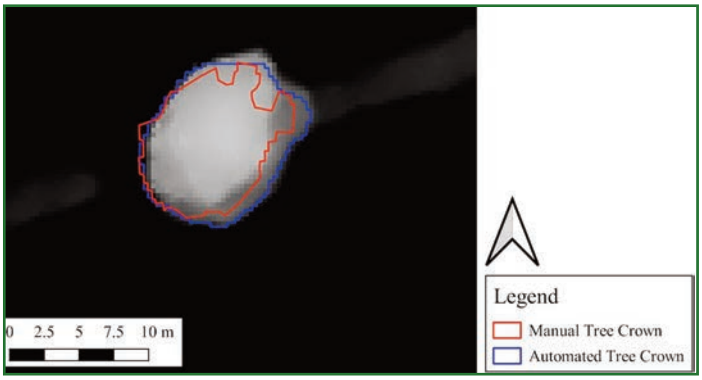

Figure 2. Example of the manual and automated identification of tree crowns at the study site in relation to the digital surface model.

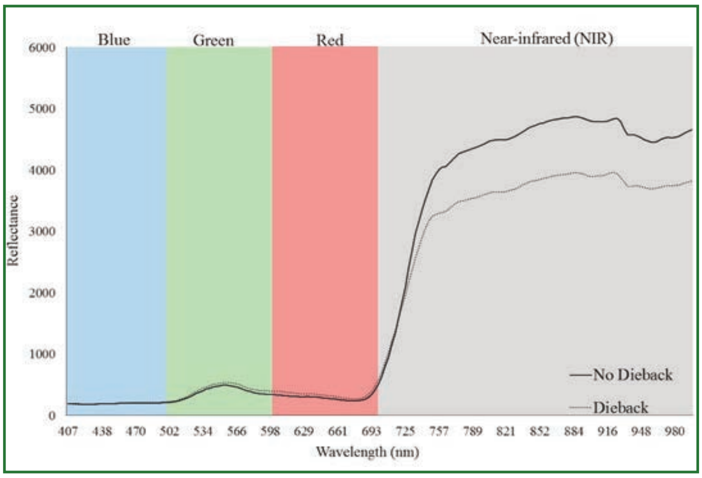

Figure 3. Spectral reflectance extracted from ash tree crowns with and without dieback

Results

The reflectance spectrum of ash trees with and without crown dieback are displayed in Figure 3. Ash trees which exhibited crown dieback (5-50%) demonstrated a suppressed reflectance in the near-infrared (NIR) region of the electromagnetic spectrum. A slight increase was also observed in the green and red reflectance of ash crowns affected by dieback. These variations in reflectance were used in this study for the identification of dieback in ash. Similar results regarding the effects of pests and pathogens on canopy reflectance have also been reported in previous studies concerning emerald ash borer (EAB) (*Agrilus planipenni)* (Pontius et al., 2008), insect damage in eucalyptus trees (Stone et al., 2001), damage to Norway spruce canopies (Campbell et al., 2004) and Phytophthora foot rot in citrus trees (Fletcher et al., 2001).

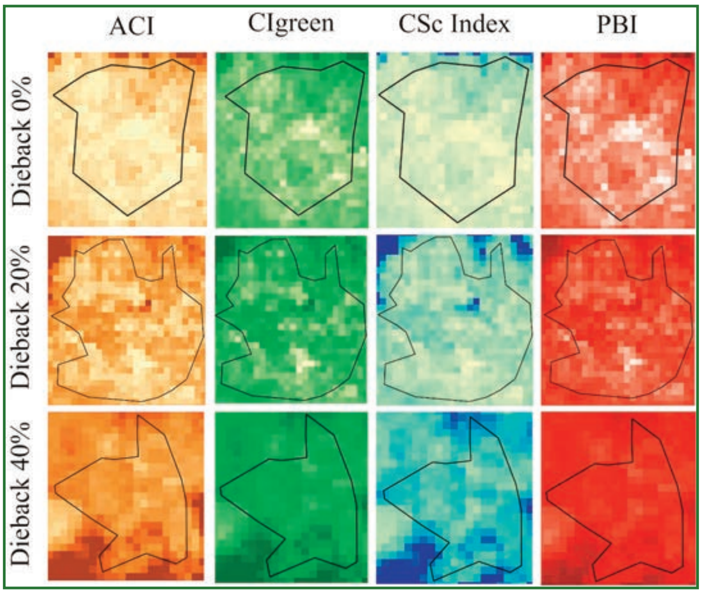

Figure 4. Four key vegetation indices for the detection of dieback in ash tree crowns (ACI: Anthocyanin Content Index, CIgreen: Chlorophyll Index Green, CSc green, PBI: Plant Biochemical Index).

The classification of dieback presence (no dieback vs dieback) in ash trees at the study site using the airborne hyperspectral imagery yielded an overall accuracy of 87%. Vegetation indices calculated using the reflectance values from the green/red (550-605nm) and near-infrared (NIR) (760-860nm) regions of the electromagnetic spectrum were particularly important for the dieback classification. Figure 4 provides a visual representation of the four most useful vegetation indices for the identification of dieback along the hedgerow.

Concluding remarks

The results from the presented case study demonstrate the capabilities of a certain sensor (hyperspectral) from a particular platform (airborne) to differentiate between individuals of a specific species (ash) in a specific

Table 1. Examples of disease detection studies from different remote sensing platforms and sensors.

	Location	Tree Species	Disease/Stress	Sensor	Reference
Satellite	*Robinia pseudoacacia* Forests, China	*Robinia pseudoacacia*	Crown decline	IKONOS (4m) and Landsat 8 (30m)	Wang et al. (2015)
	Mixed species forest, Germany	Ash (*Fraxinus excelsior*)	Ash dieback (*Hymenoscyphus pseudoalbidus*)	WorldView-2 (2m)	Waser et al. (2014)
Aircraft	Pine dominated forest, Finland	Scots pine (*Pinus sylvestris*)	Common pine sawfly (*Diprion pini*)	LiDAR (20 p/m^2)	Vastaranta et al. (2013)
	Bavarian Forest National Park, Germany	Norway spruce (*Picea abies*)	Deadwood, spruce bark beetle	CIR Imagery	Heurich et al. (2010)
UAV	Urban Forest, Lahti, Finland	Norway spruce (*Picea abies*)	Spruce bark beetle (*Ips typographus*)	Hyperspectral	Näsi et al. (2015)
	Riparian forests, Southern Belgium	Black alder) (*Alnus glutinosa*)	*Phytophthora alni*	Multispectral	Michez et al. (2016)

Abbreviations: CIR = colour infrared; p/m^2 = points per square metre.

environment (hedgerow) subject to disease with a distinct set of symptoms (ash dieback). Whilst this highlights the potential capability of this remote sensing approach to assess disease at the selected study site, transferring the approach across different environments, scales, tree species, pests and pathogens is more complex. Selecting the most appropriate remote sensing technologies for a specific disease detection challenge requires an in-depth understanding of the capabilities and limitations of different sensors and platforms and the symptom expression associated with particular agents of disease and stress in specific tree species (Lausch et al., 2016).

Remote sensing technologies for tree disease management

Current capabilities of remote sensing in tree disease assessment

To provide an overview of remote sensing capabilities in tree disease assessment, Table 1 presents a selection of previous studies, which reported successful disease classification results (>70% accuracy). In the case of satellite-based studies, freely available datasets with lower resolution such as those acquired by the Landsat sensors (30m resolution) have applications in locating areas of pest damage in expansive homogenous forest, but are typically not applicable for the assessment of defoliation intensity or identifying more localised outbreaks (Wang et al., 2015). Satellite data acquired at higher resolutions, such as the WorldView-2 imagery utilised by Waser et al. (2014) (Table 1), will facilitate a more localised assessment of canopy condition, however, this requires a financial investment to purchase data for analysis. High-resolution datasets acquired via aircraft and UAV facilitate the assessment of individual tree crowns for the presence of canopy discolouration and defoliation (Näsi et al., 2015; Barnes et al., 2017b). Optical datasets (measuring reflected solar radiation from the earth's surface), such as the true-colour and hyperspectral imagery used in the ash dieback study reported above, offer disease assessment via the detection of spectral changes associated with pigment degradation caused by stress or disease, in addition to the increased contribution of non-canopy surfaces to reflectance values following defoliation (Zarco-Tejada et al., 2018). Disease assessments conducted via LiDAR utilise changes in tree structure as a result of foliage loss for disease detection (Barnes et al., 2017a).

Limitations

To present a balanced picture of the capabilities of remote sensing approaches to disease detection in forestry it is also important to recognise the limitations of the technology. At present one of the greatest disadvantages of remote sensing approaches, as opposed to ground surveys, is the inability to attribute the observed decline in tree health with a specific pest or pathogen. In the case of many disease outbreaks, such as Phytophthora ramorum in larch and chestnut blight (*Cryphonectria parasitica*), diagnosis is achieved through the assessment of the stem and canopy by experienced surveyors in addition to field-based and laboratory testing. Therefore, it is important not to consider remote sensing as a diagnostic tool where further analysis is required to confirm infection. Nevertheless, remote sensing technologies should be considered with the view of monitoring canopy condition to provide more efficient targeting of investigative field surveys and as a tool for monitoring the spread and severity of known outbreaks.

Additional limitations also occur in mixed species environments where difficulties are experienced in identifying the exact species subject to decline. Whilst high resolution hyperspectral imagery has previously been applied to tree species classification (Dalponte et al., 2013), the additional complexities of discoloured or missing canopies can reduce the accuracy of these classifications (Lausch et al., 2016). An ideal approach to combine the remote sensing capabilities in tree species and disease detection would be to utilise the species discrimination capabilities of hyperspectral remote sensing to produce tree species maps prior to infection by a pest or pathogen. Subsequent monitoring via remote sensing would then facilitate a more detailed assessment of forest condition and provide a vital modelling input for forecasting the spread and distribution of new disease outbreaks (Holdenrieder et al., 2004).

From a data collection perspective, consideration also has to be given to the difficulties incurred by cloud cover and shadow. Satellite platforms are most affected by these factors, however cloudy conditions also impact the quality of data acquired from aircraft and UAVs (Suárez et al., 2005). The impacts of seasonality, especially in the case of deciduous species, should also be considered when remotely sensed datasets are acquired and analysed for disease assessment. Additionally, tree age and height have also been documented to influence spectral and structural characteristics of healthy trees (Waser et al., 2014; Barnes et al., 2017a). Developing an awareness of the limiting factors for the collection and performance of remote sensing technologies will enable policy makers and end users to make informed choices to select the most appropriate platform and sensor for tree disease assessments.

UK context

In the context of the UK, limited examples are presently available in the literature to inform the development of remote sensing approaches to current disease challenges. One example presented by Barnes et al. (2017a) concerned the *Phytophthora ramorum* outbreak in larch with a particular focus on plantation forest in South Wales. This study utilised the same individual tree crown approach applied in the ash dieback research above, however the disease assessment was performed using LiDAR collected via aircraft as opposed to imagery. The results of the study demonstrated the capability of the LiDAR to detect structural changes in larch trees, which presented defoliation in more than 20% of the canopy. Whilst this study demonstrates the potential capabilities of LiDAR datasets to be applied to disease monitoring, it provides just one isolated example of the capability of the technology in disease detection.

With limited examples regarding remote sensing solutions to the challenges faced by UK forestry it is difficult to build a compelling argument to alter current manual operational approaches to disease detection and monitoring across forested landscapes. Further engagement between forestry professionals and remote sensing specialists, in addition to an increased number of scientifically conducted case studies, is required to demonstrate operational capabilities of remote sensing technologies to address present and future challenges in tree disease detection and monitoring.

Conclusion

The results from the research complement the mounting evidence from the literature regarding the application of remote sensing as a tool in a multi-disciplinary approach for the management of disease in forest environments. In particular, differences exhibited in the spectral reflectance of ash trees with and without crown dieback, facilitated the classification of dieback in individual ash trees with an accuracy of 87%. This result demonstrates the potential capability of an airborne hyperspectral remote sensing approach to provide ash dieback assessment in hedgerow environments. Nevertheless, work is still required to develop operational disease detection approaches that utilise the most appropriate remote sensing technologies, especially in the context of pests and pathogens of concern in UK forestry.

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