Scottish Natural Heritage
Research Report No. 789

A review of the theory and practice of tree coring on live ancient and veteran trees

Scottish Natural Heritage
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RESEARCH REPORT

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RESEARCH REPORT

Summary

A review of the theory and practice of tree coring on live ancient and veteran trees

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Keywords

Ancient; veteran; live; tree; coring.

Background

This study has been commissioned by Scottish Natural Heritage in partnership with Historic England and Natural England on behalf of the UK Wood Pasture and Parkland Habitat Action Plan Technical Advisory Group (WPPTAG) in response to concern that coring activity may give rise to damage to *ancient and veteran trees (AVTs)*. Coring unavoidably creates an injury, which does not benefit an individual tree. The question arises, how serious and what are the implications of the injury and how to balance this with any benefits from the activity?

The varied motivations for coring trees derive from diverse, respected and conscientious interests and the need to pursue evidence based investigation for scholarship and practical outcomes. There is a need for conservation, arboriculture, climatology and dendrochronology interests to exchange knowledge and support one another. A convergence is required so that valuable knowledge gained from coring can be beneficially exploited without being at the expense of our oldest, most important AVTs.

In addition to the effects of wounding, there are biosecurity concerns from the risk of coring introducing pathogens between and within tree populations. The decision to undertake coring needs careful consideration taking all the relevant circumstances into account, such that the scientific benefits derived from the activity are weighed against the risks of injury to trees of value. In these contexts guidance is required to assist commissioning bodies and landowners responsible for important trees and for those carrying out the work.

The report reviews veteran and ancient tree interests in the context of the Wood pasture and Parkland Habitat Action Plan, and provides conclusions for the Wood Pasture and Parkland Advisory Group and the dendrochronology sector to consider. The study explores the principles and practices underpinning dendrochronology and current knowledge of tree biology and wound responses to help develop a guidance framework for increment boring good practice for AVTs. Further work would include discussion, development and dissemination of best practice.

Main findings

- On the basis of this study it can be concluded that there are potential impacts when coring live trees, be they AVTs or younger healthier specimens. Concerns that coring may cause some harm to living AVTs therefore appear to be reasonably justified. The extent of harm is variable and generally, not likely to be extensive in the short term. Concern is principally with regard to long term impacts to trees, particularly AVTs. To date, there has been inadequate research specific to coring to establish its long term effects, though reference to arboricultural experience leads us to believe that invasive wounding, such as that caused by coring, can be harmful to some trees. Therefore, at present, given the considerable value of the AVT resource and its potential vulnerability, a general precautionary approach to coring is a reasonable stance. This would suggest that commissioning bodies ensure appropriate protocols for assessing the suitability of AVTs for coring and that they, wherever practicable, consider other non-invasive methods of approximating tree age (such as the method devised by John White). Professional research/interest groups should ensure that those potential impacts are minimised by taking appropriate measures and by ensuring that the research undertaken has clearly defined aims and products that have been duly considered with respect to the overall benefit of the research in a wider context and the potential impact on the targeted trees. The methods employed must be appropriate to achieve the required outcomes of the research and hence will vary accordingly
- The quality of coring data derived from younger, more uniform trees is typically more reliable than that derived from the trunks of aged trees, as the latter are invariably hollow and contain pockets of wood decay. For most purposes, when evaluating and managing AVTs, while an understanding of individual tree condition and age-class may be important, knowledge of precise tree age is seldom required and coring in these circumstances is probably not justified. Hollowing trunks with decay pose difficulties for the practical process of boring and for the extraction of reasonable quality core samples, which as a consequence are likely to have limited value and be unrepresentative of generalised growth patterns.
- Coring trees inevitably results in a wound. External occlusion of an increment-boring wound with new callus growth should not be equated with 'healing'. The action of the augur causes some degree of injury as it screws into sound sapwood and, in addition, as it passes through internal decay there is a risk of decay migration. While decay may be contained at least for some time within the wound zone, decay activity may also be progressive and ultimately spread considerably beyond the region of the coring wound. Coring runs an added risk of inducing structural cracks at a micro-level as the augur forces wood tissue apart. Multiple coring of a trunk increases crack propagation, and in turn compounds the risks from internal decay.
- In the context of strategies to control the risk of harm to trees, operational guidance would sensibly take account of unfavourable factors that might predispose a tree to an impaired response to wounding, which might apply during periods when trees are likely to be under physiological stress, e.g. extreme weather conditions that include prolonged drought.
- National biosecurity guidance is relevant to all activities on sites containing trees, which has specific implications for coring. On certain sites coring may need to be strictly controlled where there is an unacceptable risk of pathogen introduction or cross-infection between trees.
- There is no current, broadly approved UK standard for the practice of tree coring (or for the management of data derived from the activity). Nor is there a broadly approved UK based programme of training and proficiency testing for those who wish to be engaged in coring trees. The discussion paper supplementing this report considers the findings from this current study in order to assist the development of such guidance for the benefit of AVTs.

- The Ancient Tree Hunt has produced an extensive data resource that could be further exploited for inter-agency cooperation and used to enhance the John White system for dendrochronological study.
- It is not the purpose of this report to impede valid and appropriate dendrochronology research. The findings of this report should be used to encourage the production of a workable and widely acceptable best practice guidance document in relation to the coring of live trees that can be used by all professional research/interest groups to facilitate appropriate research and knowledge enhancement that is balanced with the value of AVTs in a wider conservation perspective.
- This report is a review of current knowledge and a key conclusion is that there is a need for all professional research/interest groups to come together to improve information sharing and to explore common standards for coring practice and data recording. One way of achieving this would be to facilitate a seminar to explore these issues.

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1. INTRODUCTION

1.1 Background

Over the past two decades, particularly since the launch of the Ancient Tree Forum, knowledge about ancient and veteran trees (AVTs) has steadily grown in the UK through collaborative initiatives involving governmental and the voluntary organisations with interests in AVTs. This has resulted in the dissemination of knowledge through websites and training, and through publications on survey methods, management guidance and conservation practice. While this has drawn on contributions from a wide range of professionals and specialists, to date the implications of dendrochronology have not been particularly well considered.

While the elevated interest among the general public and organisations concerned with AVTs has resulted in enhanced awareness about their rarity and other values, concerns have also been raised about their vulnerability, declines and losses (issues explored further in Section 2 and 10).

The analysis of tree-rings may be obtained from felled or fallen cross-cut trunks. The technique of boring into trees to determine tree age allows dendrochronological data from extracted cores from standing trees, which can be analysed and cross-correlated with tree-ring data from different sources. Tree-ring patterns and chronologies have played an important role in chronicling the past and forecasting future trends. Data derived from coring trees are extensively applied to different study areas including landscape history, archaeology, climatology and ecology.

This current study is concerned with the activity and implications of coring trees[1] with particular reference to AVTs (see Section 2 for definitions). Coring unavoidably causes some measure of injury when boring into trees. This study considers the implications of coring high heritage-value AVTs, in relation to potential impacts upon tree health and condition and explores the management of the risks from such impacts.

Developing a framework to guide good practice and decision making for coring AVTs will rely on a sound, shared understanding of the principles and practices underpinning dendrochronology, as well as knowledge of tree biology and responses to wounding.

While the majority of core-sampled trees on many sites may not have exceptional current worth, those that are ancient and veteran require individual consideration. Conservation principles can lead to concern that coring may damage or shorten the longevity of individual important trees. Such concerns generally focus on potential threats to the health, condition and the continuity not only of the individual trees but also of their associated biodiversity.

This current study explores the evidence basis for making decisions with regard to coring AVTs. It is based on literature and past research. To support this, a questionnaire was prepared to obtain information and opinion from a small number of respondees, mostly dendrochronologists. Areas of enquiry included examining reasons for studying the ageing of trees, and views regarding good practice, the timing of coring, potential damage from coring, limitations that hollow trees present, data management and the use of other related evidence.

The inherent value of coring trees lies in the reliable data that is obtained from building up chronological sequences of tree-ring patterns. These are enhanced when supplemented with new technology (e.g. radiocarbon calibration). Coring has clearly contributed to the quality of

[1] Coring trees for silvicultural and arboricultural study is sometimes also referred to as 'increment boring' and 'test boring'.

data and knowledge, such as the coring of ancient oaks in Scotland. Though some non-coring methods provide age guidance, such data is mostly regarded to fall short of the exactitude valued by dendrochronologists.

Variability in the purpose of undertaking tree coring (such as investigating individual tree ageing or ageing populations for broader study) can influence professional views regarding the proposition that coring may require a standard that could impose constraints. Without criteria for determining the importance and value of individual trees, some dendrochronological practitioners question the basis for imposing constraints that might come from guidance.

In general, questionnaire responses from professional dendrochronologists suggest that there is little evidence that coring is seriously damaging to trees. Additionally any damage that there might be should be balanced against the knowledge benefits from dendrochronological evidence accrued to fields with recognised widely held importance, such as landscape history and extrapolating climate change. This could be summarised as follows - as the risk consequences of coring upon tree longevity are low and the knowledge benefits are high, the imposition of controls is broadly unnecessary. However, it should be noted that the use of microborers, which Historic England considers as a minimal intervention technique in historic buildings, has demonstrated the limitations concerning resolution with respect to deriving precise ring sequences that are suitable for the more standard dendrochronological purposes of dating and climate studies (Tyers, 2018 pers. Comm. to project officer).

In the past, increment borers have played a more significant role in arboricultural practice – for condition and safety assessments of individual trees. This practice, known as test boring (as compared with dendrochronological core sampling), is today considered controversial in arboriculture, largely due to concern for the risk of harm from the invasive wounding to the tree. For this reason the increment borer today is seldom used in Britain by professional arboriculturists. Instead, the use of increment boring for tree safety assessment has been superceded by other more sophisticated, less invasive, devices for determining the sound wood quality of the trunk and principal stems of trees. However, such methods do not provide the type of data sought by dendrochronologists.

Much of the discussion emerging from the questionnaire resolved into two main contending views:

- Coring is invasive and potentially damaging: *the unconstrained practice runs counter to a reasonable precautionary approach to the conservation of AVTs with potentially high value habitat contributing to species biodiversity.*

- The evidence basis that tree coring is seriously damaging is unproven: *the relatively limited damage that occurs is outweighed by the value of the knowledge derived from the practice.*

There are some areas of agreement as to the disbenefits of coring aged *hollow* living trees, *though for different reasons*.

- *From a conservation point of view the practice of coring hollow trees is potentially harmful and likely to adversely affect the oldest, most valuable and vulnerable trees.*

- *From the dendrochronological perspective coring hollow trees presents practical difficulties and provides restricted, unreliable data.*

All interested parties would also agree that:

- *Coring of dead trunks and branches and fallen trees has value in providing dendrochronological information without risk of harm to living trees.*

- *The emergence of new tree diseases and associated national biosecurity risks requires workable protocols for disease risk control when coring live trees.*

This review has involved consultation with professionals and specialists in dendrochronology, arboriculture and related disciplines with regard to their interests in and experience of coring. This has revealed different qualities and levels of understanding within and between dendrochronological and arboricultural communities with regard to potential arboricultural impacts of coring upon trees, indicating there is much to be gained from discussion and sharing knowledge.

In addition to this review, a separate discussion document has been drafted as a Scottish Natural Heritage report titled '*Towards a Code of Best Practice for Coring Live Ancient and Veteran Trees*'. Along with the benefit of the questionnaire responses and the conclusions of this review, the discussion document is intended to provide a reasonable basis for communication and developing initiatives to enhance a common understanding between practitioners and disciplines. Through such consultation and exchange the UK Wood Pasture and Parkland Technical Advisory Group propose to develop an agreed Code of Best Practice.

2. ANCIENT AND VETERAN TREES

2.1 Classification and importance

An *ancient* tree is one that is old for its species.

The term ancient describes an age class, a life stage where the chronological age of the individual is considered in light of the species' life cycle and typical life expectancy. This stage is generally accompanied by loss of apical dominance as the tree passes beyond full maturity, following which the crown begins to gradually shed redundant parts and accumulate dead and decaying wood. Branches die and break, and trunk *heartwood*[2] and *ripewood*[3] are increasingly prone to decay, accompanied by varying degrees of trunk hollowing (see Figure 1).

Beyond full maturity the crown begins to reduce in size (*crown retrenchment*) and the current annual increment (CAI) of woody tissue eventually reduces, compared to earlier developmental stages in the tree's growth (White, 1998). This is the final stage (when conditions are favourable this phase can be the longest in the life of the tree) (Read, 2000; Lonsdale, 2013). Various dead and decaying (saproxylic) wood and other features associated with longevity are increasingly found as the post-mature tree ages, and contribute to the quality of the saproxylic habitat (Fay and de Berker, 1997).

As the ageing process progresses specialist, wood-decomposing fungi that have colonised the trunk and major branches alter the character and condition of the woody tissue. Decay is initiated in formerly-conductive vessels in the heartwood/ripewood and in the oldest and the largest tree specimens the central core eventually becomes hollow, providing one of the rarest types of terrestrial habitats. The characteristic of hollow-core habitats is that the outer living part becomes a container for the accumulation of decades and sometimes centuries of decomposing woody detritus, which becomes a substrate for specialist microorganisms and insect colonisers.

As trees age, natural damage and the shedding of tree parts generate a complex range of habitats – such as branch cavities, live stubs, shattered branch ends, loose bark, sap runs and a range of rot types. Even the organs of saproxylic fungi (fruiting body, mycelia etc) become habitats for specialised invertebrates. Thus the ageing tree becomes a living sapwood envelope providing specialised niches for diverse organisms with a wide range of 'life-styles' (Butler *et al*., 2002). Over time physical changes affect the pH status of tree bark, creating conditions favourable for epiphytic diversity, in some cases including rare lichen communities, which may colonise from nearby old trees (Rose, 1991). These processes are accompanied by an equivalent biodiversity expansion below ground within the woody roots and about the surrounding soil system, all of which is integral to the ageing tree.

Veteran is a descriptive term that refers to the condition of the tree rather than its age class and draws attention to exceptional qualities associated with particular saproxylic habitats in trees. A 'veteran tree' has the anthropomorphic, cultural connotations of a battle-scarred survivor.

Defining the age, character and significance of trees, while important, is not necessarily straightforward, particularly when applied to survey criteria (Fay, 2002a; Lonsdale, 2013). To

[2] Heartwood is the predominantly well-defined, non-living central core of wood that is surrounded by the outer live conductive vessels that have a more or less predetermined life span, e.g., oak (*Quercus* spp.) and chestnut (*Castanea sativa*).

[3] Ripewood species show a more gradual transition where the ageing sapwood gradually transforms into heartwood, such that the sapwood is not clearly discernible e.g. beech (*Fagus* spp.).

the non-specialist, the term 'veteran' is synonymous with 'ancient' and is often used to describe both the age-class and condition of a tree.

The term veteran does not automatically equate to extreme age. While all ancient trees will have habitat features sufficient to qualify them as veteran, all veteran trees will not necessarily have entered into the ancient age-class.

Saproxylic invertebrates tend to have limited powers of dispersal and certain species will only colonise rot sites once specific conditions have become favourable. The greater the length of time a group of trees exists on a site, the greater the possibility for particular specialised and rare species to colonise decaying woody habitat. The greater the number of veteran trees and the continuity of the population on a site, the more likely there will be habitat quality to suit a wide range of species.

The Index of Ecological Continuity (IEC) (Alexander, 2004) was developed as a means for grading sites for their conservation significance based on the assessment of beetle communities (taking account of ecological rather than rarity considerations). Saproxylic sites, with greatest continuity of populations containing young through to ancient trees, provide the most likely environments for species-rich assemblages. In contrast, when the linkages between age classes break down or high losses and declines impact upon ancient trees, the niche habitats peculiar to the ancient age class is threatened and continuity can therefore be broken. The vulnerability of old trees on sites with long continuity elevates their conservation importance.

Six percent of British invertebrate fauna, comprising over 2,000 invertebrate species, depend upon ancient tree habitat (Alexander, 2012). Other indices have been developed for communities such as the Revised Index of Ecological Continuity (RIEC) (Rose and Coppins, 2002) and the expanded New Index of Ecological Continuity (NIEC) (Rose and Coppins, 2002; Coppins and Coppins, 2002) for grading epiphytic lichen species as indicators of continuity and disturbance. All of which substantiate the importance for biological diversity of treed continuity on a site (Alexander, 2002; Alexander *et al*., 1999). Some sites of considerable old tree continuity become unique refugia for dependant, rare and endangered species - an example being the Moccas Beetle (*Hypebaeus flavipes*) (see Figure 2), which is associated with a highly restricted, local community of ancient oak trees at Moccas Park, Herefordshire.

Following the review of the BAP[4] process in 2012, Wood-pasture and Parkland has remained a UK BAP Priority Habitat. The UK list of priority habitats has been used to help draw up statutory lists of priorities in England, Wales, Scotland and Northern Ireland, all of which recognise through their country biodiversity strategies the national importance of this habitat. Despite recognition of their increasing nature conservation importance, many ancient tree populations in northern Europe are currently under threat and some are in marked decline as a result of pressures, including pollution, neglect and impacts from changes in land management.

In response, conservation management has focused on developing techniques to protect and enhance the longevity of ancient trees and their populations. Sites with collections of ancient trees have been surveyed to identify rates of decline and restoration programmes

[4] UK Biodiversity Action Plans (BAPs) (UK Biodiversity Group 1998) developed out of the Convention on Biological Diversity (CBD), part of the 1992 UN Rio summit on Environment and Development.

have been put in place to reduce risk of loss and enhance individual tree vitality[5] (Read, 2000; Read *et al*., 2010; Fay, 2002; Fay and Bengtsson, 2011).

Wood-pasture and parkland, mosaic habitats that are valued for their trees owe their landscape quality and ecological character to a history of grazing (Vera, 2000). Sites with collections of veteran and ancient trees and the plants and animals that they support have enhanced value. From an historic landscape perspective, an increasing threat of decline and loss raises the status of those remaining AVTs to that of 'living ancient monuments' (Stiven and Holl, 2004) whose cultural significance might be considered comparable with that conventionally attributed to anthropogenic landscape features.

[5] Ancient and veteran tree UK sites which have been assessed for their population and individual tree longevity programmes put in place include Hatfield Forest, Epping Forest, Richmond Park, Crom (NI), Sherwood Forest, Ashton Court, Melbury Park, Grimsthorpe and Dinefwr.

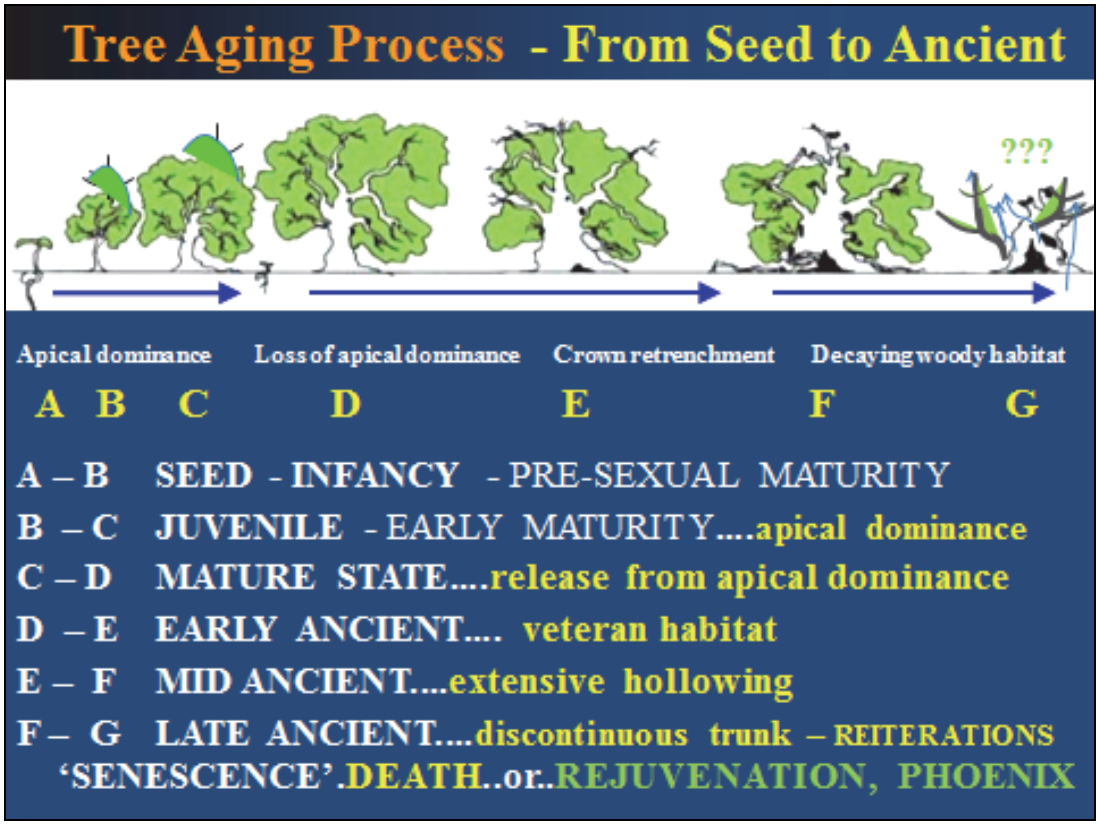

Figure 1. The Ageing Process: from seedling to death in a standard tree (modelled on native oak) showing habitat (veteran) features (Fay, 1997)

Figure 2. Moccas Oak, Moccas Park, Herefordshire: one of the few ancient oak trees host to the endangered Moccas Beetle found only at this one site in Britain.

3. DENDROCHRONOLOGY AND TREE CORING

3.1 A brief history of dendrochronology and tree coring

"If we want to study the past in real detail, tree-rings are the essential starting point" (Baillie, 1995). Baillie refers to this extremely simple method that uses annual growth rings as a "natural clock".

The pattern that can be discerned in sawn wood that portrays distinct tree-rings has been observed at least since the 16th Century when Leonardo da Vinci remarked on the effects of weather and drought on the size of rings in sawn pine (Schweingruber, 1996). Despite these early observations, dendrochronology is a relatively new, though expanding and diverse discipline.

Specialist applications have evolved over the twentieth century with the development of research that includes tree-ring sequencing to further knowledge and understanding in the environmental sciences. Today, dendrochronological principles inform the study of dendroecology, including techniques that apply to landscape history, archaeology, paleoecology, dendroclimatology, dendrogeomorphology (changes to the earth's surface), dendrotectonics, dendrohydrology (reconstruction of hydrological history), dendroglaciology and the periodicity and impacts of avalanches.

Underpinning dendrochronology is the principle that reasonable precision in identifying the date of tree-ring formation can be obtained through cross-matching ring width, synchronising patterns across a number of tree-ring series. Living tree chronology together with data from dead trees and wood from old buildings enables construction of long chronological sequences. The comparison, matching and overlapping of growth sequences from different source samples lies at the heart of the principle of crossdating (Baillie and Pilcher. 1973)

Tree coring is undertaken using a specially devised, hand-held tool (an increment borer) to extract a pencil-thin core of wood from a tree for subsequent examination. The borer is a precision instrument for collecting core samples, normally through boring radially into the lower main trunk. While coring is practiced principally to provide chronological information, as referred to above it can also provide information to help understand the quality of the wood and condition of the tree.

The increment borer device was developed by Max Pressler (1815 – 1886) in the mid-nineteenth century (see Figure 3). As a forester (as well as an economist and inventor) he intended its use for silvicultural growth analysis and assessment of forest crop trees. While the device has remained virtually unchanged in design over the years and still is used for silvicultural purposes, its applications have extended beyond wood technology research (Grissino-Mayer 2003).[6]

Trees grow outwardly, adding successive layers of cells, each year forming a 'new tree' over the old one (*exogenous growth*); readily seen in trunk, branch or root cross-section in many species as annual growth rings, the source material of the science of dendrochronology. The correlation of tree-rings to their year of formation provides a basis for analysing temporal and spatial patterns of processes that contributes to scientific and cultural knowledge (Grissino-Mayer, 2007).

[6] Max Pressler's name has since entered the vernacular, as a generic title for hand-held, increment boring tools (or 'Pressler borers'), also now commonly referred to as Swedish borers, reflecting the country of make of the most widely used devices.

In the first half of the twentieth century the scope of tree core sampling expanded to contribute to climatology and archaeology. Andrew Douglass (1867-1962) who by many is regarded as the father of dendrochronology, used tree-ring pattern analysis to explore climatic influences from solar cycles reflected in tree growth and ring dimensions.

Douglass developed and applied his methods to archaeological research (dendroarchaeology). By combining sample results from aged trees with information obtained from ancient timbers, he constructed a continuous chronological sequence reaching as far back as 700 A.D for the American Southwest. This work provided an essential key to dating ancient Native American ruins about that region. In 1935 Douglass founded the Tree Ring Society to further international study and dissemination of dendrochronology. In 1937 he pioneered the first Laboratory of Tree Ring Research (University of Arizona), which is today a leading centre of dendrochronological research.

The accuracy of environmental related data is increased when sampling is not limited to a single radius from a particular tree, or to a single tree at a site. On larger studies reference to trees from a range of sites within an area or study region also contributes to accuracy. This principle of replication helps filter extraneous confounding factors and serves to increase the reliability of data from which extrapolation can be made.

Biotic and abiotic factors that influence patterns of tree growth, that are discernible through sample analyses, can be used to understand past influences. Similarly, based on knowledge of past growth patterns for sites with trees, the model can be projected to identify and potentially forecast future environmental changes. This principle, consistent with geological investigation, not only helps to understand the present and the past, but also can contribute to predicting future patterns which may inform policy and planning.

The science of dendrochronology tries to understand the constraining variables that impose limits upon tree growth. Coring provides evidence of annual growth increment as a function of a range of principal limiting factors; typically these include temperature, precipitation, elevation etc. When analysed from this perspective, data can inform other associated investigations. For example, the exploration of trees growing at the margins of their natural species-range reveals patterns of increment that reflect growth influences more markedly than the norm, and provides scope for deconstructing the intrinsic and external factors (Speer, 2010).

Since the early twentieth century a reliable record of tree-ring data has been accumulated and constructed for a number of applications. These include heritage dating, climate history and forecasting, environmental forensics and even reconstruction of river stream-flow. After a century of dendrochronology the level of sophistication in data compilation and chronology sequencing has led to libraries of data held in various centres of learning. Dendrochronology has also been applied to legal cases such as investigation of contamination drawn from tree-ring studies of 'witness trees'[7] with forensic dendrochemistry and dendroecology submitted as legal evidence (Balouet *et al*., 2009).

In the British Isles dendrochronology has built upon a rich and growing dataset based largely on native oak both as living trees and from non-living source material (Baillie, 1995). Scots pine and yew chronologies have contributed subsidiary species that lend themselves to comparative matching and providing species-specific information on growth (Moir, 1999). The UK centres of dendrochronological study and data collection contribute to a regional and worldwide network that utilises records to build long chronologies and absolute dating, which contribute a 'worldwide synchronization of cultural heritage' (Shweingruber *et al*., 2006).

[7] A witness tree is chronologically aged and connected to historical events in its vicinity (in the USA, witness trees were also boundary markers as solitary 'sentinel' trees, used for historical mapping).

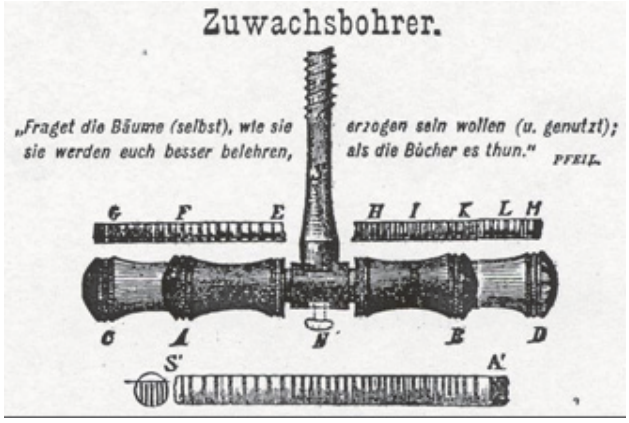

Figure 3. Illustration of the early Increment Borer Pressler, M.R. 1866. Der forstliche Zuwachsbohrer neuester Construction. Tharandter forstiches Jahrbuch, 17, 155-223 from Grissino-Mayer H. powerpoint presentation.

4. ANNUAL RINGS AND GROWTH

4.1 How a tree grows – cambium and woody tissues

Throughout its life, every year during favourable conditions, a tree lays down new outer woody tissue. In temperate regions this process is seasonal, occurring broadly from early spring to late summer. This annual growth is expressed as a radial woody expansion throughout the stem, branches and roots of the tree. Each 'ring' represents the annual enfolding of the entire living outer woody form of the previous year's tree with the current year's new woody envelope. The two-dimensional, cross-sectional view provided by the image of concentric tree-rings can be achieved in practice by the cutting of the tree – however this is destructive in living trees.

Incremental annual expansion is a function of tree *cambium*, a 'tissue generator (Shigo, 1989) of undifferentiated, embryonic cells. A sheath of living cambium, between the outer woody tissue and the inner face of the bark, known as the vascular cambium, generates new live tissues, namely woody *xylem* (principally water and mineral conducting and strengthening tissue) on the inner face. New inner bark on the outer cambial face is composed of *phloem*, a narrow layer of cells principally involved in translocating sugars, and other elaborated foodstuffs (along with plant growth regulators). Cambial cells extend beyond the *phloem* into the inner bark to the phellogen, which is responsible for generating new bark tissue as the stem expands and outer bark sloughs away.

The wood also contains thin spoke-like *rays* of various lengths and height that arise from the cambium, often in staggered arrangement, and which reach from the phloem and into the xylem oriented towards the centre of the stem (see Figure 5). The size and spacing of rays is generally more varied in broadleaf species than in softwoods, where rays are typically only one or a few cells wide. In many softwoods (e.g. pines), rays contain lignified cells[8] (ray tracheids) that facilitate radial movement and lend structural strength and resilience to the stem. Also generally present in softwood species are thin-walled *parenchyma* cells[9] (ray parenchyma).

In hardwoods, rays comprise only parenchyma cells that are mostly live within the sapwood of the tree. A function of parenchyma is to store and mobilise carbohydrates, water, minerals and organic compounds. Within many softwoods (e.g. pines, spruce and larch) rays may incorporate resin canals (also referred to as resin ducts). In some softwood species rays adapt to form wound-induced, traumatic resin canals. Similar 'gum-forming' response features to wounding are encountered in the wood of some species of hardwood (e.g. cherry family) (Kozlowski and Pallardy, 1997). Parenchyma also plays an important role in the conversion of sapwood to heartwood (or ripewood) and in certain wound responses (e.g. mobilisation and deposition of exudates and formation of tyloses), (see further Section 2.1 on wounding and compartmentalisation).

Early in the life of most hardwood and softwood trees, heartwood, or ripewood, begins to form in the woody stem as the functionality of older sapwood progressively reduces and ceases to be conductive. This takes place as the vessels, to a greater or lesser extent, become plugged with tyloses, resins, gums and other deposits (Kozlowski and Pallardy, 1997). As cells that comprise the tissues of the central core of wood in a mature tree are generally no longer living they are therefore not active.

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[8] Lignified cells contribute compressive strength, comprising hardened glue-like, brittle material.

[9] Parenchyma cells are relatively undifferentiated, thin-walled and within the sapwood are connected to the cambium (while not differentiating into different types of cell). They contribute to storage of carbohydrates and may be axially or radially arranged, connected by strands of living material.

Certain species typically form distinctive, dark-coloured heartwood, impregnated to varying degrees by extractives that help to impart a durable, decay-resistant character (e.g. oak, sweet chestnut, false acacia, pine, yew). In others, heartwood has a non-durable character (e.g. ash and horse chestnut), whilst in yet other species, an inner ripewood is formed, in which the older, central wood gradually ages without converting to form heartwood (e.g. beech, lime, sycamore). Pre-existing durable heartwood provides an important constraint to decay in the central woody parts of the tree (Lonsdale, 1999).

Although contrary to the general rule, loss of physiological and conductive functions does not comprehensively occur in all cases concerning the older wood of all species. Examples of alder, aspen and some maples have been recorded where living cells and stored starch have been found in the centre of large diameter stems. Studies in the early twentieth century report live ray parenchyma cells within wood of sequoia over 100 years age, at a heartwood depth of seventy rings (Brown *et al*., 1949).

4.2 The nature and structure of typical woody growth

The pattern of incremental woody growth provides a record of the age of a tree and also reflects how growing conditions have fluctuated over that period. In temperate regions these ring patterns are generally visible in cross-sections of trunks and branches, discernible in carefully extracted core samples, particularly from certain species of tree.

In early spring, new woody cells tend to be relatively large and thin-walled (*earlywood*), optimising for water uptake and resource deployment. As summer progresses, the production of water conducting cells slows down; at the same time the cells decline in size and become thicker walled (*latewood*), a hiatus in growth occurring during winter. This pattern of annual ring growth is initiated afresh every spring.

The distinction between late summer and early spring growth defines the demarcation between annual rings. While this is the normal overarching pattern of growth, there are exceptions as the distinction between cells of early wood and late wood may not be consistent or well defined and variations occur between different wood types, species and within the wood of individual trees (Kozlowski and Pallardy, 1997).

As a rule, functioning sapwood is widest for vigorous trees compared to trees with declining vigour. When a tree lives beyond full maturity the capacity of the root system reaches its limit in advance of the crown in its ability to sustain continued crown expansion (Raimbault, 1995) (see also Section 2). This marks a turning point when the tree enters a crown retrenchment stage with a tendency for the crown to then recoil as a result of reducing transportation distances from its roots to the furthest crown shoots (see also Figure 1). Subsequent new annual woody layers begin to reduce in comparison to earlier phases, and, as a consequence, the width of the annual ring (current annual increment (CAI)) declines as does the sapwood thickness, as a ratio of trunk radius (White, 1998).

The wood anatomy of broadleaved hardwood is divided into *ring porous* species and *diffuse porous* species. Ring porous trees show a general pattern of large spring earlywood vessels and smaller summer latewood vessels that together make up the distinctive annual rings of species such as oak, sweet chestnut, ash and elm. Diffuse porous hardwood species show more uniform transitions between earlywood and latewood having little variation in vessel size as the growing season progresses, as seen in species such as birch, beech, sycamore, alder, lime and willow.

In heartwood forming species, the width of live outer sapwood, though mostly within a certain range, can vary – influenced by genotype, age and growing conditions of the

individual tree. Softwood and diffuse porous trees tend to retain a greater number of hydraulically functional sapwood rings than ring porous trees (Thomas, 2000).

Borrowing from forestry practice and the production of timber, trees are categorised into *softwood* and *hardwood* on the basis of woody characteristics. Softwood typically refers to conifers and their allies, despite some (e.g. yew) having denser wood properties than many hardwoods. Hardwood typically refers to broadleaf species. The structure of both hardwoods and softwoods is differently adapted to provide wood strength and vascular transportation of water. In general, the wood of softwoods is predominantly composed of aggregated small-sized *tracheids* (lignified tubes) with generally narrow rays with many softwoods having resin ducts (e.g. pine, spruce larch).

Following wounding or other stress effects, traumatic resin ducts may form additionally in these species and may also develop in some softwoods that normally lack resin ducts (e.g. true firs and cedars and yew). The wood of temperate hardwood trees differs from that of softwoods by its greater range of cell types. The range of cell types comprises woody fibres, fewer (though mostly larger and longer) water conductive cells (pores or vessels), few tracheids and generally more variable and broader multi-serrate rays. Softwoods characteristically incorporate more axial parenchyma and various other forms of parenchyma tissue, involved in storage, secretion and other functions (Shigo, 1989; Kozlowski and Pallardy, 1997; Thomas, 2000).

The wood anatomy of certain softwood species tends to show a marked transition between summer latewood and spring earlywood, described as abrupt transition wood (e.g. Scots pine). In some other softwood species, as cell size is more uniform throughout the growing season, the annual ring appears less pronounced, forming gradual transition wood (e.g. Norway spruce).

4.3 Normal patterns of tree-ring growth and some unusual features

Annual rings may show considerable variability in width and concentricity depending on growth circumstances. This may occur from one year to the next between rings and may also arise locally in the distribution of new wood about an individual ring. Ring patterns from the wood of some individual trees may show a measured consistency over the years; such growth is termed *complacent* and is generally characteristic of a tree growing in conditions to which it is naturally well-suited and which over-ride the limitations of climatic variation. Other trees generally, where growing in sub-optimal or harsh conditions, are liable to be more greatly influenced by climate and more likely to have an irregular ring width pattern; such growth is considered to be *sensitive*. Samples that display sensitive sequences may be of particular use to the dendrochronologist when correlating records from separate trees.

Earlywood growth is considered to occur moving downwards from outer canopy buds through the tree to its base, including the roots (*basipetally*). With diffuse porous hardwoods this is generally a fairly gradual process and may take a few weeks to complete. With softwoods the process takes place more rapidly. With hardwoods, latewood formation appears to occur acropetally (i.e. from base upwards) and, within an increment, latewood is generally thicker than earlywood about the lower parts of the tree though this relationship may not be consistent further up the tree.

Harsh conditions, such as drought and unseasonal frost, may give rise to a *missing ring* as a consequence of circumstances which occur due to impairment in the tree's capacity to lay down an entire woody envelope during the growth season.

It is argued by some that missing rings are less likely to occur with ring porous species as these appear to lay down the new season's woody ring according to a stress response

strategy that spreads 'risk' over a longer period. Earlywood appears to be initiated in the cambium towards the end of the preceding summer, programmed to expand rapidly throughout the tree in the following spring and followed subsequently by latewood formed by cambial activity in the current season (Phipps, 1985; Thomas, 2000).

Occasionally, when under considerable stress, the tree's energy reserves and functionality may be so impaired that in some seasons, new woody growth does not reach all parts. This may affect an entire cross-section, at a certain height, giving rise to either a missing ring, or a *partial ring* where the ring is *circumferentially discontinuous*' (Phipps, 1985; Kozlowski and Pallardy, 1997; Thomas, 2000).

Discontinuous rings are more likely to occur in certain trees, *particularly ancient and veterans* (Lonsdale, 2013a; Raimbault, 1995). Discontinuous rings may also be found in trees that are suppressed, unhealthy or severely imbalanced due to uneven distribution of cambium (Kozlowski and Pallardy, 1997).

Individual cores extracted in locations which coincide with missing rings or discontinuities in annual growth are liable to lack the evidence of that year's woody growth and may lead to dendrochronological misinterpretations as a consequence.

In other circumstances, a tree may lay down anomalous growth over a season, which when viewed in cross-section gives the impression that two years' growth has occurred. This generates what are known as *false rings* and is generally an expression of a species' tendency e.g. with cypress (USDA Forest Service, 1979). The phenomenon of false rings also occurs within temperate species where the normal pattern and sizing of new xylem in earlywood and latewood over a year's increment appears to reflect a confused sequence.

Growth anomalies may derive from uncharacteristic climatic conditions or other exceptional stresses occurring early in the year (e.g. unseasonal frost, flooding or insect defoliation) followed by a return to more favourable conditions later in the same growing season. Where this occurs, core samples may superficially give an impression of two separate annual increments in a single year (Phipps, 1985; Grissino-Meyer, 2003).

Further misleading information can arise where an apparent single trunk in fact derives from two or more stems that have closely grown and fused, requiring interpretation of the 'body language' of the trunk to take account of the ring pattern (and to avoid sampling trees that are liable to produce unreliable data).

Old trees characteristically display gross distortions in trunk morphology as a result of *reaction growth* (an adaptive response to mechanical loading occurring over the life of the tree). As a consequence, in such trees individual radial cores may be distinctly different from one another, whether taken from the same tree or from its neighbour. Consideration of reaction growth is further explored in the section below.

4.4 Reaction growth – compression and tension wood

Trees have evolved to support their own mass and to accommodate variable mechanical stresses induced by wind forces within certain tolerances. Apart from when trees break under the impacts of the effects of exceptional buffeting, twisting and torsional loads, they adapt to these stresses by 'strategically' distributing new wood to provide compensatory strengthening. These variable growth responses in wood (reaction wood or reaction growth) occur at different locations throughout the anatomy of the tree, and become increasingly pronounced as the tree ages – resulting in asymmetrical distortions, far removed from an idealised image represented by the circular cross-section of a stem with regular concentric rings (Mattheck and Breloer, 1994; Lonsdale, 1999; Raimbault, 1995).

Woody material (xylem) is principally composed of *cellulose* (rope-like tissue contributing high tensile strength) and *lignin* providing compressive strength. In general, reaction growth describes woody material that the tree lays down in response to physical stresses when under compression or tension. Conifers tend to respond to mechanical loads by preferentially building up localised buttressing of supportive lignin-rich *compression wood*, typically on the underside of branches and stems. By contrast, broadleaved species typically preferentially produce cellulose-rich *tension wood* generally on the upper side of branches and stems to resist deflection and subsidence.

Extracting core samples from areas of reaction growth will be unrepresentative of the tree as a whole and provide localised tree-ring information influenced by the history of mechanical influences and anatomical changes specific to that part of the tree.

As a result of adaptive growth and decay processes, AVTs have been considerably sculptured over their long lives. Reaction growth, with woody layers overlain, contributes to the formation of complicated structures that are liable to have a distorting effect on the interpretation of growth influences. From a morphological point of view these irregular shapes describe the physiological history of the tree.

Trees that are old for their species are individually exceptional. Compared with younger trees, they are inherently more irregular, asymmetrical and morphologically complex. While there may be exceptions, as a rule, such trees do not provide a good sample basis for deriving generalised extrapolation from coring. Additionally, in such trees, on account of decay processes there is likely to be a relatively small width of sound wood (comprising living outer wood and internal heartwood or ripewood) compared with the overall trunk radius. Therefore data from coring ancient trees is commonly unreliable and will be limited and unrepresentative of generalised growth patterns, which may be better obtained from younger more uniform trees.

5. CORING DEVICES AND PRACTICE

5.1 Technical aspects of the equipment

As described above, the Pressler borer comprises a hollow, tubular, steel auger shaft (also referred to as the barrel) with a threaded head for boring into the tree, a turning handle and a sample extractor (also referred to as the sampling tray or spoon), which slides inside the barrel. Manually boring the auger into the tree, cuts and sets free a cylindrical core from the surrounding wood. As the auger is drawn into the tree, so the core passes into the hollow shaft and can then be withdrawn using the extractor. Having taken a sample core from a live tree, the auger shaft is wound back, to retract it from the stem leaving a cylindrical hole in the tree.

Various increment borer lengths and diameters are available, including for specialised applications with lengths up to 1m. In Britain borer length generally ranges from 300mm – 600mm. While the diameter of the extracted core is typically marginally over 5mm, the external diameter of the auger head is 11mm (see Figure 4) creating a corresponding borehole diameter slightly in excess of 11mm (Grissino-Mayer, 2003; Weber and Mattheck, 2006).

5.2 Practical use and some common problems

Practical operation of the increment coring device requires understanding that wood properties differ e.g. between hardwoods and softwoods and between species and individuals. Manufacturers provide different helical screw heads for different wood types (softwood and hardwood) and with coating to reduce resistance (for non-stick properties)[10]. Starter aids may also be used to reduce 'corkscrewing' effects and entry damage.

Sample cores may vary in quality and usefulness; in some cases a percentage will not be readable[11], influenced by the properties of the wood or the instrument's condition. Operationally, the cutting head when chipped, dull, damaged or corroded can affect the boring process and quality of sample. A 'cork-screwed', imprecise start-up to boring tends to result in a poor quality sample, particularly the initial length. Improper storage of even good quality cores may encourage mould proliferation and staining that impairs readability (Grissino-Mayer, 2003; Phipps, 1985).

Over time, friction and torsional stresses during use may lead to metal fatigue, causing chipping of the borer's cutting head and in extreme instances breakage of the shaft itself. Many practitioners report occasional cases when, due to torsion breakage, the embedded part has had to be left in the tree. If a borer is left in the trunk for any length of time there is a risk that the freshly compressed wood closely surrounding the shaft will grip the device, such that removal may be impossible. Despite these potential problems, practitioners report that when correctly used and well-maintained, an increment borer can last for decades taking many hundreds of cores (Phipps, 1985).

Speer (2010) advises that in order to obtain sampling reliability with accurate age profiles, *replication of coring* from *multiple samples* obtained from individual trees and sites is required.

In some instances, particularly on large diameter trees, the initial attempt to reach the botanical centre of the trunk may fail, thereby requiring further cores to be taken in nearby

[10] Some operators reportedly prefer three-thread borer irrespective of hardwood or softwood on the basis that drawing-in faster per rotation tends to ease start-up within a tree.

[11] Questionnaire canvassed practitioners identified that samples may turn out to be unreadable. This ranged from very few samples, up to 25%, being unreadable.

alignment according to a calculated offset (the *offset method*) (Jozsa, 1988). This results in at least two borehole wounds close to one another.

Watkins *et al*. (2003) large-scale coring study of Sherwood Forest oak remnants investigated a population profile which contained standing dead and living trees, using ring data to estimate dates of death and provide information on likely longevity of the living ancient cohort. The majority of old trees being extensively internally decayed, coring in many cases involved taking two or more core samples per tree[12]. Such studies are labour intensive, requiring painstaking field work, sampling, labelling, laboratory inspection and analysis.

Coring large, aged specimens with hollow trunks and internal decay and trees of unusual form (leaning, twisting and convoluted stems) is liable to provide confusing or poor quality samples. A further problem arises when coring large, old trees when the corer passes into internal hollow areas or decaying wood presenting practical difficulties particularly when retracting the barrel of the corer.

Certain trees, including large and old specimens, are likely to pose practical problems potentially presenting operational difficulties and resulting in poor quality core samples. While the desire to obtain information from old trees is based on their potential store of dendrochronological data on account of their antiquity, paradoxically core sampling may only contribute data that is poor quality and of limited use. As referred to above, samples may be unusable due to tree morphology, wood sample condition and limitations of coring instruments. Cores also have a tendency to disintegrate or be indecipherable, and may be too short. Additionally the increment borers may become blunted and on rare occasions irretrievably jammed.

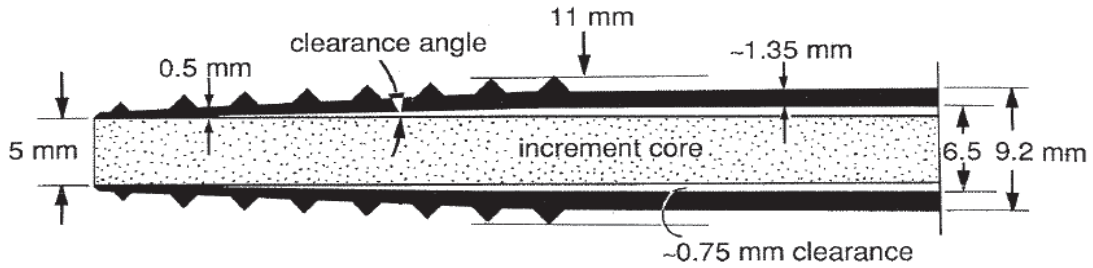

Figure 4. Section showing typical dimensions of 5mm diameter sample increment borer with external auger bit diameter of 11mm. (from: Jozsa, L. 1988. Increment core sampling techniques for high quality cores. Wood Science Dept Forintek Canada Corp.)

[12] Overall 92 trees were sampled (63% dead and 37% living), randomly selected from 406 ancient trees.

6. WOUNDING AND WOUND RESPONSES IN LIVING TREES

6.1 Wounding - compartmentalisation models of decay in trees

Coring is by its nature invasive and leaves a wound within the tree. The nature of such wounding and its significance for the health and longevity of the tree are important considerations. In order to understand the potential relationship between coring and the effect of the wound, it is necessary to consider both the general nature of wound response in trees and within the limitations of reference material, the specific response to wounds characteristic of the borehole type.

Trees have evolved to grow to a height above competitive vegetation, capable of transporting water great distances internally from soil to the atmosphere, via arrangements of specialised cell tissues, anchored below ground by a network of roots, withstanding the elements over decades or centuries, and developing responses to wounding from natural events. Over a lifetime the structure and form of individual trees becomes more complex, accommodating an array of colonising organisms, with fungi and other microorganisms playing an important role in determining the condition and function of wood and the health of the tree.

The response of trees to wounding and the behaviour of decay organisms within wounded regions are intricate and variable, involving physical and biological processes, and are not fully accounted for by any single model. The concept developed and publicised in the 1970's and subsequently extended by Alex Shigo, expresses a short hand version of the wound reaction process in terms of *Compartmentalisation of Decay in Trees* (abbreviated to *CODIT*) (Shigo and Marx, 1977; Shigo, 1979; Shigo, 1989).

Shigo's model emphasises that trees are naturally *compartmenting organisms*; organised through the cellular level, to the tissues and organs of the tree, expressed in the anatomy of wood, and discernible in annual growth processes. CODIT provides a simplified conceptual model, designed to communicate to a non-specialist audience. It describes, in visual terms, processes affecting the tree following injury to the cambium and sapwood. Interactions between the tree and microorganisms are described as a series of 'walls' offering resistance to the progression of decay (see Figure 5).

CODIT portrays a three-dimensional model of the stem, setting up boundaries that operate through the action of chemical and physical changes around existing anatomical features (Figure 5).

The CODIT model describes four wound response boundaries that, according to their position and orientation within the wounded woody stem, are numbered in a sequence, low to high (1 – 4). Walls 1 - 3 (axial, radial and tangential) are ordered according to their level of effectiveness in resisting the advance of decay processes. They are a function of the anatomy of the existing tissue up to the time of wounding, and form regions of the reaction zone.

CODIT Wall 1: Particular to this model, formation of the axial Wall 1 includes processes that, to varying degrees of effectiveness, seal-off units of xylem closely above and below the wound. Wall 1 is often the weakest of the wound-affected zones - owing to the relatively open conductive pathways that are naturally present for the movement of water through the xylem (Shigo 1989). Where damage occurs, the occlusion of conductive tissues (vessels and tracheids) protects against disturbance of function particularly the maintenance of water integrity and exclusion of air within conductive tissue.

In hardwoods, the localised occlusion of vessels is generally effected by a combination of *tyloses*[13] and pectin-rich gels (also referred to as gums) produced by surrounding parenchyma cells. Tyloses are saclike structures that balloon into conductive vessels limiting vertical spread of microorganisms.

The time of wounding is significant. The formation of tyloses and gums, associated with wounding that plug conductive woody tissues, is variable in temperate regions and is influenced by a range of factors including temperature, hydrology and season (timing of wounding). Vessel occlusion is more rapid following damage in warmer weather and in the vegetative season, and least effective in winter dormancy (Dujesiefken *et al*., 2005).

Certain ring porous hardwoods (e.g. oak, elm and sweet chestnut) appear to form mostly tyloses; others, including a range of diffuse porous trees (e.g. birch and lime), form mostly gels. Tyloses may not form until some days after the wound. Winter gel formation extruded into dehydrated conductive cells may be reversible and subsequently may allow either recovery, rehydration of vessels or, in adverse conditions, may pave the way for further embolism (Sun *et al*., 2008).

Softwoods are more dependent on their tracheid anatomy for controlling water loss and air embolism. This operates through their arrangement of relatively short and thick-walled tracheids, which are abundantly equipped with inter-connected, valve-like pores (pits) and which 'close' in response to changes in adjacent turgor pressure – so when wounding occurs, causing tracheid water loss and air entry, the normal pressure equilibrium is disrupted triggering isolation of the damaged tissue by the sealing off of pits. In addition (hydrophobic) resins are produced in ducts that contribute to effectiveness of sealing of wounded tissues.

CODIT Wall 2: Existing anatomical and physiological features of the wood contribute considerably to form the basis of CODIT Wall 2 in resisting the radial expansion of decay inwards towards the centre of a stem. Thickened, lignified cell walls of xylem tissue, particularly late wood, existing plugs formed by tyloses, gums and resins all play a part in inhibiting radial progress. As with the other CODIT reaction zones, active responses by live parenchyma in the wood contribute by secreting inhibitory substances and forming new tyloses (Shigo, 1989).

CODIT Wall 3 resists the process of decay laterally and circumferentially (perpendicular to the rays) around the wounded stem. This barrier component is considered generally the strongest of the reaction zone walls within the existing wood (Walls 1 – 3) and is principally provided by the medullary rays. According to the model, spread of fungal activity is resisted circumferentially by the nature of the location and the physical structure of the rays and by the active responses of living parenchyma cells, generally present in high concentrations within the medullary rays of live wood, particularly in hardwood species (Shigo, 1989).

CODIT Wall 4 is highly significant. It is the barrier zone formed *de novo* by the cambium. It provides a layer of modified 'protective' cells between the tissue present at time of injury and any new wood that forms subsequently. Wall 4 is typically the strongest of the CODIT wound response barriers safeguarding new living parts of the tree (see Figures 5 and 6).

In dissected trunk cross-sections examined some years after wounding, the visible extent of Wall 4 varies considerably. Whilst focussed around the injury site, the Wall 4 demarcation is

[13] These saclike structures are formed by the protoplast of a parenchyma cell in woody tissue that balloons out under turgor pressure through the pit-aperture of the cell-wall and plugs the adjacent cell; formed by many broadleaf species in the xylem in response to wounding and as part of the conversion of sapwood to heartwood.

sometimes only visible locally in the region of the wound, but in other cases, it may appear to reach around an entire stem.

Tissues that are formed to occlude (close over) wounds, include *callus* and *woundwood* (Lonsdale, 1999; Shigo, 1989) and may eventually fully or partially cover over the face of the original wound. Total callus *wound occlusion* is generally beneficial to the tree, preventing gaseous exchange and loss of moisture from wounded tissue, creating conditions that are generally, though not always, inimical to the proliferation of wood decay fungi (Dujesiefken *et al*., 2005). Callus wound occlusion also serves to integrate historically damaged territory with new functional sapwood and living bark (Boddy and Rayner, 1983; Lonsdale, 1999; Stobbe *et al*., 2002; Eyles *et al*., 2003).

Associated with the formation of Wall 4 and new tissue beyond the wound, the development of callus occurs when the cambium about the wound area resumes growth, producing large-sized non-lignified homogeneous cells about the wound edge. As the marginal callus increases, so the exposed wound face effectively reduces in area. These initially cellulose-rich cells gradually differentiate to form the elements of functional lignified tissues. In favourable circumstances the outer face of the initial wound may become fully occluded and in some instances incorporated in entire woody annual rings encompassing the stem. Despite full callus occlusion of a wound, decay processes may still be active in the region of the original wound behind the callus and beyond Wall 4, within the older wood of the stem.

There is a common view that when trees produce callus tissue, which may occlude a wound, that this equates to the notion of 'healing' (as with the animal kingdom where cells are replaced). However, wound occlusion in trees does not signify that the damaged tissues have regenerated and 'healed' – rather new tissue has been generated and laid down externally about the wound area (Shigo *et al*., 1977). Within the trunk behind the occluded tissues, the area associated with the wound and internally beyond may nonetheless deteriorate over time. Certain fungal species are well adapted to the hydrological and gaseous conditions that prevail within an enclosed trunk and can survive and digest wood in the absence of external wound openings (Boddy and Rayner, 1983; Schwarze *et al*., 2000).

Reaction zones have been described as 'temporary invasion fronts' (Lonsdale, 1999), which over time may prove be more or less effective. Shigo (1989) suggests that following wounding, Walls 1-3 may variously fail and internal decay or hollowing may result. Wall 4 being typically the strongest of the CODIT Walls it is generally least likely to fail. In instances where Wall 4 is judged to have been overcome by wood decay organisms, live growth (i.e. new outer wood, cambium and phloem) may be compromised.

Fungi that are already active and causing internal decay locally within a tree, having gained access some time ago as a result of an earlier wound incident, may be stimulated by subsequent, wounding from a later period. Further stem injury of an already internally decaying woody stem, particularly where the new injury breaches a previous CODIT Wall 4 barrier zone, potentially allows already present decay fungi in the stem to expand their zone of influence, resulting in a potentially enlarged cross-sectional decay area. For sufficient containment of decay arising from coring wounds, the rate of subsequent newly-generated sapwood needs to at least achieve parity with the rate of decay expansion (Weber and Mattheck, 2006).

Pre-existing decay columns in older trees will in most cases be present in the centre of the stem 'growing' outwards and upwards, typically from the base derived from root decay as a natural function of the ageing process, without necessarily being caused by an above-ground, externally induced wound. In such instances without an obvious external wound, where the central core of decay has no direct contact with functional sapwood, the Shigo CODIT model does not fully account for the decay response processes.

Inducing new wounds into live sapwood in old trees creates damage within pre-existing functional sapwood tissues which, in certain circumstances decay fungi may exploit. Although the extent of the initial wound area may be localised, where boring injury breaches a region of sound wood through to a locally active decay site, there is a likelihood of decay migration and coalescence over time.

6.2 Refinements to the CODIT model – water relations and wound response

The concept of compartmentalisation, while simple in essence and visually intelligibly presented by Shigo and others in the CODIT model, has led to much scientific debate and contention (Gilman, 2012). Controversy surrounds the extent to which the model describes inherent anatomical 'defences' and whether (and to what degree) this is a passive or active function of tree response to wounding and decay.

There are different views as to the dynamics of the interactions between the wounded tree and microorganisms involved in decay. Alternatives to the CODIT model have been suggested that complement and modify the compartmentalisation-decay-defence theory, and have served to contribute to a wider understanding of the interactive processes between host tree and wood decay organisms that follow wounding (Boddy and Rayner, 1983; Rayner, 1993; Pearce, 1996; Lonsdale, 1999; Schwarze, 2001; Dujesiefken *et al*., 2005; Gilman, 2012).

A deeper understanding of these processes considers the relative significance and roles of metabolic (energetic) processes, histology of the wounded host, biochemical changes, and the water and air relations within damaged vessels and how these affect functional (live active) tissues. The sapwood and under-bark phloem (moving and distributing carbohydrates) are effectively 'defended' as long as they are protected from air entry (embolism) into functional conductive tissue. Taking this latter view, compartmentalisation is less an expression of defence against fungal 'invasion' and more a function of the management of hydration, and exclusion of gas from functional tissues (Boddy and Rayner, 1983; Liese and Dujesiefken, 1996; Pearce, 2000).

Given these broader considerations the CODIT model has been refined to take greater account of the implications of dysfunction within the tree and the processes that lead to it - rather than focusing on defence against infection and consequent decay.

When damage occurs to live woody tissue (for example from storms, pruning or coring) there is a wound response. Such responses are a reflection of a range of variable factors, including species, wound timing, location and extent, wood anatomy, tree health, environmental conditions etc. Wound responses are complex, with biochemical and anatomical components; and as yet their detailed chemical nature is fairly poorly understood (Eyles *et al*., 2003).

Building on CODIT, more recent studies have sought to better understand the roles and behaviour of fungi in relation to trees; in particular how the behaviour of wood decay fungi may change under different conditions. This includes dormant *endophytic*[14] fungi. Following physical tree wounding (or major stress effects) that alter the saturated state of conductive wood vessels and causing air ingress, endophytic fungi may be stimulated out of latency to propagate and flourish. As this change progresses, the physiology of the host tree is affected such that functional conductive tissues are compromised (Rayner, 1993; Boddy and Rayner, 1983).

[14] Endophytic fungi reside in a normally healthy host tree in a quiescent state, for many years living within the hydrated system without showing obvious signs of their presence.

The key to this understanding lies in the appreciation that both trees and fungi are *hydro-dynamic* systems, i.e. they have evolved water relation strategies, are interactively dependent on water and are therefore highly sensitive to changes in hydration (particularly air ingress into hydrated systems) (Boddy and Rayner, 1988; Rayner, 1993). The evolved capacity to lift water from below ground, great distances to the foliage, where it is released to the atmosphere through *evapotranspiration* (a process that is fundamental to photosynthesis) depends on there being a continuous column of water within the outer woody vessels. The pipe-water-integrity of the hydraulic system relies on the exclusion of air from the conductive vessels to lift the water column - mechanisms that are not fully understood and which are broadly described by the *cohesion-tension* model (van den Honert, 1948; Kramer and Boyer, 1995).

Liese and Dujesiefken (1988) suggest that the CODIT model describes a tree response that is not primarily a defence against fungi but rather a general defence or delimitation response to damage and vessel disruption. They propose that within the CODIT acronym, 'decay' should be replaced by the term 'dysfunction', 'damage', or 'desiccation'.

When functional conducting living woody tissue in the trunk is affected by wounding (such as with breakage, bark damage, insect boring etc) or other abiotic stresses, moisture integrity may be locally broken resulting in water molecules moving from higher, internal to lower outer (atmospheric) concentrations, with air entering the formerly hydraulically-intact, low-oxygen system. In these circumstances vascular air embolisms occur at a micro-level, creating conditions where internally present dormant endophytic fungi become active and propagate.

Such damage effects have other possible consequences that have been studied. Fungal communities previously excluded by bark and intact outer tissues have new opportunities to initiate the process that leads to colonising internal functional living or non-functional tissues. Additionally, already established active decay fungi previously operating within the heartwood or ripewood, may migrate into newly challenged associated tissue (Boddy, 1983). *Such factors have implications for boring into old hollow trees*.

The internal hydrology of trees in contributing to both photosynthesis and control of microorganisms has evolved response strategies to wounding that include re-saturation of previously non-active tissue about the wound region, and by these means contribute to fostering conditions inimical to fungal proliferation (Pearce, 2000). Studies using sycamore indicate increased tissue water content of up to 1.7 times in the reaction zones around recent wounds, compared to previously uncompromised wood. This process also serves to initiate chemical changes including formation of suberised (corky) tissue and the distribution of compounds that inhibit the growth of microorganisms. Additionally, the restricted availability of oxygen resulting from re-wetting inhibits fungal colonisation and spread.

These studies while demonstrating the importance of water relations in response to wounding were not carried out on old trees. Such processes have evolved to contain, slow down and restrict the effects of wounding. Conversely when trees are under water stress, the effectiveness of wound response is liable to diminish and may even break down. Wounding will likely have more severe consequences for the tree following periods of drought than when favourably hydrated.

6.3 Energy factors and wound response

Photosynthesis produces sugars that are used for growth, defence, reproduction etc., and are stored in different parts of the tree ('partitioning') (Kozlowski, 1971). Mapping the carbohydrate storage zones is a basis for understanding 'energy cartography' in trees and

how energy may be deployed within the tree after wounding occurs for callus growth and processes involved in wound occlusion.

The accumulation and distribution of carbohydrate reserves occurs naturally according to an annual cycle, with maximum storage occurring just before spring bud burst and also before leaf fall (Gaumann, 1935). Reserves are not uniformly distributed about the body of the tree but are preferentially allocated to particular zones (sinks). Physical damage and physiological stresses have the effect of calling upon stored energy reserves to fuel responses to growth, defence and repair. Energy stores are concentrated in 'reservoirs' that are broadly located proximally to principal units of growth, close to the attachments of buttresses, roots, branch attachments and pollard heads) (Haddad *et al*., 1995; Clair-Maczulajtys *et al*., 1999).

Generally the greater the distance from the nearest carbohydrate sink, the higher the risk of an impoverished wound response. The distribution of areas with likely poor wound response depends on the particular morphology and condition of the individual tree. From this model the lower trunk region is potentially vulnerable to reduced wound response, depending on the distance that injury has occurred relative to the basal buttress-flair and also the lowest significant branch attachment (see Figure 7).

As trees age, the formation of sapwood with its energetic resources, becomes increasingly concentrated in separate functional, axial columns connected to discrete sectors of the root system (Lonsdale, 2013a). Vitality of other nearby stem and root parts may decline in the process and become weakened by dysfunction and decay. As this occurs, the morphology of the tree becomes increasingly complex and the 'body language' less amenable to interpretation. In such cases, healthy response to injury, even at putative optimal wound positions becomes increasingly hard to predict.

In summary, the underlying principles involved in energy cartography and seasonal carbohydrate distribution are factors that may affect wound response along with age, tree condition and morphology.

6.4 Timing of wounding - factors affecting tree response

The project sought the views of practitioner dendrochronologists about good practice. With regard to timing of coring there appears to be little consistent agreement. Views range from there being no preference, having pragmatic considerations for when best to core, to basing timing on growing season (to favour the tree's capacity for wound closure). A further choice is the dormant season (for ease of access and for obtaining a complete growth ring).

Wound responses are influenced by a number of factors including nature and extent of the wound, tree health, condition and vitality, and timing of wound. Time of year influences vessel occlusion (tyloses or gum formation), which more rapidly occurs during warmer weather and in the vegetative season, and is least effective during winter dormancy (Dujesiefken *et al*., 2005).

Hydrology, the dynamics of the soil-tree-water system, is a key factor in these processes. Evapotranspiration, the movement of water from soil to leaves and thence to the atmosphere beyond is essential to photosynthesis, producing in turn energy for all biological functions. Principally sugars are mobilised and stored as carbohydrates for growth, reproduction and defence (Kozlowski, 1971). Drought impairs the tree's water-dependent growth responses, and drought years show poorer growth in comparison to years when trees are favourably hydrated. Growth in the year following drought can also be affected by the preceding year's temperature and rainfall (Jarvis *et al*., 2000).

Carbohydrates are stored throughout the tree, concentrated in zones (sinks), partitioned for distribution for various requirements with allocation and relocation according to development phases, annual cycles and environmental influences. Seasonality has a marked influence on storage and distribution within the tree, peaking in the spring before bud break and again before autumn abscission (Gaumann 1935). Roots also provide a critical storage-sink, as do stems and subsidiary branches. Carbohydrate partitions experience greatest demands and relative levels of reduction at certain times, such as during seed and fruit production (Mandre *et al*., 1998).

While reserves are preferentially stored in sinks, they are called upon randomly in response to events such as damage and wounding, and function through gradients between zones of higher and lower concentrations. The study of mapping (cartography) of carbohydrate partitioning indicates that strategic stores are located in different anatomical zones, principally in the root buttresses and the parent stems (located behind root and branch attachments)[15] (Haddad *et al*., 1995; Clair-Maczulajtys *et al*., 1999). Trunk and branch morphology is a factor in wound response in that vulnerable zones can develop, depleted in carbohydrates. One such zone is in the length of trunk between the ground-level region of the base and buttresses and where the crown originates (lowest main branches).

The starch storage regions in the length of trunk will vary if lower branches have been lost or removed and according to past crown damage; with carbohydrate depletion in the main trunk also exacerbated by abiotic stresses such as drought. The location where trunk coring is generally carried out is close to a potentially vulnerable storage region, being between the partitioning zones in the major roots and the trunk zone supporting the first major limbs (see Figure 7).

Studies of beech energy storage and distribution describe how starch is stored in the pre-autumn leaf fall in the main trunk, and how over winter carbohydrate is translocated to roots, prior to then being re-mobilised for spring growth before break of dormancy. Summer depletion reflects assimilates being used for leaf, flower and cambial growth, the current annual increment, and seed production (Gaumann, 1935). In early spring, when phloem has yet to be fully activated and xylem conduits are the principal pathways for carbohydrate movement (Lacointe *et al*., 2004) there is a temporary period, before budburst, when strict partitioning is temporarily 'abolished' (with the entire tree as a sink). This allows carbohydrates to be readily mobilized tree-wide and for there to be flexibility of response to environmental changes. Gradually, as the growing season progresses, partitioning is re-established.

Dujesiefken and Liese (1990) suggest that pre-bud-burst tree response to April wounds (in this case mature beech) shows least stress-inducing effects, while dormant season wounding (February, December and October) shows greater levels of cambium die back. Wound staining in hornbeam indicates April pruning is optimal with December to March being least favourable with peripheral cambial die back in English oak being lower with March wounding, and greatest callus growth occurring after March pruning (Lonsdale, 1993).

Overall, studies suggest early spring (before spring growth emerges) to pose the least risk of damage from wounding. This conforms with the time when conventional guidance suggests callus production is greatest in response to wounding (Pirone, 1987). Late summer is least favoured, when autumnation has been initiated and before leaf fall, when reserves are being accumulated and reallocated for storage and for growth in the following spring (Pirone, 1987; Shigo, 1986).

[15] The primary trunk (1st order) holds compartments of energy behind points of attachment with subsidiary (2nd order) branches and along those 2nd order branches, similarly, sinks are located at unions with 3rd order branches, and so on.

With regard to coring veteran and ancient trees, the timing will need careful consideration. Pre-autumnation (late summer) coring should be most avoided, followed by the dormant season (October to February). Generally, for most species, for optimal wound response, the period of early spring (generally March or April), a few weeks before bud-burst is probably best for coring. However, with those species (e.g. sycamore and birch) that 'bleed' copiously when wounded at such time of year, it would be prudent to defer coring until a few weeks after full leaf expansion. In all cases, timing should take account of seasonal weather at the time e.g. low spring temperatures deferring leaf emergence.

The year following a summer drought particularly when followed by low winter precipitation will likely adversely affect metabolism and physiology, and the tree's resilience to stress, disease and capacity for wound occlusion.

If coring is to take place in winter or early spring, it should be some time after periods when temperatures are around 0° centigrade, due to risk of freeze-damage to wounded live tissue.

6.5 Wound response – discolouration, staining and decay

Staining of internal wood is a natural function of ageing. It is also a common aspect of tree-wound response. These two expressions of altered wood colour derive from distinct and separate processes and the latter may impinge upon the former.

The type and quality of staining reflects a range of chemical processes and interactions between wood tissue, air, water and microorganisms. Particularly in the instance of wounding, staining seldom reflects a stable condition, but rather transition processes within woody tissue. Other influences may be brought to bear on the processes including seasonal influences when wounding occurs, such as when the outer sapwood is injured and the staining response is influenced by sugar-rich conditions.

Injury extending into the tree beyond the sapwood, while principally affecting non- living tissue, gives rise to chemical changes, some of which alter the colour of the wood. This reflects dynamic interactions that are thought to be in part intrinsic to the tree (associated with oxidation of previously laid-down extracts, compounds which have both antimicrobial and hydrophobic properties (Liese and Dujesiefken, 1996)) and processes due to external agencies including those from fungi. Wound induced discolouration may look similar to heartwood, but is liable to differ chemically (Shortle, 1979).

Discolouration naturally occurs in heartwood formation where tissues that cease to be functional conductively become filled with anti-microbial (pigmented) extractives, secondary metabolites and also plugging materials that are water-repellent.

Following sapwood wounding, localised discolouration also occurs as a response. This 'false heartwood' (Shigo and Hillis, 1973) is an expression of wounding and indirectly of the response of living parenchyma cells to the presence of microorganisms within woody tissue (Shain, 1979). It may also be a fundamental consequence of changes in the status of prevailing water and air regimes within affected tissues (Boddy and Rayner, 1983), such that oxygenated compromised tissues become chromatically changed as discoloured xylem (Rayner, 1993).

Internal discolouration maps following wounding are used in the various formulations of the CODIT model to describe the somewhat imperfect territorial barriers. Discolouration maps have also been used in various studies over the past four decades as indicators of compartmentalisation barrier-zone effectiveness, established by the tree from a defence standpoint (Shigo and Marx, 1977; Lonsdale, 1999; Weber and Mattheck, 2006). They have also been interpreted as expressions of indeterminate tree-fungi interactions responding to

changes in the internal hydrodynamic environment of the tree (Boddy and Rayner, 1983). These dynamics may result in fungal decay strategies to overcome barrier 'compartments', exploiting compromised hydrology to avail sugars and other resources (Schwarze, 2007). Vessels that through damage become dysfunctional due to loss of hydration and aeration (Lonsdale, 1999) may also become discoloured, a process which may also, though not inevitably, involve fungal colonisation (Dujesiefken *et al*., 2005).

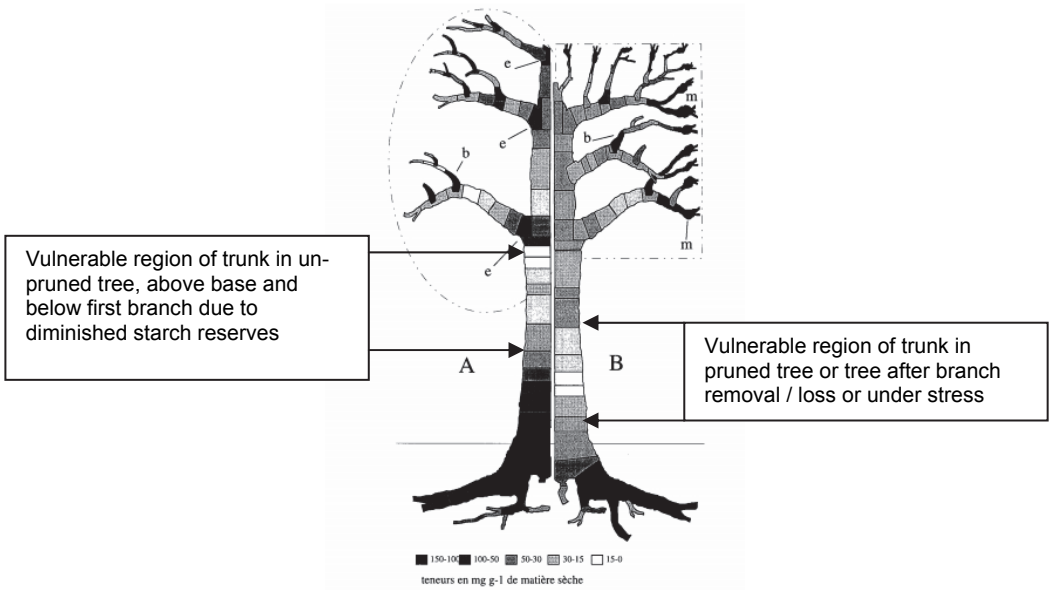

Figure 7. Comparative cartography of the distribution of starch in unpruned (pre-wounding) (A) and pruned and regularly maintained tree (B), showing depleted starch storage zones in trunk and branches (after Clair-Maczulajtys, Disquet and Bory (1999)).

Such wound-initiated discolouration may be contained in a stable pre-decay state (Shortle and Cowling, 1978) or become a dynamic expanding front, as a temporary precursor to progressive wood decay.

While similar to heartwood formation in aspects of character, these wound processes by contrast, being in a sense traumatic, constitute a rapid reaction, calling upon nearby tissue changes, metabolic energy reserve and hormonal responses. These discolouration processes, insofar as they involve the breakdown and digestion of cell tissues, reflect interactions between the host and fungal agencies, which are liable to lead to decay. When live tissues through these processes die and become dysfunctional (non-conductive) the decay may become pathogenic (Lonsdale, 1999).

The significance and interpretation of visually apparent changes in wood colour is complicated as noted in various studies. Discolouration reflects states wherein functional and biochemical changes occur within wounded, wound-affected and non-damaged wood (such as in the process of heartwood formation). Change of wood tissue colour occurs for a variety of reasons and contexts, and may be expressed according to phases of containment and expansion. This may be a natural, genetically species-programmed ageing process or may reflect environmentally induced tree interactions that also involve microorganism succession.

Various studies report discolouration in hardwoods as a consequence of coring; however discolouration is a complex issue, and the studies to date provide insufficient basis for

reliably understanding the long term implications associated with boring into AVTs. Helliwell (2007), Lonsdale (1999) and Weber and Mattheck (2006) all remark on the necessity for caution in drawing conclusions when interpreting the state of and significance of discolouration associated with wounds.

7. CORING – THE NATURE OF THE WOUND

7.1 Characteristics of wounding created by an increment borer

Core sampling a tree involves boring the steel screw-end of the increment borer, normally radially into the lower trunk and, where possible, to the centre of the stem. The extraction of each core creates a more or less horizontally inclined cylindrical wound that is typically slightly over 11mm diameter and which passes through the outer bark, phloem, cambium and sapwood on into the internal wood (the heartwood or ripewood) for the full stem radius.

When boring into the trunk, the threaded head compresses and separates fibres as it cuts a passage through the wood, often leaving fine shredded cut fibre ends. Webber and Mattheck (2006) refer to this boring action as producing lateral cracks due to the action of the cutting thread.

The nominal internal wound area of a borehole due to a core sampling device with an 11mm diameter cutting head, creating an approximately 11.3mm diameter hole (Weber and Mattheck, 2006), ranges from about 107sq cm for a 30cm length core, to about 178sq cm for a 50cm length sample. The equivalent surface area of an external wound would be a wound diameter approximately 12cm – 15cm.

These two forms of wounding are dissimilar in certain key aspects. An external pruning wound of 15cm diameter located about the lower region of a mature tree would normally be expected to expose only relatively recent woody growth, not dating back to early years of growth, and would be encompassed within a fairly wide outer ring (approx 47cm circumference) of cambial wounding, and fully presenting its wound face to the outside environment. Conversely, the core sampling wound is small diameter (11.3mm), is not two dimensional but three dimensional and is extensive in its reach.

Coring results in a predominantly internal injury and, while the amount of cambial wounding is minor (typically about 3.6cm circumference); the borehole is likely to cut through radially to the centre of the tree, thereby wounding a part of each annual ring in the process.

A distinction should be made between the potential effects of wounding that arises on the one hand from coring into a consistently sound stem of a healthy tree and on the other, to a coring ingress that passes through sound outer tissue into pre-existing internally decayed wood. While the former case introduces a novel injury that may in time degenerate, it poses a generally lower level of risk of decay than the latter case. The presence of internal decay may not be obvious in all instances. The ability to assess these conditions and associated risks to the tree and make an appropriate judgement will depend on the level of knowledge and competence of the practitioner. While new coring related wounding may result in a relatively local and small diameter wound, it nonetheless introduces a wound effect into each annual ring it passes through and a potential exploitation pathway for pre-existing decay.

7.2 Analogous wounds from other types of boring

Borehole wounds, created in trees as a result of core sampling are of an unusual penetrative nature, of a type rarely encountered in normally healthy trees in the natural environment. Natural counterparts do not readily come to mind, but the borehole wound may possibly be likened, though only to a limited degree, to the tunnelling created over time in the stems of some tree species by the wood boring larvae of a few relatively uncommon larger-sized insects (e.g. Goat moth and Leopard moth).

Core sampling wounds do however share similarities with certain kinds of wounds artificially created in the course of other practices associated with the husbandry and care of trees.

Concerns are noted regarding the practice of tapping Sugar maples, where borings risks breaching pre-existing reaction zones in the stem, including those formed in response to previous tap-hole wounds. Boring in this case can result in propagation of discolouration and decay (Rioux, 2011).

The arboricultural practice of installing bracing restraint systems by inserting metal eye-rods or screw-eyes creates long, narrow, cylindrical wounds within the tree's framework. These types of installation result in a borehole occupied by a tightly fitting metal through-rod or a shorter screw insertion and have been used by tree surgeons for many decades. With certain species, when insertions are installed in sound healthy wood (in the absence of pre-existing decay) the complex effects from the screw augur and the close-contact metal installation are not commonly considered to initiate serious decay.

As invasive drilling is potentially damaging the practice is contentious within arboriculture, particularly as over the years failure has occurred in some cases associated with decay in the bracing region. Today since non-invasive bracing techniques have been developed, invasive bracing insertions are seldom used and are regarded as a measure of last resort, only to be adopted where no other alternative is available for improving the structural state of the tree.

The German technical standard since 2006 has set non-invasive crown support systems as standard (Detter and van Wassenaer, 2006). This is because invasive drilling is regarded to present an unacceptable risk of perforating CODIT boundaries, resulting in decay propagation, and acceleration of the spread of decay where it is already present (Stobbe, 2000; Kane & Ryan, 2002).

The current guidance in the British Standard recommendations for tree work (BSI, 2010) does not exclude invasive bracing installations and includes practical guidance in some detail for both invasive and non-invasive practices. Concerns are stated, however, that drill wounding should *avoid close association with areas of existing internal decay* and that multiple *drilling can induce cracks* (BSI, 2010).

8. CORING STUDIES

8.1 Coring studies – Introduction

To date, empirical studies into damage-effects of coring are limited in the number of trees studied and in study duration. While most studies have considered relatively young trees, none has considered impacts to AVTs.

Many investigations into the impacts of coring date from the first half of the twentieth century in northern America. These mostly focus on forest species indigenous to that part of the world. Whilst the genera and families concerned may also be represented in the United Kingdom, the actual species differ from those commonly used for dendrochronological work in the British Isles, which has mainly focused on native oak and to a lesser extent yew and Scots pine and a few other species including ash, lime etc). While there are few studies that specifically consider the impacts of coring upon native northern European tree species in any depth, those that have taken place appear restricted to broadleaf hardwood species.

Over the course of research for this project we have come across limited information on mature tree wound response directly related to coring. Available studies include an assessment of *a single native oak* (Weber and Mattheck, 2006). While we have been unable to find studies looking into effects upon Scots pine or Yew, there are a few investigations into coring impacts upon mature native or naturalised hardwood tree species, including ash, Broadleaf lime, sycamore, willow and elm (Kersten and Schwarze, 2005; Schwarze *et al*., 2007; Helliwell, 2007) and Black poplar (Weber and Mattheck, 2006), however these are limited in scope.

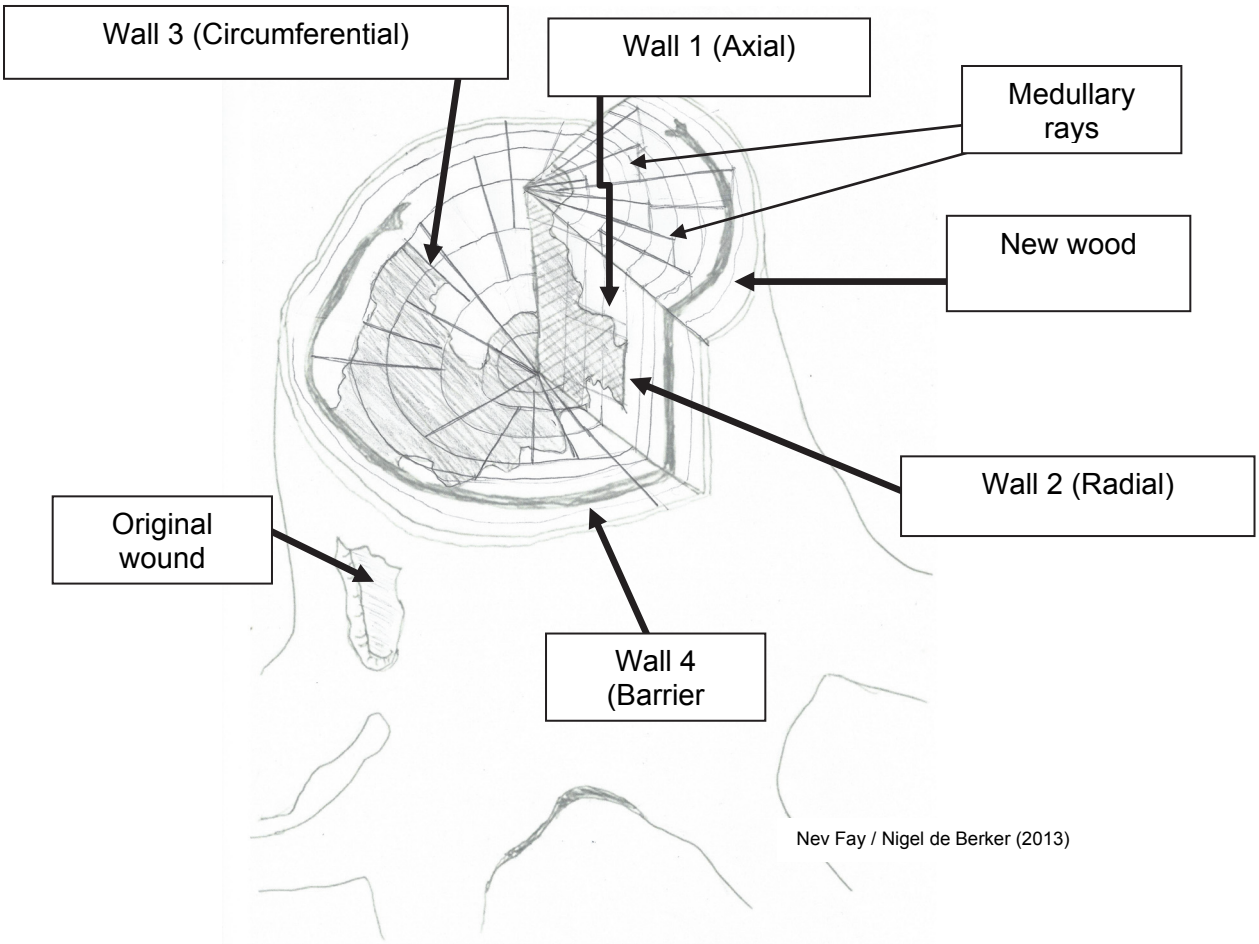

Figure 5. The CODIT model, after Shigo (1977)

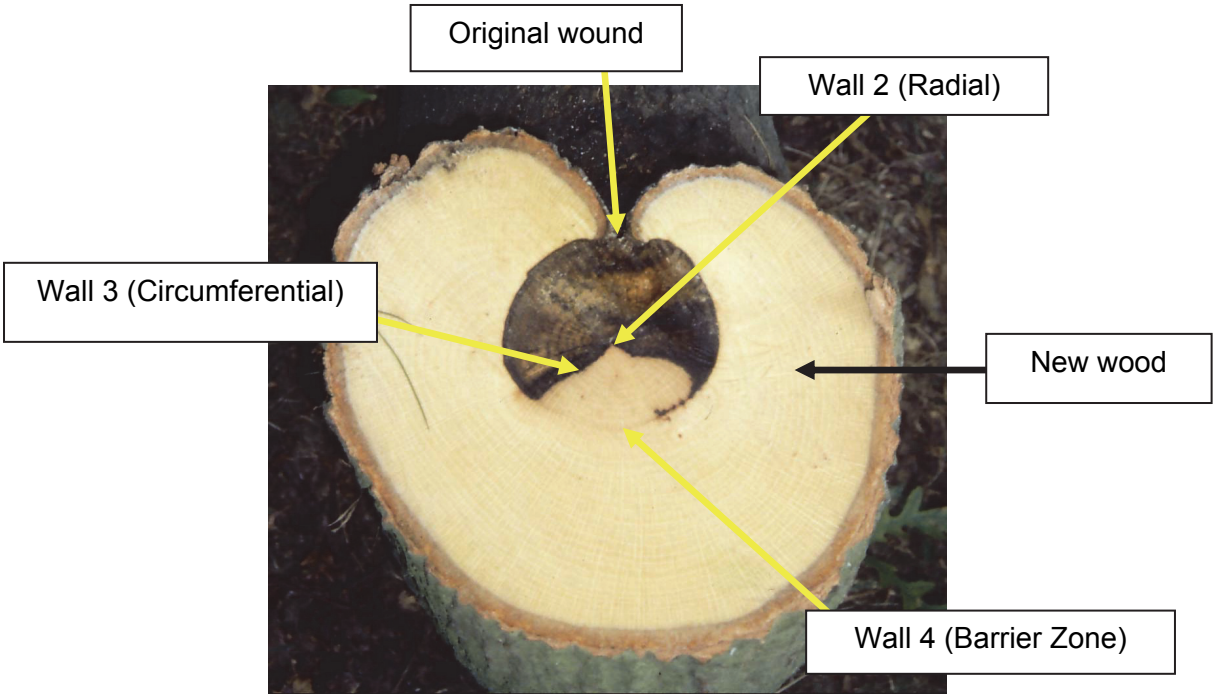

Figure 6. CODIT representation of decay compartmentalisation in a stem some years after wounding.

8.2 Studies into effects of boring – non-mycological

Tables 1 and 2 (see Annexe 1) provide a brief summary of the U.S. studies mentioned by Grissino-Mayer in his guidance manual (Grissino-Mayer, 2003), to which reference is often made by others involved in dendrochronological work with living trees when considering the impacts of coring. These tables have been expanded in the current work, to also include reference to a small number of additional, more recent, published studies, including some undertaken in northern Europe.

Hepting and colleagues (1949) conducted early, broad trials over a period of ten years at various sites in eastern USA that involved assessing and summarising observed impacts upon a range of hardwoods and some North American pine species. Species did not include English oak or Scots pine. Their studies, investigating the effects of coring with up to six boreholes per tree; they considered sample sizes of ten or fewer trees for the range of species. Trees were in their young to mature phases.

Trialled pines were reported to exude copious resin in most instances associated with the borehole region. These did not develop decay about the borehole wound. The area about the wound opening displayed little cambial dieback and occluded fairly quickly.

Hepting's investigations noted that all hardwood species to a greater or lesser extent developed localised decay about the borehole, mostly affecting the sapwood.

Diffuse porous hardwood species (e.g. birch, poplar, Tulip tree, maples) showed extensive axial discolouration in the region of the borehole combined with cambial die-back. In some cases canker from a wound fungus (*Nectria* sp), developed, retarding occlusion to the extent that, in four tree species (principally maple, birch and low vitality Tulip tree), occlusion had still not taken place after ten years. Hepting records death of two non-dominant Tulip trees with Nectria effects initiated by coring.

Ring-porous species represented by trialled oaks were reported to be less affected by decay generally but nonetheless occasional instances of heart rot were observed in the region of the holes. Hepting observed in his trials that the ring-porous hardwood species (White and Scarlet oaks) showed little bark deterioration or canker associated with the borehole region, which was subject to rapid occlusion.

Half a century later, a case study of four trees in northern Europe undertaken by Weber and Mattheck (2006) took repeat test-borings with an increment borer and micro-drill over a period of up to ten years. Two of the trees (oak and sycamore) were sound at the time of initial testing and the other two (poplar and sycamore) had pre-existing internal decay. In nearly all cases the borehole wounds occluded within a year or less. Discoloration was noted in the internal wood of all the trees to varying extents about the boreholes. In no case was decay visually observed entering the stem from outside via the borehole wounds. The sound oak and sound sycamore showed least obvious effects, with discolouration contained within the woody tissue about the boreholes wounds, with the impression of being compartmentalised. With the already internally decayed trees (poplar and second sycamore), coring provoked a wider spread of internal decay, apparently overcoming previous internal barriers. Over the period of the assessment, both trees appeared to be sufficiently vigorous for layers of new outer sapwood increment, to approximately compensate for inner tissue lost to expanding internal decay. New discoloured inner reaction zones appeared to develop in association with internal decay processes and tree responses. The results of the study were recorded from visual inspection after chain-saw dissection. No microscopic or mycological assessments were undertaken.

LaFlamme (1979) undertook trials with Trembling aspen and noted damage effects after three years. None of the trees showed borehole occlusion. There was pronounced splitting of the bark associated with the wound entry and isolated decay fungi from discoloured wood. Core related adverse effects may be influenced by temperature and climate and could similarly affect trees under certain conditions.

As stated above these studies are limited and do not include ancient or veteran trees. No detailed microscopic or mycological assessments were undertaken.

8.3 Studies into effects of boring – detailed mycological

Of all studies into boring that were reviewed, only those conducted by Schwarze and colleagues (2005 and 2007) involved detailed mycological investigation.

Over the course of two separate fairly short-term (8–16 months) studies, involving subsequent dissection along with microscopic and limited mycological assessment, Schwarze and colleagues (Kersten and Schwarze 2005, Schwarze et al. 2007) assessed wound responses of already internally decayed ash and plane to the effects of increment borer and micro-drill. Also assessed were non-decayed ash and broad-leafed lime. The studies included limited commentary on beech. The trials helped to illustrate species' variation in response to wounding. Trial borings of ash and plane passed through outer sound wood into wood already colonised with decay fungus (*Inonotus hispidus*). With all the tree species involved, external occlusion of borehole apertures was rapid. Internally, discolouration varied within the woody tissue about the borehole wounds, in all cases extending axially further above the borehole than below.

Of the species trialled, ash showed most extensive discoloration, spreading along the borehole from the internal region of pre-existing decay already infected with *I. hispidus*, breaching the previous internal reaction zone and migrating in the sapwood along the wound. Outgrowth of existing *I. hispidus* was found plugging the severed woody vessels of the heartwood along the borehole, a response possibly generated to maintain favourable conditions for survival of the established fungal colony and to ward off competition from other fungal species.

Microscopic traces of the fungus *Polyporus squamosus* (potentially a wound pathogen and decay fungus and possibly present as an endophyte) and *I. hispidus* were isolated from discoloured sapwood and the reaction zone from previously decay-affected ash and plane. In general boring impacts upon plane appeared to be less pronounced than on ash. Sound young lime appeared to be least affected overall, with only limited discoloration about the borehole and formation of a CODIT type Wall 4 with particularly modified cellular constituency likely to provide strongly resistant barrier zonation.

Kersten and Schwarze (2005) isolated a fairly wide range of saprotrophic *Deuteromycete* fungi, from the sapwood about the boreholes and from wood chippings attached to the increment borer after use in already decay-affected trees. They observe that some of the *Deuteromycete* fungi present (e.g. *Trichoderma* spp.) may be antagonistic to growth of certain Basidiomycete fungi and therefore suppress potential decay activity.

8.4 Opinions from past studies

Kersten and Schwarze (2005) conclude that well-considered tree management should avoid inflicting large sized wounds, such as severance of major branches and roots that typically allow development of fungal decay and cause levels of harm that far exceed risks of harm from use of increment borer.

The corollary of this is not that inflicting small–sized wounds is either beneficial or benign, nor does this take into account the distinct nature of penetrative wounding as compared to pruning or breakage wounds.

It should be noted that heavy limb removal and root severance do cause decay and have long been recognised as potentially seriously damaging to trees; such treatments have not formed part of normal, good arboricultural practice for decades and are clearly counselled against in current British Standard (BSI, 2010). Kersten and Schwarze's conclusion, per se, does not constitute a reasonable justification for increment boring.

Kersten and Schwarze (2005) consider there to be a low risk of cross-infection of decay between trees as a consequence of boring. A decade on, this conclusion does not take into consideration today's heightened bio-security concerns and the need for phyto-sanitary precautions, for example regarding spread of *Phytophthora* affecting a wide species range and other new disease introductions such as Chalara Ash Dieback.

Kersten and Schwarze (2005) consider that increment boring runs a risk of encouraging spread of decay in situations where decay is pre-existing; Shigo (1989) considers there to be a generic risk of causing decay from drilling into trees. Webber and Mattheck (2006) despite recognising some measure of risk of propagating decay, they consider that the use of invasive coring is justified when undertaken in the interests of evaluating trees for public safety risk. Their study does not take account of dendrochronology.

Shigo (1989) has no doubt that increment borer wounds result in injury and run the risk of starting internal cracks. This view follows his many years' observation of wound responses following arboricultural research using tree dissection.

In the field of safety assessment Mattheck and Breloer (1994) consider the use of increment borers to be liable to damage the tree, arguing that there is a generic risk of decay propagating internally from the effects of boring, and that particularly pre-existing, internally compartmentalised decay will likely spread. Mattheck and Breloer therefore advise using increment boring as a measure of last resort, and only after judicious consideration of alternatives. Additionally, (Mattheck and Breloer, 1994) concur with Shigo's views that the borer cutting head causes cracks to develop internally in the wood (perpendicular to the auger axis).

Lonsdale (1999) considers that there is a general concern when using an increment borer that decay may propagate in the vicinity of the borehole, but is uncertain as to the extent to which such decay may spread. With regard to impacts of coring on veteran and ancient trees Lonsdale (2013) argues that increment borer use is generally inappropriate on account of risk of spread of existing internal decay into previously sound wood potentially causing harm to a tree already be in a fragile state, and emphasises that judgement of the resilience of a veteran or ancient tree requires an appropriate level of arboricultural expertise.

8.5 Past studies – boring methods, location and wound treatment

Trials have been carried out to assess the effects of plugging and treating boreholes in cored trees (Hepting *et al*., 1949; Dujesiefken *et al*., 1999). Results showed no significant improvement to the tree's response in terms of wound occlusion or compartmenting reaction. Dowel plug insertion increased damage about the borehole and use of creosote-impregnated dowels was particularly harmful.

With regard to orientation and location of the borehole, Hepting and his team (Hepting *et al*., 1949) concluded that slanting the borehole upwards appeared to have no significant influence upon the extent of harm that might develop from the wound, but that boring close

to the base of the trunk reduced harmful effects. Dujesiefken and colleagues (Dujesiefken *et al.*, 1999) observed (also referencing Shigo and Shortle, 1984) that wood discoloration is greater when borings are angled away (tangentially) from stem radius. Properly undertaken with small diameter, cylindrical stems in the interests of dendrochronological study boring is unlikely to be tangential. However, tangential boring is more likely to occur in the case of large old trees with complex trunk shapes.

With regard effects of wound position trees appear generally less susceptible to decay when wounded at the base, compared to higher up the trunk (Dujesiefken *et al*., 1999), a view also expressed by Shigo (Shigo, 1991) and consistent with the model of carbon partitioning and availability of carbohydrates for wound responses (Clair-Maczulajtys *et al*., 1999).

8.6 Practical conclusions from previous studies (see also Annex 1)

Hepting and colleagues (1949) take a forestry perspective and make observations and recommendations to avoid timber damage. With regard to potential adverse effects they conclude that:

- The damage from boring into most hardwoods extends well beyond the physical boundary of the bore hole
- Hardwood species, particularly diffuse porous, are susceptible to localised decay
- Softwoods suffer lower levels of damage than hardwood species

Hepting and colleagues in the context of silvicultural use of coring make conclusions and provide practical guidance based on their 1949 studies that includes:

- Boring should be made as near to the ground as possible
- There is no advantage to be gained from slanting the core hole upwards, plugging of core holes or disinfecting the borer, since their studies showed that these practices had no influence on damage reduction

Grissino-Mayer (2003) in his manual and tutorial provides practical advice on use of an increment borer. He reiterates the guidance advised by Hepting and colleagues (1949). Taking a dendrochronological perspective he makes the following qualifications:

- The scientific importance of the information obtained from coring should be weighed against the possible injury inflicted to the tree
- Practitioners need to be properly trained and competent to asses and understand the potential injury to living trees caused by increment boring, and to make appropriate decisions for the equipment and its effects upon the tree
- Good practice requires proper maintenance and careful use of the borer (knowing where to bore, how to start and determine whether and when a borer is jamming and how to remove it)
- Coring should be undertaken during the growing season

As an arboriculturist Shigo (1989) is in no doubt that borer wounds injure trees and may also start cracks. In the field of tree safety assessment, he emphasises that information derived from the core must be carefully weighed against the injury to the tree and that increment coring should only be carried out if it is strictly necessary (such as a last resort to evaluate tree safety risk) (consistent with Webber and Mattheck, 2006; Kersten and Schwarze, 2005). In such instances he provides simple guidance for the tree specialist to follow to control risks arising from use of an increment borer and advises practitioners should:

- Practice with a borer on a cut log

- Use a sharp, well-maintained borer
- Bore as low on trunk as possible (consistent with Hepting *et al*., 1949)
- Not core at an angle (consistent with Hepting *et al*., 1949; Dujesiefken *et al*., 1999)
- Not bore above or below wounds of old branch stubs (consistent with Haddad *et al*., 1995; and Clair-Maczulajtys *et al*., 1999)
- Not bore when leaves are forming or falling (consistent with Dujesiefken *et al*., 2005)
- Not plug the hole or paint the wound (consistent with Hepting *et al*., 1949).

Moir (2012) from his research and field work endorses provides guidance that:

- Sampling should be kept to a minimum (consistent with Shigo, 1989; Grissino-Mayer, 2003)
- Coring should normally be limited to taking one core per tree
- It is acceptable to take two cores in the case of dendroclimatic studies
- Corers should be kept clean, sharp and be well-maintained (consistent with Grissino-Mayer, 2003)
- Core holes be angled slightly upwards (to help minimize water ingression) (at variance with Hepting *et al*., 1949)
- Core holes should be left open without plugging (consistent with Hepting *et al*., 1949; Shigo, 1989).

Norton (1998) considers coring from a conservation perspective and therefore that on such sites of high interest constraints will apply. Nonetheless he acknowledges that with regard to dendroclimatology study higher numbers of core samples are required and therefore careful consideration of conservation priorities should inform an impact assessment for such work. He agrees with Shigo that core wounding may breech the range of wound barriers with potential to cause damage to a tree. Before consenting increment-core permit applications for indigenous forest trees conservation staff are instructed to weigh the likely risks from previous and ongoing wounding impairing compartmentalisation. When evaluating permits for increment coring on conservation sites, guidelines require that:

- Coring will not be permitted on threatened plant list trees without overriding conservation management reasons
- Not all trees in any one population can be cored
- In fragmented natural tree populations tree coring be limited to essential conservation management work only
- Researchers are required to keep increment corers clean and sharp
- Increment cores be angled slightly upwards into trees (consistent with Moir, 2012)
- Holes are not plugged (consistent with Hepting *et al*., 1949; Shigo, 1989; Moir, 2012)
- Researchers are required to mark cored trees as basis for longer-term post coring tree health monitoring
- Increment cores are normally limited to one per tree except for dendroclimatic studies (consistent with Moir, 2012).

9. APPLICATION OF NON-INVASIVE METHODS FOR AGEING TREES

9.1 John White system, ATF and the Ancient Tree Hunt

The Ancient Tree Forum (ATF) in its Ancient Tree Guide No 4 (Ancient Tree Forum, 2008) includes generic guidance for ascribing girth size to a range of age and developmental classifications proposed for large sized specimens of eleven common tree species, classified according to 'locally notable', 'veteran / notable' 'ancient' and 'late ancient' (see also Lonsdale, 2013). This provisional contribution, being based on experience and considerable data gathering, while not taking account of systematic analysis of tree growing conditions, is valuable in providing a qualitative indication of ageing in relation to tree size and species - however, the approach does not quantify age in years.

John White, former principal dendrologist for the Forestry Commission and technical adviser to Tree Register of British Isles, and one of the consultees in this project, advises that there are very few instances, if any, when coring an ancient hollow tree is justified. If boring is to establish tree age the core needs to reach the trunk centre. Reaching the trunk centre of a large aged tree is neither predictable nor likely. This is because old trees are characterised by having trunks that are irregular in cross-sectional typically composed on high levels of compression wood and containing a decaying or hollow core.

If reliant on coring to obtain tree age information, multiple core samples would be required at the same height (potentially damaging to the tree), as ring-measurement from any single core is likely to be idiosyncratic and provide an unreliable basis for calculations. In cores, where only a few outer rings are extracted, extrapolation to establish the number and size of non-extant rings to the centre is beyond reliable calculation (White, 2013, pers. comm.).

Having experienced trees (Sitka spruce) breaking as the result of test borings, John White's dendrochronological work for the Forestry Commission led to designing an alternative methodology to coring as a means of ascertaining the estimated tree age. Forestry Commission information note (FCIN12), *Estimating the Age of Large and Veteran Trees in Britain* (White, 1998) provides a method of age estimation in old maiden and pollard trees designed to avoid wounding potentially vulnerable high value specimens. The system relies on a dataset from extensive measurements of trees and stumps of known age. The source information considers and compares different species and growing conditions.

The system builds on broadly accepted general patterns of tree growth that correlate with stages in the ageing process, which are cross-referenced with girth measurements from in their 'formative', 'middle-aged / mature' and 'senescent' phases. From this library of information, growth curves have been generated to provide a reasonable age-estimation for trees with large trunk diameter and those that are old for their species. The system, in requiring only an accurate measure of girth is easy to use.

FC Information Note (FCIN12) has not been revised since publication in 1998. However, since the inception in 2004 of the Ancient Tree Hunt (ATH) (a joint venture between the Woodland Trust, the Tree Register of the British Isles and the Ancient Tree Forum) over 100,000 ancient, veteran and notable trees have been recorded in an interactive database across the UK[16]. These data have provided an enhanced dataset for age estimation of a selected number of common species, adjusted for growing circumstances over six categories (Lonsdale 2013).

This initiative of applied dendrochronology, since John White and extending over the eight years of the ATH records, constitutes a significant data resource of tree measurements.

[16] http://www.ancient-tree-hunt.org.uk/recording

However, the system has certain limitations. It is not generally applicable to certain tree forms including outgrown ancient coppice, it has a restricted species range and is not yet calibrated to account for the wide range of growth conditions that might be encountered. Further collaborative involvement between the arboricultural, conservation and dendrochronological communities through sharing data and skills would contribute to the improvement of the system.

10. BIOSECURITY

10.1 Risks associated with coring and related activities

Throughout Britain trees are suffering increasing levels of losses and declines as a consequence of new disease introductions commonly influenced by changing patterns in the movement of people and goods. Such threats have been sufficient to warrant a risk based approach to the formulation of a plant biosecurity strategy for Great Britain (Defra, 2014a).

These effects not only threaten individual trees, woods and forests but also landscapes and associated ecosystems. Current diseases include threats to long-lived native and naturalised tree species from Acute Oak Decline (Forest Research, 2014), Chalara Ash Dieback (*Hymenoscyphus fraxineus*) (ATF, 2014), sweet chestnut blight, and a range of root pathogens including numerous *Phytophthora* strains, many of the which are relatively new to science (e.g. *P. ramorum*, and *P. kernoviae*).

In combination, these threats present unprecedented challenges for tree and site protection and disease control. Pest and disease threats to our indigenous and naturalised trees are further exacerbated by recent and predicted climate change (Defra, 2014a; Forest Research, 2014).

Additionally the disease status relating to trees in Britain is subject to rapid change with a high risk of certain pests and diseases being found in locations where they are currently absent.

There are many pathways of disease-spread including through the movement of plants and other inadvertent transmissions associated with human activity.

Paradoxically, those involved in the care and management of trees run the risk of being unwitting vectors of diseases by introducing pathogens onto sites and between trees in the course of their work. For these reasons, special awareness is required by those allied to landscape and nursery trades, in addition to forestry, arboriculture and horticulture.

Our understanding of biosecurity risks to trees is constantly evolving in response to emerging threats. As a consequence, forestry and arboricultural activities are under constant scrutiny and those practitioners involved carry a special responsibility.

Coring is a work-related activity that poses a potential unintended biosecurity risk through the transmission of disease between sites by personnel, vehicles and equipment and particularly, since being invasive, may introduce disease propagules directly into the tree.

Where dendrochronology studies involve AVTs, the risk of pest and disease introduction is brought to bear on this specific cohort. Where studies extend to AVTs at a landscape scale this also poses a potential biosecurity risk at this level.

The Forestry Commission provides precautionary practical guidance to control risks from spreading pests and diseases harmful to trees (Forestry Commission, 2012; Forest Research, 2014), and, in combination with Fera, has published a national Tree Health and Plant Biosecurity Action Plan (Fera, 2011), subject to regular review and update and which includes best practice protocols (Defra, 2012).

Guidance draws attention to the need for vigilance among professionals and practitioners and the relevance of assessing and controlling risk of disease transference from any particular activity in different types of sites and landscapes (Fera, 2013). Disease risk assessment and management extend to controls that apply to clothing and vehicles, and

sanitation of equipment including specific recommendations for appropriate 'biosecurity kit' and disinfection. Advised procedures are summarised in a biosecurity control reference guide (Forestry Commission, 2012, Figure 1).

To the extent that coring may pose biosecurity risks with the potential to spread diseases, responsibility falls to both commissioning agents and practitioners for the control of any existing diseases on a site affected by an activity. Therefore the impact and appropriateness of coring activity needs to take account of the specific circumstances in the context of disease risk assessment.

Control measures will be closely linked with such assessments. For example, where there are symptoms of certain tree diseases on a site that constitute a significant threat there will be a presumption that coring will normally not be permitted (Forestry Commission, 2014). There may be a case when coring might be permitted if an exceptionally high level of benefit can be demonstrated from the activity, together with observance of a sufficiently high level of precautionary care in the implementation.

If we consider native species that are currently at considerable risk of decline from disease, whose loss would have a detrimental consequence for the landscape and natural heritage, the current biosecurity threats to native oak and ash illustrate the need for stringent risk assessment and management.

Acute Oak Decline (AOD) is a complex and spreading disease affecting oak trees and leading to rising mortality rates (Forest Research, 2014). AOD is also reportedly associated with the two spotted oak buprestid beetle (*Agrilus biguttatus*) which, while perhaps not a primary cause of the disease, indicates that the presence of AOD is correlated with bark boring activity and so also may be the spread (Denman et al 2014). If these dynamics hold, coring would have similar implications for the risk of AOD transfer between trees and the direct introduction of infection of new tissue within a tree through boring.

The incidence of Chalara Ash Dieback has increased considerably since 2012 with a total of 89 UK infections recorded in 2012, increasing to 368 by February 2015 (400% increase). In Scotland, infections during this period have increased from 7 to 55 sites (780%) and have reached as far as Elgin (Forestry Commission, 2015). Chalara is considered a threat to ash at a species level with a reduction in Scotland's current biodiversity forecast. Without adequate controls, this would have significant financial, conservation, landscape and societal consequences (Forestry Commission Scotland, 2013).

Given the scientific evidence that Chalara poses a potential epidemic threat from the transference of fungal spores (which carry inherent problems of practical control), exceptionally high levels of vigilance and commensurate restraints are required. Accordingly, under current knowledge of the virulence of Chalara and the attached risk, unwitting operator contamination may occur through casual transmission including the direct 'injection' of the inoculum. In the context of a potential epidemic, there may be a case to consider a moratorium on coring ash.

Similarly, serious threats from other disease infections being spread within and between sites (e.g. *Phytophthoras*) need up-to-date risk assessment based on local site knowledge and tree and plant pathology advice and guidance.

11. DISCUSSION

11.1 Limitations to previous studies relating to living trees

No research to date has studied coring impacts upon the health and condition of trees in their ancient phase.

Research to date has been mostly derived from silvicultural sampling, based on large numbers of trees and considering restricted age class range generally looking into the impact of coring on the timber quality of trees with a determined, relatively short crop life (trees typically grown to a maximum annual increment, i.e. not beyond to post-maturity).

Certain other studies have drawn on arboricultural interests, including concerns for tree safety, for which coring, in the form of test-boring, has had a specific role in assessing wood condition, particularly in regard to trunk decay and hollowing.

The comparative long life of trees (compared to humans) contributes to their dendrochronological interest. From our investigations, in the context of the general lifespan of trees, studies have been relatively short-term; the longest study trials spanning between two and ten years.

Coring impact studies that conclude that there is a low impact on longevity on the basis of observations that study trees may be still standing and alive one to two decades after coring, do not necessarily take into account the timescales of normal life expectancy of many tree species and the related implications of decay processes. They also cannot account for declining condition beyond the study period. In any case, it is hard to envisage a research programme that might be resourced to span fifty or more years i.e., one that might better model the study-species' life expectation.

Currently, and in the past, studies have been based on destructive, post-damage, investigations involving felling of low quality trees. Future, meaningful long-term studies of impacts upon AVTs would likely require alternative, more costly methods of investigation, e.g. possibly involving sophisticated internal trunk mapping (acoustic or even using x-ray techniques).

11.2 Opportunities for data collaboration

Non-coring derived information that is concerned with classifying the age class and estimating the chronological age has a potentially complementary role to that gained from coring, despite comparative variability in precision. As already referred to, the complex structure and convoluted morphology of ancient trees combined with their degraded woody condition and hollow trunk centre, renders the value of coring questionable due to the number of samples required to accurately model the growth pattern. The Ancient Tree Hunt has generated a vast amount of data, containing girth dimensions on more than 100,000 trees.

John White's system (see Section 9.1) of non-invasive age-estimation has particular relevance for AVTs. While non-coring methods have clear limitations compared to the precision that invasive coring of (non-hollow) trees offers, there is potential benefit in combining data from both non-invasive sources (including ring counts from stumps, fallen trees and forestry and amenity felled trees) and from invasive dendrochronological coring.

Data sharing and integration could also assist in the calibration and accuracy of the John White system, improving its role as a complementary resource for conventional dendrochronology. An enhanced John White system would provide an additional path for

dendrochronological study. A physical library of stored cross-sectional rings from stumps and fallen trees would further contribute to the scope of this resource.

11.3 Towards an integrated approach

We understand that the revision to the Historic England 2004 guidance will add advice with regard to coring living trees. The main content in the 2004 guidance is devoted to other issues including coring of non-living wood material and the management of data. While recognising some risk of damage, it classifies this as 'minor' though advice to mitigate this is limited. Some guidance is offered against plugging core holes though there is no preference expressed for when during the year it is most suitable to take cores from living trees.

The precautionary approach is consistent with that taken by Historic England, which is aware of concerns over coring living trees and is currently updating its dendrochronology guidelines (Historic England, 2004). We understand that the forthcoming revision to its guidance will cross-refer to and draw upon the findings of this Scottish Natural Heritage report, and furthermore that all Historic England commissioned coring data will in future be in a publicly available database. Historic England Gardens & Landscape Team has established the principle that coring live trees should be avoided due to concerns about its possible effects on tree health. Guidance points to obtaining evidence directed to sampling and measurement analysis of non-living wood material, reference to historic maps.

With regard to obtaining high quality data from living trees Historic England age recognises that at least two cores are required and therefore emphasises that coring should only be practiced in response to answering clearly defined questions. There are many ways and sources of obtaining high quality data, not all relying on coring.

Dendrochronological practice is commonly undertaken by independent practitioners. In the absence of formal standard guidance for coring living trees as a framework for practitioner competence, there is considerable scope for variation in the quality of field work and analysis. In this context it is left to those agents commissioning dendrochronological analyses to keep abreast with relevant evidence and published work and to ensure that only reputable practitioners are engaged.

The development of a set of commonly agreed field work standards for coring trees that addresses the concerns of heritage, conservation and landowning interests, along with those of practitioners playing their appropriate roles, would need to be sufficiently broad to address the implications for living trees, the need to assess and manage biosecurity risks as well as including protocols for recording data.

Developing guidance for when it is appropriate to core AVTs and when not requires an exchange of information between specialisms and interests, particularly as stakeholders may function at different levels of objectivity and bias according to their perspective and their knowledge community. Opportunities for improved knowledge exchange would therefore serve in setting standards for making decisions for the benefit of AVTs. Opportunities for knowledge exchange are considerable; particularly given the wealth of information that resides in the fields allied to dendrochronology and that the different sectors have so much to gain.

12. CONCLUSIONS

12.1 Towards a shared view of guidance

The value of much of the knowledge derived from dendrochronology is undeniable. To say there is a conflict between dendrochronologists and conservationists is to oversimplify the issue, as both value ancient trees.

Over its relatively short life, the discipline of dendrochronology has shed considerable light on earth history, providing new and emerging insights and applications into climatology and other fields, including informing more recent human concerns about climate change. Studying the detail and timing of events in the distant past locked up in cellulose of trees provides an evidence basis for future projection (Baillie, 1995).

Good conservation practice requires that the value of operations be weighed against their potential consequences. In the context of evaluating and managing AVTs for biodiversity, coring is rarely appropriate. Additionally, coring such trees will likely provide limited information due to internal trunk condition (hollowing and decay) and may encourage pre-existing decay to spread within the trunk. In such instances, non-invasive methods of approximating tree age need to be considered where appropriate.

Studies into the effects upon living trees of coring for dendrochronological purposes (see Section 8) have been fairly short term, mostly involving population samples from forest stands with non-veteran trees. These studies in the main conclude that boring does not give rise to serious damage in most conifers, though it may cause low levels of damage in hardwoods (broadleaves). These studies report general occlusion of the bore-hole aperture with callous tissue after a few seasons. From these observations, the non-expert may conclude that boring wounds, at best, 'heal' without consequence for the tree or, at worst, that boring wounds cause a measure of biological disruption without serious detriment.

A number of studies report internal wood discolouration as a by-product of coring, whose effects have been generally judged by dendrochronologists to be neutral to the health and condition of the tree. However, discolouration of woody tissue as a response to internal wounding is an expression of microbiological and chemical interactions, such processes will be considerably influenced by the pre-existing state and condition of the tree and may be a precursor to an advancing front of decay.

Invasive wounding which causes damage to the functional sapwood, resulting in staining of inner woody tissues, has the potential over time, to cause some measure of harm to a living tree. A greater risk is posed to ancient and veteran specimens, where there is a high likelihood of a borer penetrating the live outer tissue and traversing into pockets of internal decay, thereby providing opportunities for further spread of decay over time.

Given their contemporary and their prospective longevity, it is difficult to extrapolate the conclusions from studies of trees in earlier life stages to the context of long-term impacts upon AVTs. While posing inherent risk to valued trees and without any guarantee of a clear outcome, very long term study might provide more useful information on the impacts of coring AVTs.

Trees in general are currently subject to pressures from a range of pests and diseases (see Section 10) in addition to anthropogenic stresses (e.g. climate change effects, pollution etc). AVTs, by their very existence in the landscape, tell of a capacity to accommodate a measure of gradual change. In this sense old trees may be considered natural survivors. But this tells us more about their history than their future prospects.

Despite the apparent durability of AVTs, experience from the Ancient Tree Forum and other studies show a vulnerability to rapid change and, where collections of trees are present, unsustainable rates of decline have been recorded. Veteran tree population declines and losses at several sites across southern England show rates of over 1% per annum for oak and for beech (Fay & Bengtsson, 2011). In the absence of evidence that coring does not cause demonstrable harm in the long term, there is a reasonable case to argue a precautionary approach with regard to coring AVTs, and "legacy trees" (Grissino-Mayer pers. comm. 17 October 2011).

From the conservation standpoint, an ancient or veteran tree may be considered as potentially fragile and also a relatively rare component of the environment, encompassing the tree itself, its colonising species, its root and soil ecosystem, as well as the tree's biological and cultural connectivity with the landscape. Where these interests are considered sufficiently high, the management impetus will be to protect against risk of harm. In the absence of reasonable scientific certainty there is a general presumption to avoid activities and operations that may be thought likely to cause damage or loss to things of such importance.

Conservationists and arboriculturists, particularly those specialising in ancient and veteran tree management guidance, broadly agree that intervention with such trees should be minimised to reduce risk to their health and longevity (Shigo, 1989; Clair-Maczulajtys *et al*., 1999; Fay, 2000; Read, 2000; Lonsdale, 2013). Such a view requires that due regard be given to the way that an old tree is likely to respond to disturbance of any kind, including wounding. Factors that might predispose trees to vulnerability to wounding are numerous and in effect defy accurate full determination.

The precautionary approach is consistent with the Rio Declaration precautionary principle[17] (Principle 15 of Agenda 21)[18] that ''Where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be a reason for postponing measures to avoid or minimize such a threat" (Defra, 2011; UN DESA, 2011)[19].

Grissino-Mayer (2003), whose guidance on using increment borers is widely quoted as a key reference for good practice by dendrochronologist experts, was consulted in the course of this study. He advocates a precautionary view on coring historically significant 'legacy trees' for accurate ageing, as often the innermost rings are typically absent. In old trees (such as oak and yew) with a tendency to greater wood density, boring also runs a high risk of the core-barrel breaking within the tree, contributing to a chain of events that could jeopardise 'legacy' trees.

Not all trees are ancient or veteran, in fact very few in any population are. Those that are, may vary considerably in their historic, biodiversity and heritage value, some having exceptional importance such as the Moccas Oak, Tortworth Chestnut and Ankerwycke Yew. Others may have less obvious individual value, while being exceptionally important through their contribution to habitat mosaics within a network of other trees.

Similarly, not all information derived from dendrochronology is of equal value. Governmental and non-governmental agencies (Historic England, Scottish Natural Heritage, Natural England, Natural Resources Wales and National Trust) with responsibility for heritage trees

[17] Adopted by UK and other governments at the United Nations Conference on Environment and Development in 1992.
[18] UN Convention on Biological Diversity
[19] First defined in the 1987 Brundtland *World Commission on Environment and Development: Our Common Future* report to the UN (Annex to document A/42/427).

raise reservations about the value gained from coring aged, heritage trees when compared to the risks posed to them.

Establishing the level of value and reasons for the importance of particular trees is generally the role of tree and conservation specialists, whose opinion is important with regard to the formulation of project briefs, where coring of AVTs is proposed and whose advice may be pivotal to the selection of trees that are most suitable for coring.

There is wide and genuine value in the different sector interests. Various authorities advise that the scientific benefits derived from coring should be carefully considered and weighed against the potential injury to trees (Grissino-Mayer, 2003), their habitat and their related biodiversity (Norton, 1998). Other authorities have yet to be convinced that the level of risk to AVTs is sufficiently proven for there to be a basis for any additional constraints imposed on professional dendrochronological investigation to safeguard against potential harm to this cohort of trees.

Biosecurity risks and the potential for spreading infection through coring is an important additional consideration that imposes a necessary constraint. Any future guidance will need to specify protocols for managing the risks of environmental harm that might result from coring.

This report has been prepared for consultation as a review of current knowledge with the UK Wood Pasture and Parkland Technical Advisory Group members. It is the first stage in the formulation of an agreed Code of Best Practice.

A key conclusion of the report is that there is a need for all professional research/interest groups to come together to collaborate in the production of a best practice guidance document on tree coring in order to facilitate appropriate research and knowledge enhancement that is balanced with the value of AVTs in a wider conservation perspective.

The concerns and interests of the dendrochronological community and the conservation and arboricultural interests are all too important to allow the process of developing guidance to be detrimentally affected by entrenched opinions. This study is intended to provide source material for the respective communities to explore, as a potential basis to share and exchange knowledge. Collaborative meetings and seminars would likely also serve this process.

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ANNEX 1: PREVIOUS STUDIES INTO THE EFFECTS OF CORING – SUMMARY

Table 1. Conifers/Softwoods

Tree Species	Age/ Maturity	Size of tree (trunk dbh)	Discoloration/ Staining	Fungal decay	Other effects	Length of trial	Reference
Abies balsamea	Not recorded	Not recorded	Minor	None detected	Not recorded	-	Campbell, 1939
Abies concolor	ca. 20 yrs	>5cm & >20cm	Not assessed	Not assessed	No apparent impact upon mortality rates	12yrs	Van Mantgem *et al*., 2004
Abies magnifica	ca. 20 yrs	>5cm & >20cm	Not assessed	Not assessed	No apparent impact upon mortality rates	12 yrs	Van Mantgem *et al*., 2004
Picea rubens	Not recorded	Not recorded	Minor	None detected	Not recorded	-	Campbell, 1939
N American Pines	Not recorded	Not recorded	Minor	None detected	Not recorded	-	Campbell, 1939
Pinus echinata	Not recorded	30 – 35cm	Minor	None detected	Slight cambial dieback about borehole; no canker; closure only delayed by hardened gums/resins	10 yrs	Hepting *et al*., 1949
Pinus rigida	Not recorded	30 – 43cm	Minor Resin soaked	None detected	As *Pinus echinata*	10 yrs	Hepting *et al*., 1949
Pinus merica	Not recorded	18 – 38cm	Minor Resin soaked	None detected	As *Pinus echinata*	10 yrs	Hepting *et al*., 1949
Pseudotsuga menziesiii	Not recorded	Not recorded	Minor	None detected	Not recorded	-	Meyer and Heyward, 1936
Tsuga canadensis	Not recorded	Not recorded	Minor	None detected	Not recorded	-	Campbell, 1939

Table 2. Hardwoods

Tree Species	Age/ Maturity	Size of tree (trunk dbh)	Discoloration/ Staining	Fungal decay	Other effects noted	Length of trial	Reference
Acer pseudoplatanus	Early-mature	12 – 23cm	Moderate extent of staining; greatest axially	None detected	Boreholes occluded within 12 months	2 yrs	Helliwell, 2007
Acer pseudoplatanus	Early-mature & Mature	ca 30cm ca 80 cm	Broad , local staining Major	No decay evident in younger tree Decay attributed to *Ustulina deusta* already present within trunk of older tree and gradually expanding	No obvious loss of vitality. No obvious loss of vitality. New reaction zones form within trunk about existing decay. Localised bark death about borer entry holes	4-5 yrs	Weber & Mattheck, 2006
Acer rubrum	Not recorded	15 – 35cm	Major	Major on some trees	Moderate axial cambial dieback about hole	10 yrs	Hepting *et al*., 1949
Acer rubrum	Not recorded	Not recorded	Major	None detected	Not recorded	-	Campbell, 1939
Acer saccharum	Not recorded	8 – 20cm	Minor – Major	Long reach of decay about wound on some trees	All holes closed after 10 yrs on Site No.1, though with long axial cambial dieback. *Nectria* cankers delay closure on site No. 2	10 yrs	Hepting *et al*., 1949
Acer saccharum	Not recorded	Not recorded	Major	Major	Not recorded	-	Campbell, 1939
Acer saccharum	Not recorded	Not recorded	Minor	Major	Not recorded	-	Lorenz, 1944
Aesculus hippocastanum	Not recorded	Not recorded	Moderate	None detected	No advantage in sealing/treating borehole	10 yrs	Dujesiefken *et al*., 1999

Betula alleghaniensis	Not recorded	Not recorded	Major	Major	-	-	Campbell, 1939 Lorenz, 1944 Hepting *et al*., 1949
Betula lenta	Not recorded	20 – 28cm	Long band of discolouration about hole	Moderate reach of decay about wound on some trees	-	10 yrs	Hepting *et al*., 1949
Betula lutea		18 – 20cm	As *Betula lenta*	Long reach of decay about wound on some trees	ca. 50% bore apertures open after 10 yrs on account of *Nectria* cankers	10 yrs	Hepting *et al*., 1949
Betula papyrifera	Not recorded	Not recorded	Major	Major	-	-	Campbell, 1939
Betula papyrifera	Not recorded	Not recorded	Major	None - Major	-	-	Lorenz, 1944 Hepting *et al*., 1949
Betula pendula	Not recorded	Not recorded	Major – extensive axially	None detected	No advantage in sealing/treating borehole	10 yrs	Dujesiefken *et al*., 1999
Carya spp	Not recorded	Not recorded	Minor	None detected	-	-	Campbell, 1939
Celtis laevigata	Not recorded	Not recorded	Major	Major	-	-	Toole and Gammage, 1959
Fagus grandiflora	Not recorded	20cm	Long, water-soaked or brown band about hole	Decay detected only on some trees	Borehole closure rapid; no surface defects	10 yrs	Hepting *et al*., 1949
Fagus grandiflora	Not recorded	Not recorded	Major	Major	-	-	Campbell, 1939
Fagus sylvatica	Not recorded	Not recorded	Not recorded	Not recorded	When boring, transfer of fungus, from one borehole to another, judged to be unlikely	8 months	Kersten and Schwarze, 2005
Fraxinus americana	Not recorded	Not recorded	Minor	None detected	-	-	Campbell, 1939
Fraxinus excelsior	Early mature	12-23cm	Limited staining; greatest axially	None detected	Holes occlude within 1yr	2 yrs	Helliwell, 2007

Fraxinus excelsior	Mature	Not recorded	Staining migrates in sapwood along borehole; spreading from existing internal reaction zone already infected with Inonotus hispidus	*Basidiomycetes I. hispidus, Polyporus squamosus* and a range of *Deuteromycetes* - isolated from discoloured sapwood about wound region	1.Severed vessels along borehole plugged by *I. hispidus* fungus 2.When boring, transfer of fungus, from one borehole to another, judged to be unlikely	8 months	Kersten and Schwarze, 2005
Fraxinus pennsylvanica	Not recorded	Not recorded	Minor	Minor	-	-	Toole and Gammage, 1959
Liquidambar styraciflua	Not recorded	Not recorded	Major	Major	-	-	Toole and Gammage, 1959
Liriodendron tulipifera	Not recorded	10 – 40cm	Major ; Extensive blue band of discolouration about hole	Localised decay in a few cases	Holes occlude rapidly in dominant trees - otherwise Nectria canker invades. Two trees die from canker effects	10 yrs	Hepting *et al*., 1949
Magnolia acuminata	Not recorded	20 – 30cm	Major : Long axial section of blue staining	None detected	Closure rapid; no surface defects	10 yrs	Hepting *et al*., 1949
Platanus x hispanica	Mature	Not recorded	See Fraxinus excelsior (Kersten and Schwarze, 2005)	See *Fraxinus excelsior; Trametes gibbosa* also detected	See Fraxinus excelsior (Kersten and Schwarze 2005)	8 months	Kersten and Schwarze, 2005
Populus deltoides	Not recorded	Not recorded	Minor	Minor	-	-	Toole and Gammage, 1959
Populus nigra hybrid	Mature	ca 1m	Major	Decay from Armillaria sp already present within hollow trunk spreads internally	No obvious loss of vitality. New reaction zones form within trunk as pre-existing internal decay expands	10 yrs	Weber and Mattheck, 2006

Populus tremuloides	Not recorded	Not recorded	Major; extensive axially	Major	Long bark splits about borehole. Boreholes not occluded after 3yrs	3 yrs	Laflamme, 1979
Prunus serotina	Not recorded	Not recorded	Minor	None detected	-	-	Campbell, 1939
Quercus spp (N. USA)	Not recorded	Not recorded	Minor	None detected	-	-	Campbell, 1939
Quercus alba	Not recorded	10 – 28cm	Minor : Long narrow black line about hole	Minor: A few instances of heart rot but internal defects generally slight	Borer entry holes occlude rapidly Little cambial dieback. No canker or other surface defects. No obvious loss of vitality.	10 yrs	Hepting *et al*., 1949
Quercus coccinea	Not recorded	13 – 30cm	Minor: Long narrow black line about hole	As Q. alba	As Q. alba	10 yrs	Hepting *et al*., 1949
Quercus nuttallii	Not recorded	Not recorded	Major	Major	-	-	Toole and Gammage, 1959
Quercus robur	Mid-mature	ca 50 cm	Localised about bore	None detected	Borer entry holes occlude rapidly No obvious loss of vitality.	7 – 9 yrs	Weber and Mattheck, 2006
Salix caprea	Early/mid-mature	12-23cm	Limited extent: greatest axially	None detected	Full occlusion of only 50% of boreholes in 2yrs	2 yrs	Helliwell, 2007
Tilia americana	Not recorded	Not recorded	Very dark discoloration	Localised decay about borehole in a few cases	-	≤4yrs	Hepting *et al*., 1949
Tilia americana	Not recorded	Not recorded	Major	None detected	-	-	Campbell, 1939
Tilia americana	Not recorded	Not recorded	Minor	Major	-	-	Lorenz, 1944
Tilia americana	Not recorded	Not recorded	Minor	None detected	-	-	Hepting *et al*., 1949
Tilia cordata	Not recorded	Not recorded	Minor - Clearly zoned and localised about bore wound	None detected	Wound effectively compartmentalized No advantage in sealing/treating borehole	10 yrs	Dujesiefken *et al*., 1999

Tilia platyphyllos	Early-mature 15 yr old	Not recorded	Minor	Minor	Lime shows less staining than ash (esp. axially) in comparative boring trials	16 months	Schwarze et al., 2007
Tilia platyphyllos	Not recorded	Not recorded	Minor - Clearly zoned and localised about bore wound	None detected	Wound effectively compartmentalized No advantage in sealing/treating borehole	10 yrs	Dujesiefken *et al*., 1999
Ulmis glabra	Early mature	12-23cm	Limited extent: greatest axially	None detected	Boreholes occluded within 12 months	2 yrs	Helliwell , 2007

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