This book aims to stimulate connections and communication between disciplines, to encourage integrated approaches to study and practice and to build upon shared knowledge. Considering the tree over its lifespan and looking more deeply at the ancient phase, a better understanding of the ageing process helps to illuminate the way tree respond to damage and injury. The lifespan approach provides insights into how this understanding may be applied to pruning practices for trees in their young and mature phases. The book explores pruning requirements of the young urban tree in the first 25 years after planting and outlines the Dutch pruning system along with indicative costs. It also considers the practical implications of compartmentalisation of damage in trees (the CODIT Principle) and provides management guidance with particular reference to pruning of trees in the mature phase.

From the lifespan approach, an "ancient tree paradigm" emerges as an important and guiding concept, which requires that the special qualities and interactions between the tree and its environment are taken into full account. In this sense the ageing tree is considered not alone as an individual but rather as a colony and also an ecosystem, one that functions within and beyond the tree, and, fundamentally, includes its ancient soil.

Foundation for Sustainable Development (Fundacja EkoRozwoju, FER), a Wrocław-based NGO active since 1991 in environmental education, nature conservation and local sustainable development issues. It operates an innovative environmental education center – EkoCentrum Wroclaw. In recent years one of the FER's leading activities was Roads for Nature – a programme to promote proper tree conservation and management practices.

Roads for Nature (Drogi dla Natury) Programme was conceived by the Foundation for Sustainable Development. It started in 2009 seeking to reverse the decline of tree-lined routes and avenues in Poland, by way of joint work with authorities and communities. In its framework, a vast knowledge base was accumulated, books published and several thousand of public officials responsible for trees trained in tree management. Close to 40 thousand trees were planted along Poland's roads. The programme gained nationwide and international recognition and inspired further initiatives to improve tree management in man-made landscapes. More information on the project can be found at www.aleje.org.pl.

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Trees – a Lifespan Approach Contributions to arboriculture from European practitioners

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Roads for Nature

aleje.org.pl

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I

Introduction

Foreword

Dear Reader,
In our adventure of discovering trees we crossed our paths with passionate and open-hearted experts in arboriculture. In spring 2015, while preparing for another book, the idea of a publication considering tree care throughout its' lifespan was born. Our aim was to engage authors from different countries and backgrounds, and to bring them together to share knowledge and experiences.

The three main phases of a tree's lifespan – which may be termed young, mature and ancient – require different management approaches. As it happens, the specific skills needed to tackle these phases have been developed in various countries. A practical and effective approach to forming young street trees has been developed in the Netherlands (Jan-Willem de Groot). Comprehensive guidelines on the treatment of mature trees have emerged in

Germany, based on the country's strong science and practice in tree management (Dirk Dujesiefken). Finally, the United Kingdom, as a result of its long experience of managing an exceptionally large, yet vulnerable, ancient tree population, through a multi-disciplinary, collaborative approach, has developed conservation management techniques for ancient trees (Neville Fay and Nigel de Berker).

The milestone in preparation of this book was a seminar held in Bialowieża Forest in September 2015. The event brought over 30 delegates from Poland, the Czech Republic, Germany, Holland, Italy, Russia, the USA and the UK to deepen our understanding of trees, their life-cycle, physiology, morphology and to experience trees in the place where they grow, mature, and die freely

This book is a result of a truly international efforts, sharing tree-care experiences and practices. The connections that we've made became friendships and as Ted Green says, friendships made under a tree last a lifetime.

The concept of this publication

Neville Fay, Nigel de Berker

Conventional arboriculture has developed from a series of specialisms, mostly derived from forestry, landscape and horticultural disciplines. The influences on arboriculture range across botany, dendrology, plant physiology and pathology. Allied disciplines with connections to arboriculture include mycology, microbiology, soil science, lichenology, ecology, morphology, etc. Despite the list of specialisms involved, there tends to be little coherent communication between the contributing parties.

The ancient tree inhabits a range of terrestrial landscapes and an expanse of time that functions on a fundamentally different scale from that experienced by human beings. As the tree reaches the ancient phase it becomes increasingly complex, not only as an individual, but also as a colony of potential successors that express earlier developmental stages. Along with these processes, over the passage of time, the ancient tree and its soil environment become host to an ever-increasingly rich ecosystem.

The study and appreciation of ancient trees paves the way to an improved understanding of natural processes, providing evidence upon which to base management decisions for trees in all their life-stages. Such knowledge is particularly important in designing strategies to enhance tree longevity and ecological value. Over recent years, this approach has increasingly influenced both mainstream theory and practice, finding its expression through 'Conservation Arboriculture'.

This book aims to stimulate connections and communication between disciplines, to encourage integrated approaches to study and practice and to build upon shared knowledge. In the following pages we consider various aspects of the tree over its lifespan. We look particularly closely at the ancient phase and the lessons we can learn from a better understanding of this period. Chapter 2 explores how the tree responds to certain types of damage, and how an understanding of these responses may be applied to pruning practices, with particular reference to trees in the young and mature phases. The theoretical understanding of wound response, compartmentalisation and species survival strategies is developed in detail. Chapter 3.1 considers the pruning requirements of the young urban tree in the first 25 years after planting and outlines the Dutch pruning system along with indicative costs. It focuses on the long term benefits of repeated small-dose treatments in early life that minimise pruning trauma and set a pattern of growth for mature phase crown architecture, compatible with the contingencies of the urban environment and in particular, with the requirements of trees close to structures and roads. Chapter 3.2 considers the practical implications of compartmentalisation of damage in trees (the CODIT Principle) and provides management guidance with particular reference to pruning of trees in the mature phase. Chapter 3.3 considers the "ancient tree paradigm", which includes the special qualities that derive from the interactions between the tree and its environment and which over time constitute the tree as an ecosystem, and include its ancient soil. The paradigm considers the ageing process, compartmentalisation, decay and rejuvenescence through the perspective of evolved survival strategies that have implications for the management not only of ancient trees but also of trees in earlier life stages.

II

Tree lifespan approach

2.1. Arboriculture – the perspective from ancient trees

Neville Fay, Nigel de Berker

2.1.1. The evolution of modern arboriculture – the utilitarian paradigm

Many influences have contributed to the evolution of modern arboricultural practice. The majority of the world's population today lives in cities (United Nations 2012) and as trees deliver health, welfare, economic and security benefits for urban dwellers (Konijnendijk *et al*. 2005; Alliance for Trees and the Community Forest 2011), it is not surprising that a major strand of arboricultural theory and practice derives from the need to serve the requirements of urban forest management.

Horticulture and architecture, based on concepts of 'natural design', form and symmetry, have helped to determine the kind of tree that arborists have in mind when using their trained and controlling hand to shape the way trees grow. The domestic and commercial cultivation of orchard fruit trees has helped to mould arboricultural practices in propagation, pruning and productive management. Silviculture has played a role in applying models of 'peak use-value', leading, in a sense, to trees being 'designed' for optimum commercial production using wood technology. These contexts influence the relationship of practitioners to the acceptability of decay processes and the normal longevity and physical scale of trees being managed and have to some extent defined a path that leads *away from nature*, towards expectations of performance and design, perhaps more applicable to man-made, rather than natural, objects.

These drivers, along with concerns about public safety, have influenced arboriculture in a direction broadly biased to a *utilitarian paradigm*, whereby trees are considered within an accounting framework in terms of 'rates of return', 'service-life extension value' and 'useful-life value' (Vogt *et al.* 2015).

Under typical management systems, a significant proportion of urban trees die, or are removed before reaching full maturity. Some US estimates suggest a 'population half-life' (the maximum age that half of the planted trees can be expected to reach) that averages 20 years, with an overall mean life-expectancy of less than 30 years (Roman & Scatena 2011). These estimates are supported by UK studies that suggest most urban trees in England are aged between 10 and 50 years, with only 17% that are mature or older (Britt & Johnston 2008), of which very few are ancient .

The conventional perception of tree architecture has been based on a particular aesthetic, principally modelled on early growth phases and drawing upon a restricted morphological vocabulary. This model takes little account of trees in their late life-stages and is therefore deficient in life-span morphology. The result is biologically simplistic, over-emphasising the virtues of bilateral symmetry and equipoise (e.g. crown balance). The influence of commercial silviculture, which places primary value on the tree as a crop, adds to the model (and its limitations) by determining the character of the objectivised tree as one that is free of decay and of morphological 'defects'.

In recent times, considerable technical advances have improved the speed and efficiency of tree pruning and crown access. This has been accompanied by the development of national and international arboricultural standards, which have tended to reinforce the utilitarian paradigm by placing emphasis upon pruning for safety and visual amenity. This paradigm leaves little room for the complexity of the tree in its ancient state.

The greatest proportion of corporate arboricultural expenditure is allocated to municipal and state budgets for urban trees and street tree management. As a consequence, over recent decades, arboricultural research and tree care investment have generally been directed towards improved understanding of the growth and management of trees in the urban environment. Minimal resources have been devoted to the study of trees in their ancient phase, and their ecosystem relationships; perhaps this is not surprising, given that the majority of ancient trees are found in non-urban landscapes.

2.1.2. The paradigm of the ancient tree

Overall, research in arboriculture, as opposed to agriculture, forestry and horticulture, has been somewhat restricted and weighted towards *in vitro* study and the study of nursery stock, and trees in their early developmental stages. Evidence from such studies cannot always be applied reliably to trees in older age classes and extrapolations present difficulties, as in older age classes there is greater physiological and morphological complexity with, for example, higher levels of branch autonomy and increasing independence of functional units (see Fig. 2, also Lonsdale 2013b).

Apart from a few exceptions (e.g. Watson 2004; Cermak & Nadezhdina 2010) there is little arboricultural study of fully mature trees, let alone ancient trees. Below-ground studies of such trees are exceptionally rare. The exponential flowering of the tree's biological and microbiological complexity that occurs in the post-mature state (see Fig. 1), which includes both the ancient tree *and* its ancient soil, imposes extreme challenges on our current levels of knowledge, and our understanding of how to frame practicable studies into what may be considered the tree-root-soil system as an entity, akin to a 'superorganism' (an organism of co-evolved organisms (Buchen 2010) analogous to coral reefs and the ecosystem of the human gut (Molloy 2006) (see later section on soil as superorganism).

Understanding the exceptional, long-lived potential of many species of trees and the increasing complexity that accompanies longevity suggests the need for a theoretical model and a management approach capable of embracing the entire lifespan of the tree not only as an individual organism, but also as an ecosystem. In this sense, the paradigm of the ancient tree provides the basis for conservation arboriculture in contrast to one founded on use-value and short-term disposability.

2.1.3. Ancient trees, ancient soils

Appreciation of the 'ancient tree paradigm' requires an understanding of the reciprocal natural processes that occur between the tree and its surrounding soil. When young, a tree is an introduction into the soil environment. At this stage the soil and tree are two different constituencies. If we then consider the ancient tree, having grown throughout its life embedded in a living soil system, the tree and the soil have evolved together into an inseparable, married entity. The ancient tree, which has stood 'sentinel' over its rooted territory, eventually harbours what we might consider to be *ancient soil*. Such soils are rich in host-space and the length of time over which they have developed is sufficiently long for there to be a continuity of habitat capable of high biological diversity. Despite the importance of such habitats, there is relatively little detailed knowledge of the below-ground ecology and the assemblages of micro-organisms associated with ancient rooted soils.

Through the impetus of conservation arboriculture, it has become clear that management of veteran trees can no longer be relegated exclusively to above-ground considerations. Instead, a broader view is called for, whereby root- and soil-system management is integral to the care of ancient trees and their successors. Such involvement requires an understanding of the likely extent of the mycorrhizosphere and other components of the tree's soil ecosystem, both spatially and biologically. Land-use changes and their effects upon the functioning and health of the rooting environment are also key considerations.

2.1.4. The development of conservation arboriculture

Conservation arboriculture aims to foster tree longevity for ecosystem benefits in both natural and man-made landscapes. By observing ancient trees we are able to study in retrospect the mystery of their biology, as inter-connected organisms that have survived over long lifespans, functioning within ecosystems. Ancient trees have typically been subject to climate changes, and other stressful or damaging impacts, and yet have experienced renewal processes and rejuvenation – a storyline that enhances arboriculture. The ancient trees that have survived for centuries with massive hollowing must have evolved survival strategies to endure, to adapt to and even capitalise on decay. Our interpretation of these processes is challenged when attempting to forecast tree response to damage that we induce through pruning.

Experience at various sites in Britain has demonstrated that old trees are prone to decline following rapid change, including from unduly severe pruning interventions. A fundamental guiding principle of conservation management of old trees is that interventions should be assessed carefully, with management operations implemented in such a way as to minimise impacts. This is now typically achieved by applying gradual doses that are phased over a long period of time and the approach has proved a step-change in veteran tree management, with far-reaching implications for the development of arboriculture.

The transition phase from the mature to ancient state, observed as crown retrenchment, has prompted the development of a technique referred to as '*retrenchment pruning*'. The pruning is thought to induce a reciprocal root system retrenchment response that influences water and hormonal relations in the tree. The technique is used to address physiological decline, drought stress management and biomechanical risk of failure. The procedure involves attention to the tree's rejuvenescence system and is used now in the treatment, not only of old trees, but also of important mature trees. Retrenchment pruning has been taught as a specialist technique in the UK over recent decades and has been adopted since 2010 within the British Standards for tree work (BSI 2010).

While empirical case studies support the hypothesis that the reciprocal dynamics between crown and root systems can be influenced by directed pruning techniques, further research is required to evaluate and understand the processes involved.

2.1.5. Tree safety management – what is reasonable and what is safe?

Professionals concerned with assessing risk are subject to both rational and emotional (affective) influences (Slovic 2000). Arborists (as 'risk-entrepreneurs'[1]) are not immune from such influences (Bennett 2010)'.

Studies indicate that the annual risk of harm posed by trees in general is 'extremely low' and that such risks are considered by the public to be normal everyday concerns (HSE 2007; NTSG 2009). Good practice therefore needs to consider the *real risks* posed by trees rather than the *perceived risks*, and to assess and manage these in a reasonable, balanced and proportionate way (NTSG 2011; ISA 2013).

Without a rational appreciation of the *real* risks, arborists are vulnerable to risk-aversion and in the absence of strong professional leadership for proportionate and balanced risk management, due to a fear of litigation there is a tendency to practise 'defensive arboriculture' (Fay 2007), which promotes unreasonably high levels of management intervention. Such

[1] A risk-entrepreneur is one who, in some form or other, gains their livelihood from assessing or otherwise contributing to the management of risks and who may influence societal expectations and standards by consciously or otherwise affecting the perception of risk (Haythornthwaite 2008).

practice potentially threatens important trees, including ancient and other veteran trees (Ball & Watt 2013). Twentieth-century arboriculture operated largely under the influence of a model of the idealised tree, leading to deviations from the norm being considered as 'defects' that compromise safety . This is particularly true of the hollowing and decay which until relatively recently were considered predominantly antagonistic to tree health, strength and longevity (Davis, Fay & Mynors 2000).

Clearly, the ancient tree does not conform to the solid, decay-free paradigm. While being decayed and long-living, it does not normally pose a high public risk. Emphasis on defects leads to taking action in response weighted to *hazards* (those features that might cause harm), rather than assessing and responding to *risk*s (the likelihood of harm occurring). The hazard-led approach falls short when dealing with trees in general, and ancient trees in particular.

While recent developments in tree hazard assessment and management rely on improved understanding of principles of tree biology (Lonsdale 1999; Rust 2016), innovations in tree statics (Wessolly & Erb 2014) and in biomechanics (Mattheck, Bethge & Weber 2015), the fundamentals of reasonable tree-safety management require sound appreciation of risk philosophy (Ball 2007) and risk assessment (Ellison 2005; ISA 2013).

2.1.6. The ageing process: a morpho-physiological model of the life stages of a tree

The life cycle of a tree is conventionally considered to be a linear progression *from seed to senescence* – passing through developmental stages, from the *juvenile,* through the *mature stage,* culminating in *death*. However, a linear view does not fully account for the subtleties of the complex and dynamic nature of ageing in trees. Apart from the very early stages of seedling growth, the morphological phases that characterise the ageing process can apply to the whole tree or parts of the tree and can refer to architectural units in the roots, trunk and crown. In essence, younger stages can be found to recur at different times throughout the life of an individual tree (Fig. 1).

These morpho-physiological stages in the ageing process are characterised by specific patterns of growth, influenced by hydrology, hormonal interactions, tropisms and evolved attributes of the species. A range of growth patterns have been identified and recorded which describe a standardised model that can be used to identify life stages consistent with the changing morphology of temperate woody plants (Halle 2004).

The lifespan approach set out in this book applies a ten-stage model of ontogenetic tree development based on the paradigm formulated by Raimbault (1995). By reference to such a model it is possible to identify anomalies in the sequence for diagnostic purposes. In this book we characterise the ageing process in three broad categories of developmental *phases* – namely *Young* (Stages 1 to 4); *Mature* (Stages 5 to 7) and *Ancient* (Stages 8 - 10). These phases are particularly relevant to Chapters 3.1, 3.2, and 3.3 respectively.

The young, maturing phase

The management of young trees is concerned with their *maturing* states. Fig. 2 illustrates how, over the course of the maturing phase, energy is expended primarily in optimising leaf volume, canopy surface area and trunk vertical exploration, at the expense of stem girth. This occurs under the influence of hydrology and the organisational influence of apical dominance. The root system initially retains a relatively simple, barely branched form under the influence of the tap root, which progressively ramifies as the developing crown evolves, forming a rudimentary tiered structure. Towards the end of Stage 4, the influence of apical dominance in the crown is beginning to wane, with increasing ramification and complexity in the branch and twig-structure. In the transition to the early mature stage (Stage 5), signs of branch autonomy arise, along with early-stage natural self-pruning, principally of sublaterals growing on the undersides of branches.

The transition between developmental phases is a function of the inherent hierarchy that determines the orders and arrangements that impose organisation and interaction between architectural units of a trunk and crown. These units are simpler and less complex in the young phase (Stages 1-4) and become increasingly complex *and colonial* (i.e. the tree operates as a colony of individuals) in the mature and later ageing stages (Stages 5 onwards).

The mature phase

During the middle, mature phase of the ageing process, the crown becomes increasingly rounded. It gradually loses its former peripheral vitality. Growth above the axes of the branches is accentuated, while growth on the underside is inhibited. Self-pruning on the lower and inner parts of the crown occurs under the influence of 'umbrella' light-restricting effects of the outer periphery of the canopy. Branch autonomy and inter-branch competition become more pronounced under the influence of hormone and carbohydrate-partitioning systems.

While these processes take place above ground, the root system becomes increasingly tiered and woody, supporting a framework of secondary and tertiary radiating and sinker roots that exploit different levels of soil space. Larger diameter root components ramify into smaller-dimension and eventually fine roots, that support the crown's photosynthetic requirements. Over these middle-age stages, dieback of the tap root and of some other original components of the root system initiates the progression of below-ground decay into the base of the trunk. Root-architecture is influenced by crown behaviour, resource allocation and water relations. In the mature phase, crown hydrology functions through 'self-managed' shedding and replenishment of small and peripheral parts, by cladoptosis (Rust & Roloff 2004; Rust *et al.* 2004; Roloff 2016), as well as other processes that are dynamically adaptive and also paralleled in the root system. Taking the tree as whole, levels of redundancy, changes in morphology and architectural organisation in both root and crown systems reciprocate and converge.

The ancient phase

As trees transition from full maturity to the ancient phase, they enter the first of a potential sequence of three ancient stages - the early-ancient stage (Fig. 2, Stage 8). Root, crown and stem parts are subject to local zones of degeneration and mortality, accompanied - in favourable circumstances - by rejuvenation and replacement growth. Towards the end of Stage 9, hormonal and water relations impose conditions that bring about *natural root and crown retrenchment*.

From the early-to mid-ancient stages (Stages 8 and 9), pulses of local outer root-decline and inner root-renewal occur as replacement second, third and fourth orders develop closer to the trunk, and ramify, extend and explore. Adventitious roots develop from buttresses and main laterals, and mycorrhizal community associations are reallocated. Wood-decomposing fungal colonisation of the root system and lower trunk becomes more pronounced, with decay affecting the inner core of heartwood[2] or ripewood[3]. Hollowing of larger-diameter branches and occasional dieback and breakout occur naturally.

Dieback and foliar decline associated with natural age-related crown retrenchment have commonly been interpreted as diagnostic indicators of a decline-trajectory leading from maturity through senescence to death. However, the implications of plant and tree senescence have been more deeply explored in recent years and evidence indicates that age-related apparent decline reflects a highly complex condition: one that signifies a state which may have negative *or* positive outcomes. As such, this may be subject to misinterpretation, particularly when trees are observed over the short term range of a human lifespan (Thomas 2013).

As part of natural crown retrenchment, a reduction in crown height (See Figs. 70a and 70b on page 116) results in decreased translocation distances for photosynthates, water and nutrients, as a result of which physiological efficiency is improved in the functions of a rescaled 'permanent' ancient crown. The waning and redundancy of the former outer-crown signifies this transition ('centripetal mortality'). Foliar capacity increases in the re-formed ancient crown as newly stimulated dormant and adventitious buds grow from the trunk and main branches (these have been also referred to as 'a second chance' or 'life insurance system').

Management interventions based on observation of natural crown retrenchment in the transition to the early ancient stage (Stage 8) can be practically applied to check decline processes and enhance tree longevity. Such treatments can be applied in the interests of reducing physiological decline trends in all life stages.

---

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

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

In the mid-and late-ancient Stages 9 and 10 (Figs. 70a and 70b), contraction of the root system conserves water and energy. Basal hollowing proceeds up the trunk and becomes increasingly pronounced. In the mid-ancient stage, annual rings generally become discontinuous and in the mid-and late-ancient phases *reiterative growth* exerts a strong influence on the organisation and hierarchy of influence between architectural components (Raimbault 1995; Hallé 1999).

In Stage 10, the tree *may* enter a phase of terminal, senescent decline. However, senescence may also be counter-acted through *rejuvenescence*, a process whereby the age-clock is 'reversed' (Fortanier & Jonkers 1976; Del Tredici 2000). The longevity of the tree depends primarily on the effectiveness of the emerging cambial vascular columns and their connectivity to the root system. Stage 10 is frequently characterised by the development of a complex arrangement of independent and inter-dependent mini-trees (developmentally equivalent to stages 3 to 5) within the body of the parent. These have the capacity to carry the genetic memory of the parent tree, and progress through some or all stages of the developmental cycle.

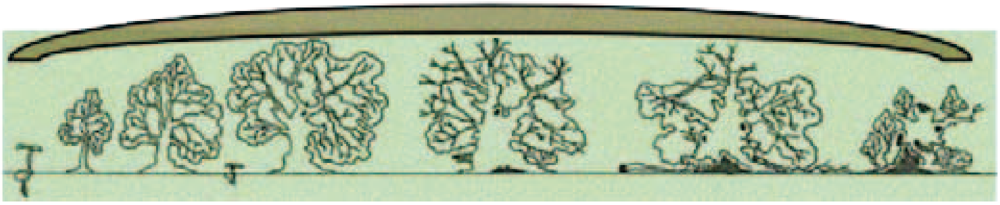
2.1.7. Transition dynamics of ageing

We draw attention to three important *transition states* in the ageing processes:

- a first one, leading from the developmental into the mature phase
- a second one, occurring as the tree passes from the mature to the ancient phase
- a third one, occurring as the tree in the ancient phase transitions *from senescence to rejuvenescenc*e – or passes into full decline

The first transition state between morpho-physiological Stages 4 and 5 occurs when the tree shifts from being a unitary organism with an apically-dominant, hierarchical organisation to being a more complicated arrangement of competing architectural units. This also marks the initiation of a crown with colonial properties, where different components replicate earlier developmental stages and exert a local influence on subordinate branching. As units become increasingly autonomous, they progressively compete for resources. By Stage 6, the tendency for branch autonomy starts to become pronounced, and growth patterns are established that will later support the development of further individuation within the trunk.

The second transition state occurs when the tree is at its peak maturity (Stage 7) and enters a physiological tipping point. There is an amplification of background morpho-physiological processes, which are built during maturity and now lead to increased organisational complexity. This is accompanied by increased influence of fungal activity and diversity, and the generation of saproxylic communities. Enhanced ecosystem values are also amplified (Fig. 1). The transition phase is triggered at the end of Stage 7, when the root system's capacity to continue to support crown extension is first depleted, and then exhausted. This constrains the crown's productive capacity and vitality of parts is reduced about the crown's outer reaches. The tree is set for the recession of the upper 'mature transitional crown' in favour of a lower, reduced-scale 'permanent crown'.



A B C D E F G

YOUNG PHASE	FULL TO LATE MATURE PHASE	ANCIENT PHASE		
MORPHO-PHYSIOLOGICAL EQUIVALENT STAGES (Raimbault, 1995)				
1–4	5–7	8	9	10
Seed to Early **Mature** **Developmental/ Sexual Maturity**	**Full – Late Mature** **Expansion/ Consolidation**	**Early Ancient** **Rejuvenation/Decline**	**Mid Ancient** **Rejuvenation/Decline**	**Late Ancient** **Rejuvenation/End of Life**
A–C	**C–D**	**D–E**	**E–F**	**F–G**
Current Annual Increment (CAI) increases in volume. Width of rings rises in early years, then reduces and becomes fairly constant.	CAI general trend: CAI tends to constant volume and reducing ring width.	CAI general trend: CAI starts decreasing in volume and ring width. CAI local trend: with successful crown retrenchment CAI may increase in local sectors of the main trunk and around developing functional, cambial columns.	CAI general trends: CAI continues to decrease in volume and ring width. Rings become discontinuous in circumference. CAI local trends: In conditions favourable to juvenescence, CAI resurgence continues about parts of the main trunk, including developing individual trunk columns, particularly where connected to vigorous reiterative growth.	CAI general trened: CAI reduction continues to mortality. Counter trend: CAI may stabilise with minimal sustainable volume and ring width. In favourable conditions where rejuvenescence is underway, CAI resurgence continues, including about developing individual functional columns, particularly where connected to vigorous reiterative growth.
Low habitat high vitality. Minimal disfunctional tissue.	Growth to peak crown size, fungal colonisation, onset of natural limb loss, increase in dysfunctional conductive tissue, fungal activity from below ground initiates base inner trunk core decay.	Onset of crown retrenchment; contraction of live crown, increased lower crown vegetative growth, increased fungal activity, inner trunk and large branch saproxylic habitat, coalescence of decay columns, formation of cambial (functional) columns.	Advanced retrenchment & decline in live crown size & CAI, internal dieback from peripheral shading branch, branch breakage & epicormic response, heart / ripewood decay & hollowing, increased insect, bird & lichen colonisation, increase in reiterative growth about crown and trunk, peak saproxylic activity.	Reduced vitality, saproxylic habitat, fungal activity and colonisers transitional towards decomposition and recycling communities, increased root decay & nutrient recycling. Tree may die or rejuvenate vegetatively (phoenix growth).

Fig. 1: Morpho-physiological stages

The third transition strategy state, while to some extent underlying all age phases, becomes increasingly significant for ancient-tree longevity during senescence (Stages 8-10). Rejuvenescence functions through vegetative biological mechanisms that operate as a counterflow to (and within) the stream of senescence (Thomas 2013). Senescence in trees might therefore be thought of as an elastic condition that may persist for decades or hundreds of years. While senescence may progress to terminal decline, it also may undergo a transition under the influence and the stimulation of rejuvenescence, and go on to repeat earlier stages of the life cycle.

The vegetative capacity for rejuvenation is inherent in the survival strategies that trees have evolved. It functions through embryonic (generative) tissues on the shoot and root meristems, and in dormant buds and the cambium. This power is retained throughout the lifespan, including in the ancient phase, and confers a capacity for longevity and self-replication (at a topophysical or whole-tree level).

As trees pass through the ageing process, the characterisation of damage and decay becomes more complex, reflected in dynamic morpho-physiological processes and anatomical expression of functional units within the trunk.

Conceptually, time-extended wound responses represent vegetative strategies that can lead to the tree being 'reborn'. In the ancient phase, vegetative survival strategies promote rejuvenescence through adventitious root and shoot development within decaying branches and the hollowing trunk. When able to grow through the internal decay-substrate and reach the soil, these can then sustain the parent, in favourable circumstances developing a 'phoenix' successor to the parent tree (Fay 2002). The formation of functional cambial vascular columns within the trunk's sapwood ('vegetative individuation') connects sectors of the crown to components of the root system, thus paving the way for total independence of these emerging, functional units from the parent (Lonsdale 2013b). Over the period that a young clonal tree remains attached to the parent, there is a reciprocal physiological exchange along with a contribution to stability. Over time, as the balance of structural strength and vitality shifts from the parent to the young component, the potential for total separation increases and the independence of the vegetative offspring is favoured.

2.1.8. Lifespan management – the young tree

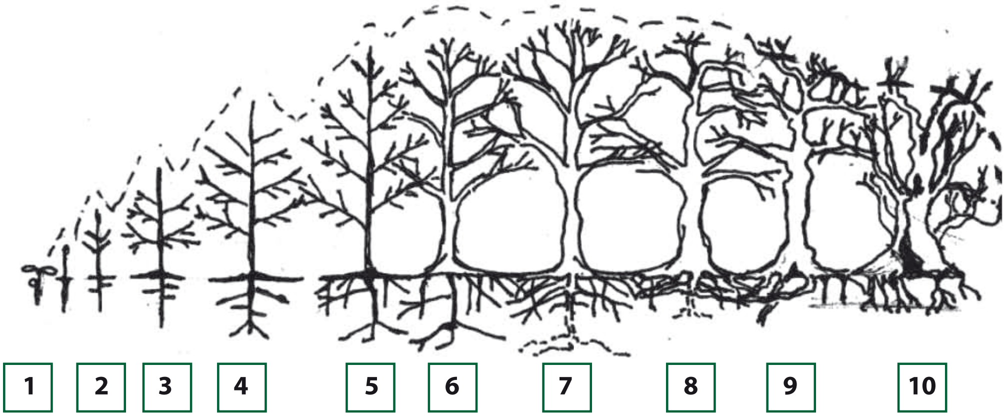
This book aims to bring lessons learnt from the study of ancient trees and good practice to the current generation of arboricultural managers. It is important that practitioners have the skills and knowledge when working with tree-time (the fourth dimension), so that they are able to plant and nurture trees with confidence in a viable future, on a trajectory towards ancientness.

Applying the perspective of the ancient tree, the future starts with the young tree. While young maturing trees might be considered physiologically and mechanically plastic, with

Young phase
Life Stages 1-4
Apical dominance

Mature phase
Life Stages 5-7
Lower units break free of apical dominance

Ancient phase
Life Stages 8-10
Early-, mid- & late-ancient
Crown/root retrenchment, decay, hollowing, functional columns and reiterative growth



Developmental Life Stages

Fig 2: Morpho-physiological stages of development: Developmental stages of (a) aerial & root systems through the ageing process corresponding to (b) trunk decay habitat (after Raimbault 1995; Lonsdale 1999; Fay 2002).

high potential to adapt to their surroundings, at this stage they are nonetheless relatively small unitary organisms, lacking the complexity and mass that confers heightened capacity to counteract the longer-term effects of damage, including from pruning. On the other hand, in these early stages, the potential for full wound occlusion is high. Sensitive and practical pruning methods in the young and mature phases, based on an understanding of the adaptability of the young tree, engender resilient patterns of structural development that will sustain the tree throughout the ageing process.

Unplanned reactive pruning of mature trees that have not been adequately subject to systematic and sympathetic early-stage training typically leads to expensive mature-crown shaping and remedial safety work, including reparative work to faulted and damaged large-diameter branches. In the context of the built environment, it is particularly important to minimise the costly requirement for mature tree intervention.

In Chapter 3.1 we discuss the Dutch young tree maintenance model (de Groot *et al.* 2016), which sets out to lay the foundation for a robust maturity with a high potential to deliver trees that are capable of attaining their ancient phase. The system takes account of the CODIT compartmentalisation model (Shigo & Marx 1977) and advocates methodical light pruning for the first 25 years of a tree's development. The system advises multiple-return visits, involving pruning that is limited to the removal of the minimum quantity of small-diameter material, necessary to achieve the shaping objective.

Despite its planned duration, the system is cost-effective in light of the considerably higher costs that would otherwise be involved further down the line from pruning requirements when mature.

The Dutch system claims high levels of success in reducing rates of young tree losses and minimising wasted planted stock and costs that would commonly otherwise be incurred in later stages of management. A foundation is provided by the 25-year pruning system to positively influence the dynamics of the tree population as a whole, and the potential for its long-term viability and ecological sustainability.

2.1.9. Lifespan management – lessons from the old tree

Trees have an evolved capacity for long-lived perennial growth, to the extent that individuals in some species have a theoretical potential for indefinite growth. Arborists and managers therefore need to understand the nature of these processes, if they are to safeguard against unnecessary loss of ancient trees, or mature trees that will become their successors.

The evolution of modern arboriculture is bound together with concerns about the significance of decay in trees. Dead wood was once considered to harbour pathogenic organisms (the 'sugar stick' theory), including fungi which were seen to be harmful to tree health as well as posing a threat to tree stability from the effects of decay. By this logic, the removal of dead wood was considered beneficial to the tree, given that it limited the food source for fungi and thus helped control against fungal 'infection' and decay (Shigo 1989).

Shigo and Marx (1977) in their theory of *Compartmentalisation of Decay in Trees* proposed a model to explain how trees react to and survive wounding through an evolved, orderly response. As the theory became more widely recognised in the arboricultural literature, it became popularised as the 'CODIT model'. Relatively recently, ideas about the relationships between trees and decay fungi have been subject to further consideration, which has led to a revised understanding of CODIT, that now places the emphasis on *damage* rather than decay (Dujesiefken *et al.* 2005; Dujesiefken & Liese 2015).

Both the original and revised CODIT concepts consider the tree to be intrinsically predisposed to compartmentalisation, functioning through pre-existing three-dimensional anatomical spatial arrangements within wood structure, together with physiological changes that take place after wounding.

In the ancient phase, with the advance of the ageing process, the tree becomes more complex and progressively endowed with an increasing range of compartmenting options and expressions. In addition to the CODIT wound responses, there are high levels of autonomy between branch units. The crown no longer functions as a singularity containing subsidiary architectural components – rather, semi-autonomous crown units begin to function more like an organised colony. In addition, reiterative growths become compartmented within the larger parent branches, with vascular traces making their way from branch to trunk. These become vertically compartmented, as columns within the sapwood, eventually to be integrated with elements of the root system.

Most old trees have been subject to hundreds of years of storm damage, and some also to historic pruning. *Non-damage induced decay* is also manifest and extensive, having risen up from the roots and expanded internally. Ancient tree survival thus points to evolved responses, whereby wounding and decay are *accommodated* to the extent that the well-being of the entire organism is not threatened – and overall longevity is supported and even enhanced.

Conservation management requires an understanding of both the CODIT model and of non-damage-induced decay processes. However, taking account of the shortcomings of the pathogen-host concept, tree management in general needs to consider the influence of time (the crucial *fourth dimension*) that shapes the ancient tree; and to adopt techniques sufficiently subtle to work with the 'age clock', and the tree's rejuvenation capacity. An appropriate model for understanding relationships between wounding, damage and decay through the lens of the ancient tree is one that imagines the repertoire of compartmenting strategies available to the tree as it becomes increasingly flexible, dynamic and apparent as the tree ages.

Conventional arboriculture (influenced by landscape design and silviculture) has held the view that trees when fully mature have reached their optimised amenity potential and their peak value. Therefore by the end of the mature stage, the conventional view has been that the tree represents a diminishing asset (with reducing crown size and increasing dead wood and decay, along with allied risk concerns).

We now know that, contrary to previously held models of the ageing process, senescence is not the inevitable forerunner of terminal deterioration. With increased study, particularly of long-lived ancient trees, we have come to understand that this sequence of events is not a programmed inevitability, and may be reversible.

Senescence may be misinterpreted, and whole-tree decline attributed wrongly. With appropriate training, understanding and technical knowledge, we can manage restoration by working with the tree's rejuvenation systems. This knowledge contributes to the management of younger age classes. Consideration of a tree as an ecosystem, integral with its roots and soil, opens up a vast and exciting challenge for conservation management and the study of above-and below-ground functions as an integrated system.

Consideration of the ancient tree paradigm opens a door of perception into the late ancient stage *and beyond*. Encounters with trees of such an age are not the norm, and any understanding of them requires a different quality of knowledge of tree statics, biomechanics, energy allocation, and hydraulic processes. It is precisely for these reasons that our sense of the wonder of trees is enhanced. Time and complexity amplify the underlying influences of colonising species and decay processes that function through physiology and have their outward expression in tree morphology.

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2.2. Biology and survival strategies of trees

Prof. Dirk Dujesiefken

As a result of their longevity and size, trees are unique organisms on this planet. They grow in a huge range of locales, some extreme, like the humid tropics, the semi-arid deserts and the cool, mountainous zones. Certain species can grow to more than 100 m in height, and some individuals may live for several thousand years. They must withstand, not only the extremes of weather and injuries resulting from broken branches and lightning strikes, but also environmental and age-related changes. In order to survive under these ecologically varied conditions, trees have developed various strategies to deal with damage and to persist.

The main wound reactions happen in the wood to compartmentalise damage, and in the cambium to create a callus and later wound wood to grow over the wound surface to encapsulate the damage. Another survival strategy is the development of new shoots or axes, or even entire branching systems, by way of reiterations (see Chapter 2.1).

2.2.1 The wound reactions of trees

Reacting tissue

When serious damage is caused by injury (e.g. pruning cuts or broken roots), cells near the wound site react initially through physiological processes such as the activation and transport of growth substances, the formation of resins, and the synthesis of phenolic substances, as well as through cell conversion (Dujesiefken & Liese 2015). The dying woody tissue changes colour (undergoes discolouration), with decay in the wood being a later consequence.

Following wounding, it is only living cells (i.e., those of the phloem, cambium and sapwood) that are able to mount an active defence. However, these tissues have various options when it comes to their reactions. For example, the inner bark can convert parenchyma cells and develop wound periderm as a new boundary tissue. The cambium forms completely new tissue when an injury has been sustained (i.e. the callus and the barrier zone, a protective boundary formed by the still-living cambium near the wound), whereas the conversion and formation of new cells is no longer possible in the wood. Instead, damaged tissue can only be sealed off from healthy tissue through the closure of water-conducting elements and the formation of embedded substances (Fig. 3–5). As a result, the tissue abandoned by the tree is separated from the healthy, functional wood, which leads to compartmentalisation. This boundary layer is also called the reaction zone.

Fig. 3: Wound reactions after pruning: the cambium forms completely new tissue at the wound edges, the decay in the wood is compartmentalised by the boundary layer.

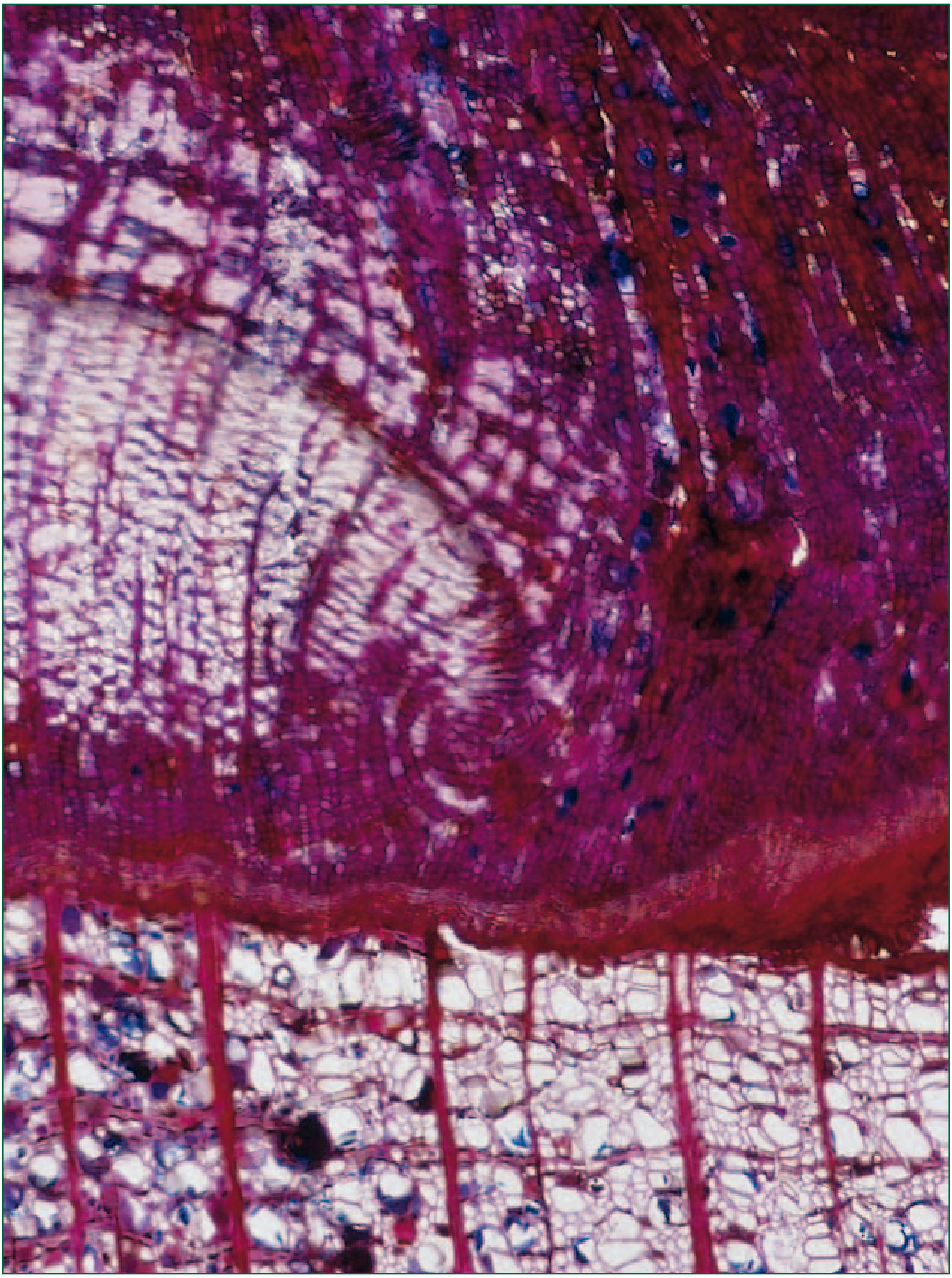


Fig. 4: The wound wood with new woody tissue in the middle, new bark at the outside and a barrier zone between the new and the old woody tissue (at the bottom of the picture).

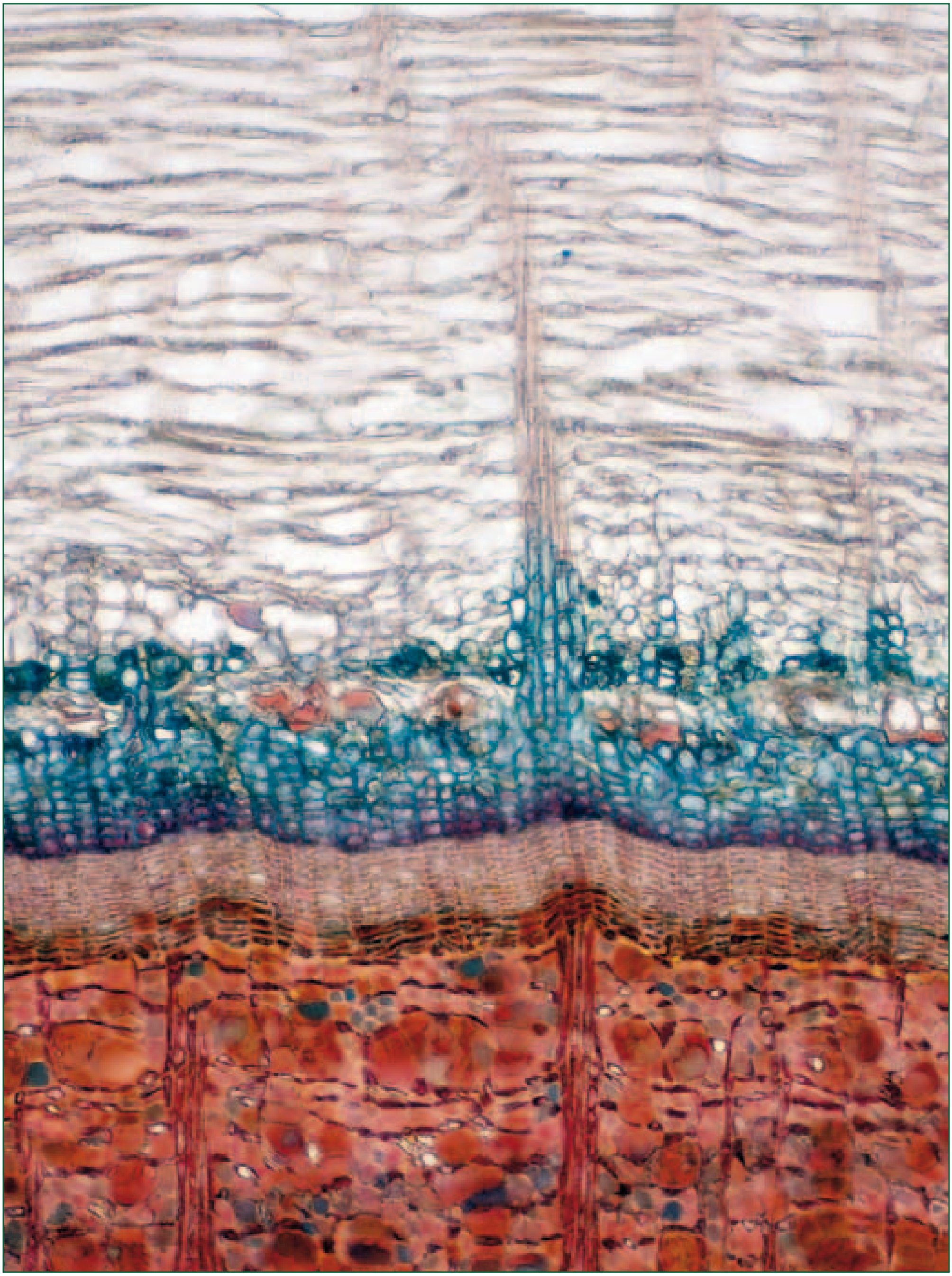


Fig. 5: After injury, the cambium near the wound forms new tissue: the barrier zone (blue stained cells), it consists exclusively of living parenchyma cells.

Effective and weak compartmentalisers

Practical experience has long dictated that extensive rot often develops following injury. This is true of poplars and willows, for example, but less so of beeches and pedunculate oaks (Lonsdale 1999; Gilman 2012). However, observations to the contrary can also be made, depending on location, wound size, age and vitality. Researchers have in fact inflicted injuries on trees (such as branch wounds and drill holes) on purpose, in order to compare the responses of different species and genera. The results of this research combine with practical experience to show that tree genera can be divided into two main groups (Dujesiefken & Liese 2015) where compartmentalising ability is concerned:

> The weak compartmentalisers include ash, birch, horse chestnut, poplar and willow, fruit trees, spruce, and tsuga, among others. Of these, birch, poplar and willow react relatively weakly to injury, as do fruit trees, while ash compartmentalises slightly better by comparison.
>
> The effective compartmentalisers in turn include beech, elm, hawthorn, gleditsia, hornbeam, sycamore, pedunculate oak, pine, and yew, among others.

Any injury extending into the wood, e.g. as a result of pruning cuts or the severing of roots, also affects the cambium. This cell layer (secondary meristem) is capable of division, and then forms a new, anatomically modified tissue, both at and near the immediate margin of the wound. A callus first develops at the wound margin, followed by the formation of wound wood. Near to the wound, the cambium forms a new layer of living cells: the barrier zone. This zone is able to react very effectively to spreading microorganisms.

Wound reactions and wound treatment

A special form of wound reaction on the part of cambial cells is the surface callus. If cells capable of division are still present on the wood surface following the loss of bark (e.g. after collision damage), these can form a layer of callus tissue on the wound surface (Fig. 6). New tissue forms from these callus cells, and has a periderm towards the outside and new cambium towards the inside. All deciduous trees are able to form a surface callus. If no surface callus can be formed, the wood dies off from the wound surface and is subject to colonisation by microorganisms. However, if a surface callus is formed, underlying wood remains alive (Fig. 8; Dujesiefken *et al.* 2001; Stobbe *et al.* 2002b; Gaiser *et al.* 2006).

A precondition for the formation of a surface callus is that the thin-walled, divisible cells on the wound surface do not dry out. If the bark is loosened from the wood body but not removed, it will protect the divisible cells and provide for the formation of a new cell layer on the wood surface. This formation of a surface callus in deciduous trees can be stimulated if the wound surface is protected against desiccation and UV light with opaque plastic wrap (Fig. 7). Many years of study have shown that film coverage results in a significantly more effective wound reaction, compared with non-treatment or coating with a wound dressing.

Fig. 6: In the middle of the wound surface a partial surface callus has grown.

Fig. 7: The formation of a surface callus can be stimulated by protecting the wound against desiccation and UV-light with opaque plastic wrap.

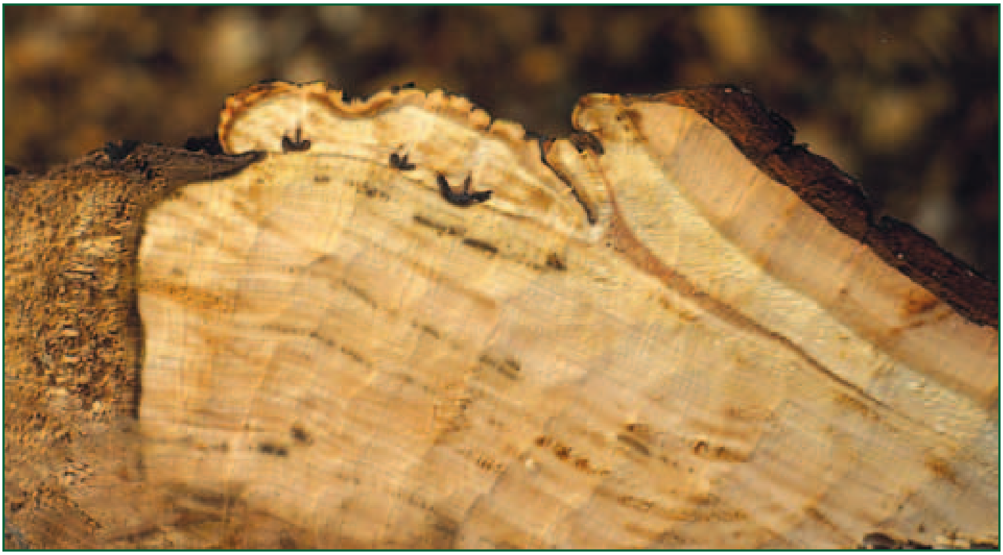


Fig. 8: Below the surface callus the wood remains alive and therefore, discoloration and decay do not occur.

Above all, the treatment greatly stimulates the formation of surface callus on fresh damage to the trunk (e.g. collisions or logging damage) (Dujesiefken *et al.* 2001; Stobbe *et al.* 2002a; Gaiser *et al.* 2006). Whether a surface callus can form, and how strong it will be, depends on how many reaction-capable cells are still present on the wound surface, and how soon after the accident the cover is applied.

In the days of tree surgery, disinfectants and wood preservatives were used on trees to sterilize the wood surface and protect the wood. However, these materials damaged the cambium and led to significantly weaker compartmentalisation in the wood. They were never tested and approved for the treatment of wounds on trees and nowadays their use is prohibited (Dujesiefken & Liese 2015).

Since the mid-1980s, studies into wound dressings have been carried out at several institutions. These entailed treatment of artificially-induced wounds on roadside, park, and forest trees (Dujesiefken 1995). Infection-free wounds were not found to be achieved by using any of the compounds. Despite the coating, wood was colonised and decomposed in the wound area by wood-decaying fungi. Even the addition of fungicide fails to offer sustained protection against infection. However, the compounds examined do in fact have a somewhat positive effect on wound reaction, given that more limited cambial necroses and stronger callusing are apparent to varying degrees on treated wounds, depending on the season and the tree species. However, among the wound dressings examined, the differences in effectiveness are seen to be relatively minor.

Timing and wound reactions

The effectiveness of wound reactions in trees (especially of deciduous species) is also affected by the time of year that an injury occurs. Wound reactions are determined by living cells whose physiological activity depends largely on the storage of reserve substances and the ability of the tree to mobilise them. The type, quantity, and mobility of these reserve substances are subject to pronounced seasonal variation, as determined by the tree's growth cycle and the temperature (Dujesiefken & Liese 2015). Consequently, injuries to wood are compartmentalised within a smaller area during the growing season than in winter. Aside from the time of year, the weather and temperature during winter are also important. Wound reactions following an injury that occurs either before or during a period of frost tend to be less effective than those following injuries sustained during milder weather, even within the same month.

Cambium reactions also vary over the course of the year. The cambium dries out after injury in winter, forming so-called cambial necroses. Depending on the tree species and weather during winter, larger necroses form during dormancy, often during the months of October and November. Only small cambial necroses form during the growing season, the smallest of all resulting from injuries that occur in spring. From a biological perspective, large cambial necroses are disadvantageous to a tree. The size of the wound is increased because of the cambial dieback at its edge, meaning that complete callusing (and thus encapsulation of the damage) requires more time than with small cambial necroses. Studies into the growth of wound wood in the same kinds of trees, but during different seasons, have shown that spring wounds form stronger wound wood than injuries sustained during other seasons.

Summary with practical implications

The consequence for arboriculture can be summarised as follows:

Trees are injured when tree work, such as pruning is performed. Wound reactions limit any negative effects. Therefore, strong wound wood growth, small necroses and effective compartmentalisation in the wood should be the goals of proper arboricultural practice. These reactions can be influenced by the timing of pruning activity and the size of the pruning wood.

During the winter months, a tree's reaction is significantly weaker than in other seasons. The most effective reactions related to compartmentalisation in the wood, the spread of cambial necroses and the strength of callusing occur during the growing season. The smallest necroses form after injuries sustained during March and April, the strongest growth of new tissue at the wound edges between April and June, and the most effective compartmentalisation in the wood between May and August, depending on the parameters. The period between September and February is unfavourable from all points of view.

On the basis of such findings, the recommendation included in the German "ZTV-Baumpflege" guidelines (2006) was: "To minimise possible tissue damage and to facilitate compartmentalisation and rapid callus growth, pruning should be completed during vegetative periods."

A significant impact on tree care is exerted by the size of crown pruning wounds, coupled with a tree's ability to compartmentalise (whether weakly or effectively, see p. 33). As crowns are pruned, the only branches cut should be those of diameters up to 5 cm in weakly compartmentalising species, and those of up to 10 cm in effectively compartmentalising species. These findings are now included in the regulations for tree care in Germany (ZTV-Baumpflege 2006).

2.2.2 The CODIT Principle

A model of wound reactions in trees was first developed by Shigo and Marx (1977). This model, dubbed CODIT, provided arborists with a simplified description of the structure of trees and their reaction to decay. Trees were depicted as chambered organisms that form compartments in the event of injury or decay (Shigo 1986). CODIT initially stood for Compartmentalization of Decay in Trees. This model was primarily concerned with the spread of decay in trees following injury, as well as the compartmentalisation it triggers. In the CODIT model, the boundary layers of the compartments are referred to as walls. Depending on their orientation in the wood, the boundary layers are distinguished as walls 1, 2, and 3. Wall 4 is the barrier zone.

This model was highly controversial and sparked heated debate in the expert community. A key aspect of the discussion was the insight that, immediately after injury, trees react to air infiltration rather than rot (Tyree & Sperry 1988; Liese & Dujesiefken 1989; Rayner 1993; Dujesiefken *et al.* 1997). It is air embolism in the water-conducting elements that represent the significant change in the immediate aftermath of injury, and it constitutes a functional disorder. Only thereafter does the tree begin to compartmentalise. Consequently, CODIT is now understood to mean Compartmentalisation of Damage in Trees. The concept of damage is broader and includes all changes after injury, from air embolism and functional disorder through to decay.

Nowadays, CODIT is viewed in a more comprehensive way, describing the compartmentalisation of damage in trees, as well as the growth of wound wood, in chronological sequence. Wound reactions can take very different forms in individual cases. Nevertheless, the same principle is always recognisable: compartmentalisation and encapsulation of damage take place in sequential phases (Fig. 9 and 10; Dujesiefken & Liese 2015). Regardless of the type of injury, the discoloured wood is colonised by microorganisms from the wound surface (Shigo 1975; Schwarze & Fink 1997; Kowol *et al.* 2001). These organisms grow rapidly up to the boundary limit in the discoloured wood. In small, and therefore less problematic injuries, their spread is usually stopped effectively by the boundary layer. If the wound is sealed further by woundwood, the rot becomes encapsulated. Once this happens, the fungus dies off (Balder 2007; Kehr 2007). However, there are also wounds that are not compartmentalised within a limited space and closed by wound wood. Wound size is of particular importance in this context. Additional factors include the tree species, wound type, the time of year of the injury, and wound treatment. The type of cut as crowns are pruned is also critical. Arboricultural practice must therefore demonstrate an acute awareness of the principles underpinning wound reactions in trees, as well as the various factors influencing them.

Trees react consecutively after injury. The **CODIT Principle** divides the reactions of the tree into four sequential (though in part also concurrent) phases:

Phase 1: Entry of air

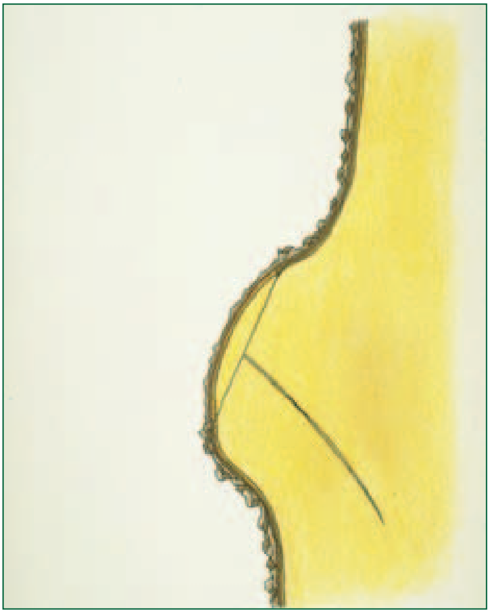
The tissue near the wound dies off in consequence.
As a reaction:
- the bark forms a wound periderm
- the cambium forms a callus at the wound margin and a barrier zone near the wound
- the wood forms a boundary layer for compartmentalisation, and discolouration of wood near the wound begins.

Phase 2: Entry of microorganisms

- into the bark up to the wound periderm
- into the wood up to the boundary layer

For subsequent closure of the wound:
- a wound wood is formed from the original callus.

Fig. 9: The CODIT Principle illustrated on a small wound, resp. on an effectively compartmentalising tree:



Phase 1: Entry of air

Phase 2: Entry of organisms
(e.g. wood-decaying fungi)

Phase 3: Spread of organisms

Phase 4: Encapsulation of organisms –
the wood-decaying fungi die as a result.

Fig. 10: The CODIT Principle illustrated on a large wound, resp. on a weakly compartmentalising tree:

Phase 1: Entry of air

Phase 2: Entry of organisms
(e.g. wood-decaying fungi)

Phase 3: Spread of organisms

Phase 4: The wound remains in Phase 3. The damage is not encapsulated and the organisms in the wood remain active, therefore representing at least a latent threat to the tree.

Phase 3: Spread of microorganisms (e.g. wood-decaying fungi)

The boundary layer can be breached, especially in older woody tissue.
As a reaction:

- the wood then forms a new boundary layer
- more accessory substances (e.g. phenols) are formed in the wood as a means of defence if the organisms reach the barrier zone
- simultaneously, the wound wood keeps growing to cover the wound.

Phase 4: Encapsulation of the damage colonised by microorganisms

The wound wood closes the wound and encapsulates the damage causing the wood-decay fungi to die off. Further spread of the organisms is not possible.

Encapsulation following injury is a tree's survival strategy

If a wound cannot be encapsulated, harmful organisms remain active and represent at least a latent threat to the tree.

If Phase 4 is not achieved (e.g. with large wounds, or in weakened or slow-growing trees), the wound remains in Phase 3 and the wood-decay fungi can continue to spread. The same applies when encapsulated damage in trees is reopened, via cracks in the trunk, or where woodpeckers are active. Resupplied with oxygen as a result of the new damage, the previously encapsulated wound can be re-infected by wood-decay fungi, which can grow through the boundary layer. Extensive damage may then be sustained by the entire tree. If wounds are small, or damage overgrown quickly, Phase 3 will be short or may not even occur at all (Dujesiefken & Liese 2015).

In terms of applied tree care, the above means that major interventions in the crown, trunk and roots must be avoided. Depending on the tree species, any treatment must be such that the tree can still encapsulate its injuries.

2.2.3 Reiterations and trees' "second chances"

Reiterations are the development of new shoots or axes, and even entire branching systems. They are the processes by which a tree duplicates its architecture, giving birth to new copies of its architectural unit. This is therefore a special sort of branching that produces "new trees" on the original tree that have branches, flowers and fruits. Older reiterations can also have a stem.

Reiterations can reflect:

1. changes in the environment or the surroundings (adaptive reiterations)
2. sudden damage (in traumatic reiterations), probably as a result of major injuries following a storm or the failure of limbs because of decay.

Traumatic reiterations are developed mostly by dormant buds or adventitious (newly formed) buds. Years of reiterations result in the development of smaller sub-crowns on a tree, which look like small trees growing in the crown of the mother tree (Pfisterer 1999; Roloff 2001, 2016).

Young trees can react very effectively to changes in the environment or the surroundings, with new shoots in the crown, at the stem and from the root system. But the ability to build reiterations changes over the years. Older trees have different survival strategies. Trees of some species can build many new shoots even when they are old, while others cease to be able to activate dormant or adventitious buds. These trees will have no second chance and die in parts or totally immediately following any negative environmental influences. Thus far this inability has tended to go unnoticed, but is important for a better understanding of older trees sustaining damage, and their recovery. In what follows, the differences in reiterations of older trees are described and divided into types. Such knowledge of the **different types of reiteration in older trees** is important for the planning of proper tree care.

However, trees of most species are also able to react to drastic changes when they are old. Some trees are able to survive felling, or following the death of the crown or stem because of disease (as with elms with Dutch Elm Disease). The tree is gone, but the organism can stay alive thanks to new sprouts from the stub and the root system (Type A, Fig. 11–14). After years, the former tree (e. g. alder, elm, lime) can look like a bush; or in the case of Ailanthus, white poplar, or robinia, a dense little “forest” can arise from the root system.

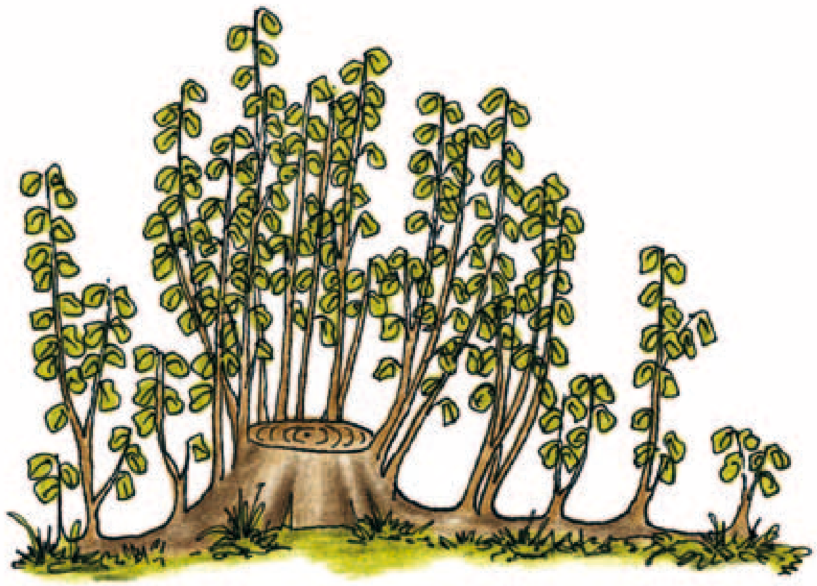


Fig. 11: Species of Type A are able to survive felling, or following the death of the crown or stem. After years, the former tree can look like a bush.

Fig. 12: The former tree is dead, but this lime tree can stay alive thanks to new shoots from the stub and looks now like a bush.

Fig. 13: This poplar tree isn't dead after felling and has developed new sprouts on the stub (Type A).

Fig. 14: New shoots from the root system after felling is also a type of a survival strategie of some species, like elm, poplar or robinia (Type A).

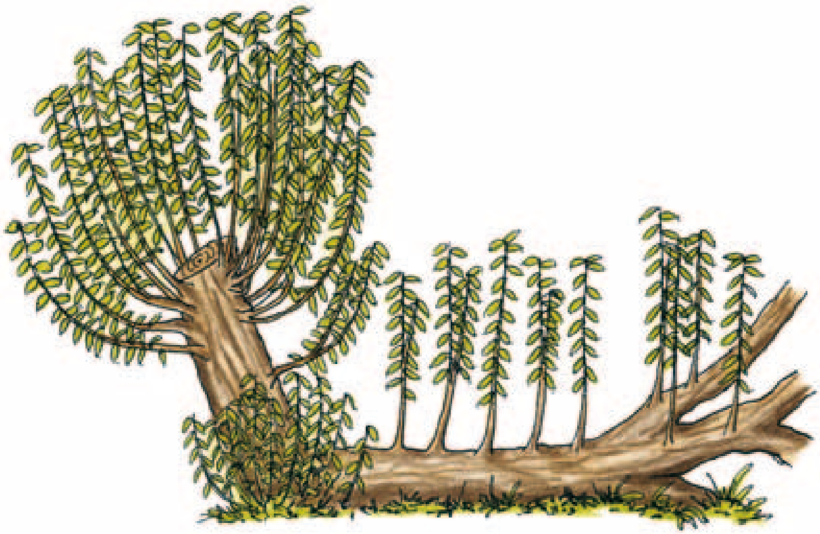


Fig. 15: Type B are the most accomplished survivors with a capacity for reiterations in the crown, at the stem base, from the roots, and also from broken parts like stems or branches. Typical species in the group are alder, limes, and willows.

The most accomplished survivors are trees with a capacity for reiterations in the crown, at the stem base, from the roots, and also from broken parts like stems or branches (**Type B**). Typical species in this group are alders, willows and also limes (Fig. 15). These trees enjoy, not only a second chance, but also third or perhaps fourth chances, to survive.

It is long known from practical experience that trees of some species lose their ability to react by reiteration following sudden damage. Trees of some species cease to be able to activate dormant or adventitious buds e. g. at the stem or from the stub or the root system. Only the crown can react in different ways (**Type C**). In trees that have sustained major damage or are in decline, the upper crowns fall apart through the dieback of branches. When trees have recovered and there are new shoots in the lower parts of the crown, a secondary crown will arise (**Type C1**; Fig. 16). The tree can survive on the basis of this small crown. Typical examples of this type are provided by oaks, but also robinia and elm trees. Another kind of sudden damage done to crowns is that due to major injuries caused by storms, topping, or the failure of parts of the crown resulting from decay in a previously vital tree. What is involved here is the loss of parts of a crown or the whole crown. In this case a tree will react mainly in the upper crown with new shoots near wounds (**Type C2**; Fig. 17). Typically, plane trees, limes, poplars and willows are also able to react with many reiterations that result in the development of sub-crowns on the tree (Fig. 18–19). When vital trees are damaged mechanically because of decay, a storm, or unprofessional use of a chainsaw, the new shoots compensate for the loss in the crown. After some years a tree may reattain the same height as it had before the damage.

Fig. 16: Reaction of an older tree following drastic changes. In this example the tree recovers with new shots in the lower part of the crown (secondary crown, Type C1).

Fig. 17: Recovering after a sudden damage done to the crown to major injuries caused by storms, failure of parts of the crown, or topping in a previously vital tree. The reiteration results in the development of sub-crowns on the tree (Type C2). Typical species are limes, plane trees, poplars, and willows.

Fig. 18: Two willow trees, the right one was broken and later on topped.

Fig. 19: Only some years later the topped trees reacted mainly in the upper crown with new shoots and developed sub-crowns on the tree (Type C2).

Type D are trees with (nearly) no second chance. Older birches and maple trees are an example of this type of tree (Fig. 20 and 21). Soil compaction or severe root loss can lead to the sudden death of older maple trees. Birches furnish another example. Following a summer drought, no regeneration will happen. Even vital birches can die immediately after this kind of stress. These trees die after sudden damage and have no capacity to take advantage of a second chance.

If trees are to be cared for properly, knowledge of wound reactions, the CODIT Principle, reiterations and possibilities for a second chance at growth is important, and must be integrated into the management concept for mature and ancient trees.

Fig. 20: Sudden death of a maple tree after a severe stress. This tree cannot react by reiteration and has therefore no second chance.

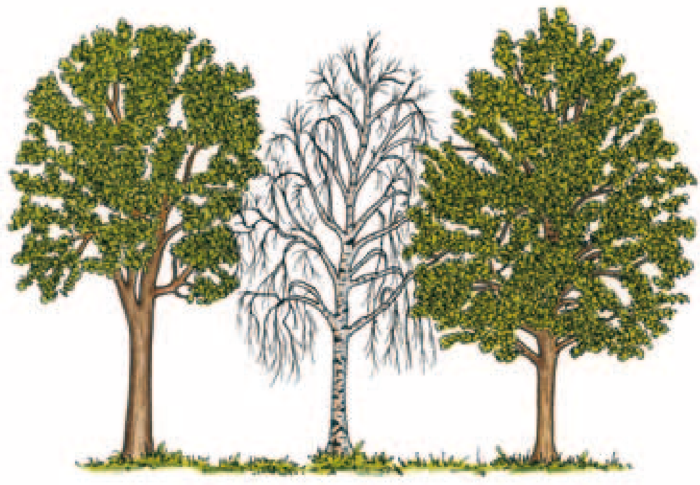


Fig. 21: Type D are species with (nearly) no second chance, like birches or maple trees. Also vital trees will die immediately following any negative environmental influences. They have no or very little chance to recover by reiteration.

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III

Tree care throughout their lifespan

3.1. Maintaining young trees

Jan-Willem de Groot

3.1.1. Introduction

Arboriculture has developed into a professional branch in which thousands of tree-specialists earn their daily living. Within this branch one of the major activities is the pruning of trees in the urban environment. In spite of the generally recognized necessity of pruning trees, there is evidence that the existing tree-management practice in this respect fails in many cases. A considerable share of all trees go into decline before they are able to accomplish their function, or suffer from serious damage and problems because pruning in the youth phase was either not performed, or performed too late or improperly.

We remain insufficiently aware that good maintenance of a tree in its younger years is of decisive importance to the long-term development of trees in urban areas. At a time when the general importance of trees in an urban setting is gaining more and more attention, it seems that, due to a lack of knowledge and vision, tree maintenance is failing far too often. Fewer and fewer trees in urban areas are able to grow to maturity and perform the function for which they were originally planted. At the same time, we know that the benefits of trees only increase as they grow and mature.

Fortunately, there are also examples in which the maintenance of young trees proves effective. In these situations it is typical for maintenance to have been based around a plan with a pre-determined pruning cycle. The success stories show us that (in general) the first 25 years in the life of a young tree are decisive if a good structure is to develop and failure is to be prevented. To accomplish the good structure referred to it is necessary that a tree be pruned in an effective, systematic way. This means the use of a methodical system of pruning, which starts at an early tree-age is continued with at regular intervals, and is performed by professionals. Besides a good structure, pruning can also be necessary with respect to the site conditions determined by the environment. A general example is the necessity in an urban environment for a certain branch-free space providing sufficient clearance for traffic to be generated. Pruning should start at an early phase of tree development, as it is in this way that heavy interventions at a later stage, with all the subsequent negative consequences for the tree, can be avoided.

The incorporation of trees (or groups of trees) into a previously established pruning-cycle guarantees the achievement of goals as originally defined. Structural pruning of young trees thus constitutes one of the most sustainable contributions to the lifespan of an urban tree. The financial consequences of methodical (systematic) maintenance on a short-interval basis are also relatively favourable, all the more so when these costs are set against those incurred by failures of trees and consequent need for them to be replaced.

3.1.2. A short history of the pruning of trees in the Netherlands

In the Dutch capital Amsterdam, avenue trees have been planted for more than four hundred years now. It is well-known that trees were subject to systematic planting as early as in the 17th century. Along canals, trees were planted at fixed equal distance of two "Amsterdam roedes" (or 7.36 m) apart. In 1567 the famous historian Lodovico Guicciardini called Amsterdam the Venice of the North (Guicciardini 1567). But it was the trees that distinguished the two cities from each other. Tomaso Contarini, the Ambassador of Venice, wrote in 1610: "It's the common practice of the people of Amsterdam to plant big trees in straight rows along the canal sides which greatly contributes to the beauty of this city" (Bakker 1995).

Trees by canals quickly became a standard ingredient of the urban plan. Alongside aesthetic reasons, there were also other reasons for planting trees. An important one was the stabilization of the canal bank, thanks to the action of tree roots. Others entailed the use of elm wood in the manufacture of furniture, clogs and construction, as well as the use of elm leaves as forage. Trees were also planted increasingly on squares and market places. The aim, according to a city regulation, was to make the city comfortable for people and animals. Cattle need shade, and the decay of market goods could be prevented thanks to cooling delivered by tree crowns. As early as in the 17th century "Trees for a healthy city" was an actual item.

Fig. 22: "View down a Dutch Canal" by Jan van der Heyden (1637-1712) ca. 1670.
(source: http://www.nga.gov/content/ngaweb/Collection/art-object-page.135093.html)

Maintenance of trees was also practised in the 17th century. The painting of Jan van der Heyden, "View down a Dutch Canal" shows us an everyday image of the Herengracht about 1670. The imposing monumental buildings were decorated by likewise imposing trees. That these trees were cared for is obvious: the crowns of the limes alongside the canal are raised several meters. The purpose was probably diverse: providing clearance for traffic and space for markets underneath the crowns of the trees, as well as enabling the loading and unloading of ships.

Now, four hundred years later, Amsterdam has more than 350,000 trees. The tradition of planting trees in almost every street has continued. As is true in many other cities, the growing space for trees is under pressure. Tree maintenance requires more attention than ever before. The need for sufficient branch-free space underneath tree crowns is increasing. Liability of the tree-owner in the case of damage caused by trees plays an important role. Trees in the urban environment are supposed to be safe. Dead and otherwise dangerous branches must be removed from the crown in time, if accusations of negligence are to be avoided. There is growing awareness that proper tree maintenance could reduce premature failure. Trees, whether in streets or parks, or on squares and alongside avenues, would all profit from good and, most importantly, systematic maintenance.

Over the last decades different companies and organizations have taken care of the further development of pruning plans, but also developed long-term tree management plans. These are plans that take account of the location in which the tree is planted, the life stage it

Fig. 23: View down a Dutch canal (Herengracht) in Amsterdam anno 2016.

has reached and ultimate size when full grown. One of the key developers of such management plans in The Netherlands was Pius Floris, who developed a model for pruning trees within a predetermined schedule. His vision always has been that the development of sound and functional trees starts in the early life stages of a tree.

The foundation of a safe, well-functioning tree is laid in planned, periodic pruning during the younger years.

3.1.3. Principles of young-tree care

Objectives of pruning young trees

The location of a tree goes a long way to determining how it will develop, both below and above ground. As a result of competition, trees in a forest stand usually develop a slender form, while their free-standing counterparts normally show more horizontal growth than growth in height. The conditions dictated by the environment and society in a city play an important role in determining possibilities for development among street trees. Trees' natural behaviour is to keep their branches low and grow out horizontally. For a free standing tree in a park this will work, but when it comes to street trees, there is usually a need for a specified branch-free space providing clearance for traffic and meeting safety requirements.

Fig. 24: A young Elm in Amsterdam (The Netherlands). In a location like this, trees must have branch-free space to provide clearance for traffic and meet safety criteria.

Fig. 25: To provide clearance for traffic and meet safety criteria, these young Oak trees in the city of Arnhem (The Netherlands) are pruned on a regular basis.

The main objective of pruning is to create safe trees with a good structure. In an urban environment, stability of a tree structure is an especially important matter from the safety point of view. Besides safety risks there is the fact that breakage of a tree (or part thereof) can mean its loss. One of the major objectives of pruning young trees is therefore to create sound trees of sustainable structure. Besides this, there are certain circumstances in which trees must meet boundary conditions set by the environment. In this respect a distinction can be drawn between trees allowed to develop freely and those that may not. In the former situations, most common in forests and parks, trees can be allowed to keep their branches low, and grow out horizontally. In contrast, urban areas usually need branch-free space in order to provide clearance for traffic and meet safety criteria.

Tree structure – develop safe trees

In areas of human presence trees are expected to be as safe as possible. Even though the presence of trees is beneficial for the wider community, there are many countries in which tree owners are legally responsible for the damage caused by their tree. While a tree that can be regarded as 100% safe does not exist, we know that those of poor structure are more likely to fail than trees with good structure. In considering a tree, we can draw a distinction between habitus and structure. The habitus relates to the outer shape of a tree, which is the

Fig. 26: Trees like this, of poor structure, face a high risk of failure.

Fig. 27: When a tree of poor structure fails, it is very often the loss of the whole tree that we are faced with.

result of the exterior volume of its crown and trunk. The structure is in turn the specific arrangement of trunk and branches. Trees with identical habitus may have different structures. Besides the fact that trees of poor structure can give rise to a safety hazard, breakage of a tree can result in failure and total loss. In those situations all the investment that has gone into planting and maintaining a tree is lost at a stroke.

Since we know that structural defects may lead to tree failure, or even the loss of an entire tree, we need to recognise the key threats responsible for poor tree structure, and therefore greater risk of tree-failure. Recognising features of young trees that might in the future compromise the safety of their surroundings might help in preventing flaws from developing further. The four most common threats faced are: co-dominant stems, included bark, unbalanced crowns, and large branches in the crown.

Co-dominant stems

Co-dominant stems are two or more stems originating from the same point on the tree that continue to be characterised by similar size as the tree grows older. This is to say that neither stem assumes dominance during the development of the tree, with the result that a V-shaped fork is formed. Stems of this kind are at greater risk of splitting off from the tree than are non-codominant stems. Research shows that the force required to pull off a branch increases where the diameter ratio of the branch-stem is lower. In other words: the smaller the branch, the stronger the connection between stem and branch (MacDaniels1932; Miller

Fig. 28: Removal of large branches in the temporary crown results in major pruning wounds that initiate decay in the trunk.

1950; Gilman 2003). Consequently, the optimal branch-trunk diameter ratio to be strived for is 0.65 or less. In such a situation it is no longer possible to speak of co-dominance. Thus trees with relatively thin branches have a lower risk of breaking off. Pruning techniques which lead to a better branch-trunk diameter ratio can reduce the development of codominant stems. Furthermore, the injuries caused by the splitting of codominant stems are more serious and are often followed by severe decay within the trunk. A relatively thin branch breaks off at the branch collar and can therefore be removed easily without permanent damage being done (Shigo 1985).

Fig. 29: Co-dominant stems with included bark. The poor structure of this tree will result in its loss.

The young stage of the life of a tree is based on strong apical dominance. However in the case of co-dominant stems the dominance of a single stem decreases and competition between stems becomes transparent. Our aim is thus to have a balanced tree, as opposed to the unbalanced one that co-dominance gives rise to.

Included bark

Included bark can develop between two stems, two branches, or between a stem and a branch, when the union is V-shaped. It is bark pinched in between the wood of the two parts and thus creating a weak union. It is weak because the bark inclusion prevents any physical connection between the two stems. Instead of overlapping wood creating a strong connection, the two stems push each other apart as they grow and a crack develops (Gilman,2003).

An unbalanced crown

An unbalanced crown occurs when one side of the tree crown is much heavier than the other, or when most of the crown weight is at the tips of branches. The latter is a product of lions-tailing or over-lifting, a poor pruning practice that removes all of the live foliage along the lower and interior parts of the main branches. This practice makes trees more susceptible to wind damage (Gilman 2003). Moreover, heavy pruning in the inner-crown encourages growth of epicormic shoots that often have weak connections to stems. In general, the consequence of crown-unbalance is a higher risk of branches breaking off.
There are circumstances in which an unbalanced crown does not denote an unhealthy tree, and development mechanisms can be deployed to ensure adaptation and safe growth in the future. However, heavily unbalanced crowns can have serious implications for future development.

Large branches in the temporary crown

Urban trees are often limited in their natural development by a required minimal branch-free space for clearance. In the cases of trees for which clearance is needed, determinations of the minimal height of the branch-free trunk should be made, so it becomes clear which branches are to be removed. In this respect, we use the terms "temporary" and "permanent" crown. Pruning of the temporary branches should lead towards a branch-free trunk and a permanent crown.

In practice, pruners often neglect to remove the lower branches in the temporary crown. Too often such branches are only dealt with after they have already grown large, are sinking or have otherwise become an obstacle. Removal at this late stage results in major wounding that can initiate decay in the trunk, especially in species prone to this. Other problems ensuing are of a mechanical nature, for example entailing excessive end weight. Branches in the temporary crown are temporary, and will have to be removed in future anyway, if clearance

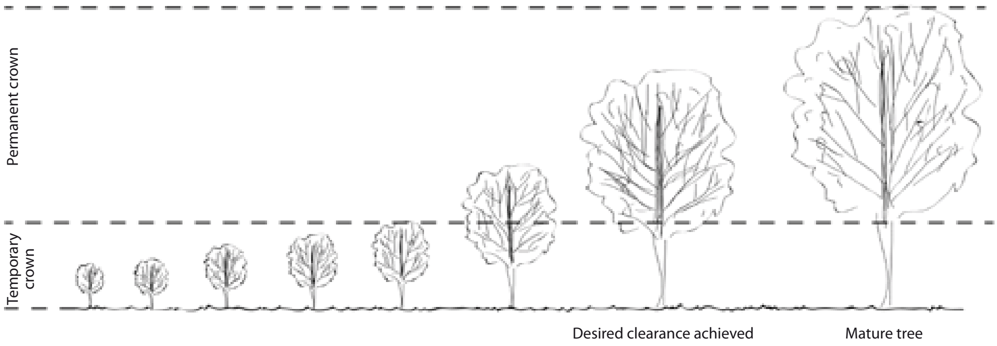

Fig. 30: The principle of the temporary and permanent crown.

Fig. 31: Large pruning wounds resulting from the late removal of branches from the temporary crown.

requirements are to be met. This leaves it most profitable for a tree to be pruned of branches that are still relatively small and will thus leave behind only small pruning wounds. During every single pruning treatment, it is a matter of principle that the largest branches are first to be removed.

Is clearance required?

To answer this question it is necessary to know if a tree is allowed to grow freely or if limits are set as regards the surroundings. In the case of a free-growing tree, branch development just above the ground is permitted, with no clearance required. However, natural development in street trees is often limited by the minimal branch-free space required to achieve clearance. Thus, before giving any thought to pruning, the pruner should have in mind a desired future image for a particular tree at a particular location. The determination regarding the necessity or non-necessity of clearance follows on from that.
Guidelines for minimum clearance depend on the location. In The Netherlands, the minimal required heights for clearance, as prescribed by the *Rijkswaterstaat*, are 2.5 m for foot and cycle paths, 4.2 m for all road and street traffic, and 4.6 m for (motor) highways.

Table 1: Minimum required heights, as distinguished by the ***Rijkswaterstaat*** in The Netherlands

Category	Minimal required heights
Foot- and cycle paths	2.5 m
Roads/streets for all traffic	4.2 m
Motorways and highways	4.6 m

Fig. 32: In this situation clearance for traffic should be minimum 4.2 m. The actual height of branch-free trunk is 5.0 m. This is to assure that the clearance of 4.2 m will be maintained also in the future with branches leaning down.

Once the desired final habitus has been determined for a given tree, the minimum height of branch-free trunk can next be envisaged, and branches slated for removal as necessary. At this point it becomes clear which part of the crown is permanent and which temporary.

There is a difference between clearance and a branch-free trunk. In general, the height of branch-free trunk should exceed the required clearance. As the latter is determined in practice, in relation to traffic, account needs to be taken of the growth habit of branches, and it is this that may increase the required minimum clear trunk-height. How far branches 'bend down' depends greatly on species, cultivar and growth habit; but clearance for traffic of 4.2 m will in many cases only be accomplished where there is a branch-free trunk height of 6 m.

German research shows that, when done too late, pruning to create a clear trunk will result in extensive wounding, with a higher risk of internal decay. Results further show that most in-rotting pruning wounds up the trunk are at heights 3.80-4.70 m above the ground. The research in question concluded that early pruning of thin branches could have prevented such problems from ever arising (Aepfelbach *et al*. 2008). This conclusion is in line with the knowledge and experience obtained where practice maintenance programmes for young trees have been pursued successfully.

Fig. 33: To accomplish clearance for traffic of 4.2 m, it will in many cases be necessary to achieve a clear trunk height of 6 metres.

3.1.4. Before pruning: a good start is half the work

"A good start is half the work" Is a Dutch saying that certainly applies to tree maintenance. The good start in question includes tree selection, delivery, site preparation, planting and aftercare, which are all essential to the good development of a young tree. Although this handbook focuses on tree care in the period after planting, this chapter will draw attention to a few aspects relating to tree acquisition and planting.

The acquisition of trees needs to be preceded by a determination regarding species. "The right tree in the right place" is a well-known one-liner, and the relevant factors include (future) site conditions (above- and below-ground); specific tree properties, such as growth form; final dimensions and susceptibility to disease; and defects in general.
Above-ground aspects are available space, function, and use of the environment and geographical position of the site. Below-ground aspects in turn relate to physical and chemical properties of the soil, space available for root development, the water regime, and the presence of cables and pipes. The well-thought-out selection of tree species can be followed by the actual process of acquisition of trees.

Selection

It is not possible to buy trees from a brochure or via a website. Rather, the selection process has to be carried out at a nursery. Individually selected trees will need to be marked to make sure that the desired specimens are the ones delivered. Although selecting trees in this way can prove expensive, the advantages are obvious. The general requirements for avenue and park trees will need to be addressed, but it is also important that poor branch attachments be focused on. If a defect of this kind is already present in a young tree, it is probable that a genetically linked phenomenon continuing through the entire life of the tree is involved.

Order

An order placed in respect of trees should include at least the numbers and sizes of required trees, as well as information on the number of times trees have been transplanted at the nursery. This number is important if subsequent rooting of the tree is to be achieved successfully. The preparation of root-balls will entail a considerable amount (up to 90%) of root remaining at the nursery. Transplantation at regular intervals ensures the generation of a compact root system with many fine roots. Tree size is represented by stem girth at a height of 100 cm, as measured from the root collar. Smaller sizes are often used in planting stock (6-8 cm) for forest and landscape (8-10 cm, 10-12 cm), while bigger trees (16-18 cm, 18-20 cm) are planted in urban areas. In the context of prestigious urban development projects and parks an even greater size is favoured.

Table 2: Stem girth categories versus number of times transplanted (Stadsbomen Vademecum 2B, IPC Groene Ruimte, Arnhem 2011)

Stem girth (cm)	Minimum times transplanted
6-8	1x
8-10	1x
10-12	1x
12-14	2x
14-16	2x
16-18	3x
18-20	3x
20-25	3x
25-30	4x
30-35	4x
35-40	4x

Calling for an order, loading, and transport

There are considerable risks inherent in the process between the time ordered trees are called for and actually planting. The time interval between a tree being dug up and re-planted should be minimized to reduce the risk of desiccation. However, the loading and unloading of trees also involves other risks such as damaging to the stem. Careful lifting and loading should minimize stem-damage. Air currents and wind can dry out roots as trees are being transported, unless efforts to prevent this are made. Trees have already lost so many roots at this stage that every root in the root ball is essential if a good start is to be made following planting.

Delivery and Approval

It is critical for each delivery to be checked out by an experienced expert. In the case of trees that have been selected at the nursery, correct tree species should be checked for, along with any damage incurred during transport. If trees were not selected in advance, they should gain the approval of an expert at the planting site, in line with general quality standards.

Fig. 34: Planting too deep often leads to the loss of newly-planted trees

The planting hole and planting

The digging of a planting hole would not seem to be a more difficult part of the tree–care process, but this is not in fact the case. If work at this stage is done incorrectly, the risk of a newly-planted tree not establishing well or even dying is great(er).
In the first place, a planting hole should always be dug in dry weather conditions. If soil being dug is wet, its structure will be destroyed in the course of the work. The width of the planting hole should be at least twice that of the root ball. The soil around the planting hole should be broken up to ensure incorporation of air and moisture in the right proportions.
Only once a tree has been placed carefully in the planting hole should the iron basket surrounding the root ball be removed. Since planting at too great a depth is one of the most common causes of death in young trees, it is very important to focus on how far below the surface the root ball is. In general, arborists agree that it is better to plant a tree in too superficial a position than to too deep. Best of all is to plant the tree at the same depth as it experienced when growing in the nursery.

3.1.5. Pruning young trees

The main objective as trees are pruned is minimised risk of tree failure, through the establishment, maintenance or recovery/reinstatement of good structure. A tree management plan entailing effective pruning practice is necessary, most favourably with pruning performed on a structural basis, in line with a cycle defined from the outset, beginning at an early age, and carried out by professional people. Bad tree structure ranks high on the list of main causes of tree failure, but this can be forestalled by good pruning practice representing one of the most effective contributions to tree sustainability. The overall concept entails:

1. General rules to be followed as young trees are pruned.
2. Analysis of the tree prior to pruning
3. Pruning!

General rules for the pruning of young trees

The concept as regards the pruning of young trees is based on four basic rules:

1. Do not remove more than 20% of the foliage in the course of any one pruning.
2. Remove branches of largest diameter first.
3. Do not remove neighbour-, opposite-, or above/under branches.
4. Only remove whole branches.

The first rule is to not exceed the 20% foliage limit during any one pruning

Pruning often but on a small scale is a key feature and principle underpinning this pruning concept. In any one pruning the 20% tree-foliage limit should not be exceeded. This rule can be followed in determining how many branches can be removed at one go. Relatively small pruning cuts ensure few large wounds inflicted, with nothing more than small gaps appearing in the crown. No reaction growth (e.g. via epicormic sprouts) is then initiated, unlike with heavy pruning.

In the case of young, healthy trees, the percentage limit may be increased to 25-30% in certain situations.

The second rule is to remove branches of largest diameters first.

Removal of the thickest branches during each pruning session ensures that branches in the temporary crown do not grow too large. This precludes large pruning wounds being made at a later time. The lowest scaffold branch of the permanent crown of street trees with a minimum branch-free space of 4.2 m is usually located 5 to 6 m off the ground. All lower branches should be removed in a timely manner, as the importance of preventing temporary branches from growing too large cannot be overstressed.

The third rule is not to remove neighbour-, opposite-, or above/under branches

These branches should not be removed at the same time, as to do so will disturb the transport structure of the tree too suddenly. Where the presence of a collar of clustered branches leaves the pruner with no choice, it is the largest or worst-attached branch that should be removed.

The fourth rule is, as a matter of principle, to remove whole branches only

The principle holds that only whole branches are removed, being cut off at the base, as close as possible to the tree. The objective reason is to ensure pruning of maximum efficiency. Branches in the temporary crown have to be removed anyhow, and it is cheaper to remove a branch in the course of a single pruning treatment. The exceptions in which it becomes necessary for part of a branch to be removed reflect the twin aims of reducing the growth of one branch while stimulating other. Where possible the branch involved will still be removed in its entirety during one of the subsequent pruning sessions.

Analyse the tree before pruning

Within the pruning-concept a number of steps are followed in the order shown in the table below. The four basic pruning rules as stated before need to be kept in mind as this is done. Analysis of the tree is essential before pruning starts. This requires a good picture of the structure of the tree of the kind best gained by observation from a distance. The questions to be asked then are:

1. Which branch is the dominant leader?
2. Are problem branches present?
3. Is clearance needed?

Which branch is the dominant leader?

A single, dominant leader is important for a strong tree structure. This leader has to be determined first (step 1), but this is not always easy to do. Where trees have more leader stems of the same diameter choose the one closest to the heart of the crown.

Are problem branches present?

The next step is to identify the problem branches, i.e. attachments with included bark, co-dominant stems, competitors of the dominant stem, suckers, and thick branches.

Is clearance needed?

The last question is to determine whether clearance is needed. This space depends on the tree species and location. In a newly-planted tree most of the crown is temporary, in that all the branches in it will disappear eventually. Many people fail to realise that branches stay at the same height during the growth of a tree. Those about to prune should always make sure to identify where the temporary crown ends and the permanent crown begins.

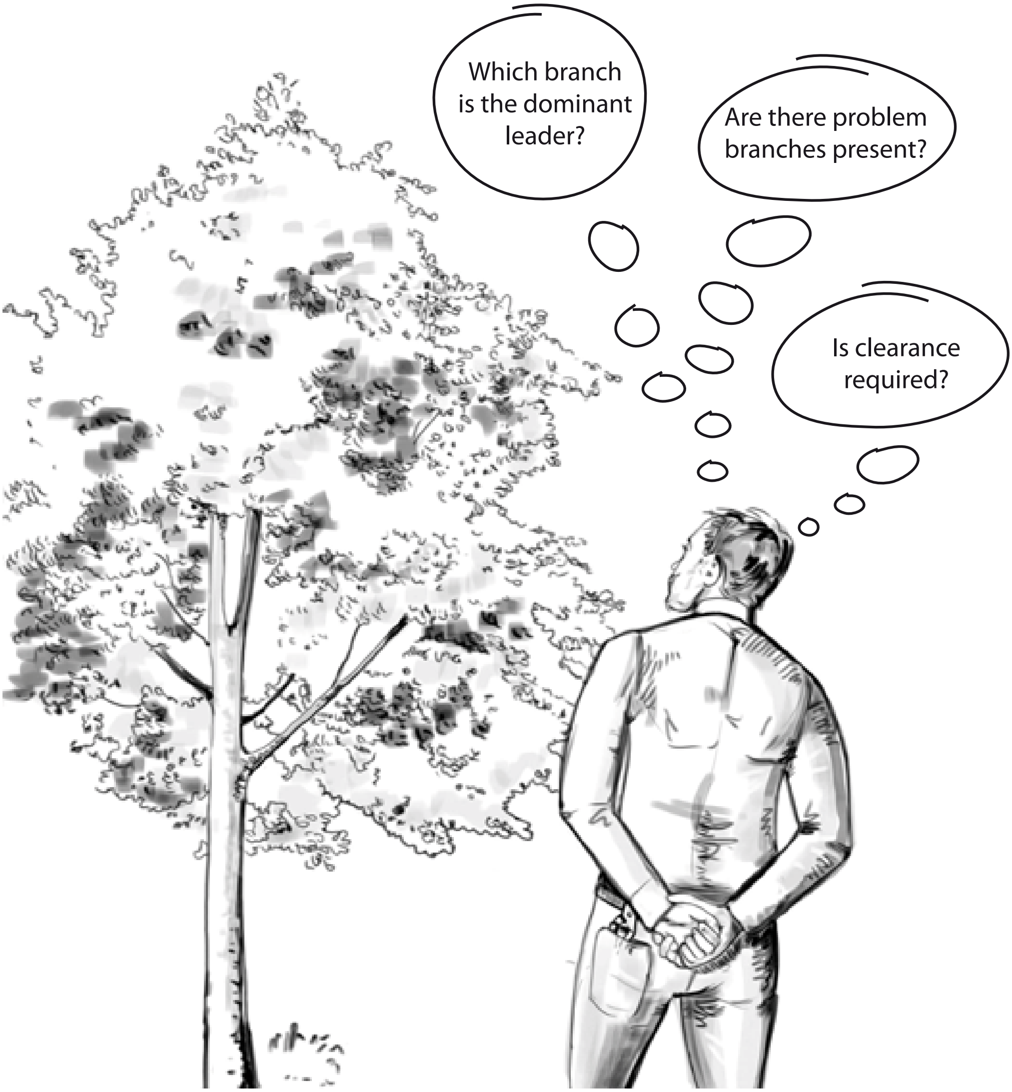

Fig. 35: Tree-structure analysis should be undertaken before any pruning works begin.

Prune

Keeping in mind the 4 basic pruning-rules, the pruner determines how many and which branches should be removed at the time.

1) Competitors of the central leader are removed as the first step.
2) Problem branches are removed or reduced as the second step.
3) Finally, lower branches in the required branch-free space are removed.

The pictures show examples of the preventive pruning of young trees.

Pruning tools

Trees in the youth phase can be pruned with minimal use of tools. In the first 15 years after planting in particular, a handsaw will suffice. Branches higher up the tree can be pruned from a short ladder or from a platform. Those using a ladder should take care not to damage the stem, e.g. by covering the highest step of the ladder with something soft, such as a piece of rubber or a towel. Greater care must be taken in spring, when bark is soft and the risk of damage is increased. A worker on a ladder of platform must or course respect safety regulations.

Fig. 36 a, b: Young tree before (left) and after (right) pruning

Fig. 37 a, b: Young tree before (left) and after (right) pruning

The shorter the distance between pruner and branch, the more likely that careful pruning will prove achievable. Correct assessment of branch attachment is of decisive importance if the pruning wound is to be correct. Those working with young trees will find a hand-saw much more suitable (than a chainsaw) for careful work at a slower pace. One wrong move with a chainsaw and the consequences for young trees can be profound. However, as young trees develop, the diameters of branches needing to be removed increase, to the point where the use of a chainsaw becomes inevitable. Even then, a ladder combined with a climbing rope and harness is preferable. In this way the pruning wounds can be minimised. Young trees are often pruned with a pole saw - a tool preferred to a ladder because the work involved is less labour-intensive. There are certain risks, however. From ground level it is hard to assess the right location of the cut, and especially the optimal pruning angle. Considerable experience and muscle power are both required, and experience indicates that both tiredness and laziness conspire to ensure that pruning wounds can be severe.

The use of motor pole saws poses an even greater threat to young trees, for which any mistake made can prove disastrous. Sawing at the correct angle is almost impossible, due to the weight of the saw, hence the active discouragement of the pruning of young trees using this tool.

3.1.6. The pruning plan

The pruning-plan for young trees specifies intervals between pruning treatments. Based on knowledge and experience, an interval of two to three years is applied. The average youth phase of a tree lasts 25 years, and in that period it is important that the pruning plan and intervals are adhered to. In any case, the frequency and length of interval should never be changed, with differentiation at most revolving around the amount of foliage removed with each pruning. Within the pruning concept we distinguish Phases A and B plus an optional extension.

First comes the period of 15 years following planting (phases A1-A7). Pruning frequency is once every two years during this time. The second period (A8-A10) extends to 25 years after planting. Here the frequency is once every third year. The aim is to use the timespan of approximately 25 years to put in place a fundamental tree structure and a functional tree which corresponds to the boundary conditions set by the immediate surroundings. Since trees do not develop in a linear way, this goal can be achieved sooner or later. For this reason the pruning plan for young trees can be extended for one or more pruning measurements. Tree maintenance does not stop once the youth period is over. The management must continue to retain the dominant leader, to prevent the development of problem branches, as well as parts of the tree capable of colliding with the surroundings.

Table 3: Pruning schedule

0	Year 1 - planting	Pre-phase
A-1	Year 3	"Phase I Pruning every second year"
A-2	Year 5	
A-3	Year 7	
A-4	Year 9	
A-5	Year 11	
A-6	Year 13	
A-7	Year 15	
A-8	Year 18	"Phase II Pruning every third year"
A-9	Year 21	
A-10	Year 24	
A-11	Year 27	Optional extension of pruning plan
A-12	Year 30	
A-13	Year 33	

Fig. 38: The result of the pruning concept at the end of phase B

Fig. 39: The ultimate goal is to create trees like these: of sufficient clearance and sound structure.

Table 4: This table shows a simplified example of a systematic young tree pruning plan, with predetermined, periodic pruning intervals. Young tree management starts at the moment of tree planting and continues in general for a period of 25 years. When necessary the pruning plan can be continued. For example in the case of slow growing trees. This table shows the pruning plan of 15 young trees. Based on the year of planting they are implemented into the pruning plan. In this example it means that in the year 2016 seven trees have to be pruned.

Species	Pruning already performed before 2016															
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Quercus robur																A-0
Quercus robur																A-0
Quercus robur										A-0		A-1		A-2		A-3
Quercus robur									A-0		A-1		A-2		A-3	
Quercus robur					A-0		A-1		A-2		A-3		A-4		A-5	
Quercus robur									A-0		A-1		A-2		A-3	
Quercus robur									A-0		A-1		A-2		A-3	
Fagus sylvatica	A-0		A-1		A-2		A-3		A-4		A-5		A-6		A-7	
Fagus sylvatica	A-0		A-1		A-2		A-3		A-4		A-5		A-6		A-7	
Quercus robur				A-0		A-1		A-2		A-3		A-4		A-5		A-6
Quercus robur				A-0		A-1		A-2		A-3		A-4		A-5		A-6
Quercus robur				A-0		A-1		A-2		A-3		A-4		A-5		A-6
Fagus sylvatica													A-0		A-1	
Fagus sylvatica													A-0		A-1	
Fagus sylvatica													A-0		A-1	

Pruning starting in 2016 according to pruning plan

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
	A-1		A-2		A-3		A-4		A-5		A-6		A-7			A-8			A-9			A-10		
	A-1		A-2		A-3		A-4		A-5		A-6		A-7			A-8			A-9			A-10		
	A-4		A-5		A-6		A-7			A-8			A-9			A-10								
A-4		A-5		A-6		A-7			A-8			A-9			A-10									
A-6		A-7			A-8			A-9			A-10													
A-4		A-5		A-6		A-7			A-8			A-9			A-10									
A-4		A-5		A-6		A-7			A-8			A-9			A-10									
	A-8			A-9			A-10																	
	A-8			A-9			A-10																	
	A-7			A-8			A-9			A-10														
	A-7			A-8			A-9			A-10														
	A-7			A-8			A-9			A-10														
A-2		A-3		A-4		A-5		A-6		A-7			A-8			A-9			A-10					
A-2		A-3		A-4		A-5		A-6		A-7			A-8			A-9			A-10					
A-2		A-3		A-4		A-5		A-6		A-7			A-8			A-9			A-10					

3.1.7 Financial benefits

A common argument against short time-intervals in the pruning-cycle concerns the high costs involved. The pruning concept for young trees and the required pruning frequencies have been developed to prevent damage caused by neglect or postponement of necessary pruning measures. Only when working according to a fixed plan with boundary conditions and a fixed interval between pruning treatments is it possible to develop young trees up to the age of 25 into functional units of good structure.

In The Netherlands the average total costs of pruning a young tree in the first 25 years amount to €212.50. This means €8.50 per tree per year on average. These numbers are calculated without inflation and price-corrections and based on the 2016 price level (table 5).

When compared with the costs arising from tree-failure, such as those involved in removal and the planting of a new tree, annual pruning costs are seen to be relatively low. Moreover, it is questionable whether a lower frequency of pruning reduces costs overall. What is obvious is that less-frequent pruning results in larger pruning wounds and a greater risk of trees being damaged.

Fig. 40: This beech tree with a large pruning wound and symptoms of internal decay in the temporary crown is analysed with a resistograph. Pruning at the right time could have prevented these problems. The total costs of one tree risk assessment like this, including a report, amount in general up to twice the overall costs of pruning a young tree during a period of 25 years!

For example, the assessment of a tree with large pruning wounds and symptoms of internal decay amount in general up to twice the overall costs of pruning a young tree during a period of 25 years.

Table 5: Average cost per tree per year over the first 25 years

Unit per day	
2 Treeworkers, including equipment	€ 800.00
Traffic services	€ 30.00
Disposal of pruning material	€ 20.00
	€ 850.00
Average number of trees per day per unit	40
Average costs per tree per pruning	€ 21.25
Number of prunings per tree in the first 25 years	10
Average total costs for pruning in the first 25 years	€ 212.50
Average cost per tree per year over the first 25 years	€ 8.50

3.1.8 Summary

Rules

1. Do not remove more than 20% of the foliage in the course of any one pruning.
2. Remove branches of largest diameter first.
3. Do not remove neighbour-, opposite-, or above/under branches.
4. Only remove whole branches.

Analyse

1. Which branch is the dominant leader?
2. Are problem branches present?
3. Is clearance needed?

1. **A** is the dominant leader
2. **B** is a competitor of the central leader
3. **C** is a co-dominant stem.
4. Clearance at this location should be 4.2 m

Prune

1. Remove the competitor of the central leader **B**
2. Remove the co-dominant stem **C**
3. Remove branch for clearance **D**

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3.2. Maintenance of Mature Trees

Prof. Dirk Dujesiefken

3.2.1 Introduction

Historically, trees were subject to maintenance in line with people's short-term desires, with less attention paid to the effects on tree structure, stability, and health. However, these factors can only in fact be managed well, when the biology and growth patterns characterising trees are understood. The beginnings of arboriculture, and knowledge regarding the methods of treating older trees came down from the work of gardeners serving kings and the very rich, as well as from farmers, as planters and pruners of fruit trees. Foresters wanted (as they still want) the rapid growth of trees with straight trunks providing timber. In contrast, Royal Parks and forests were also important as hunting areas, with these different requirements prompting arborists to start with new treatments: cutting big branches flush to the stem (Fig. 41), painting wounds, and filling cavities. This was the beginning of the so-called "tree surgery". Such methods became common around the world, e.g. in Germany up to the 1980s and 1990s.

However, tree surgery is now history worldwide, as today's arborists take responsibility for trees in urban areas. They do not seek to make use of those trees, but do want to maintain them, and keep them alive. Established mature trees take quite a lot of maintaining, and in most cases pruning is primarily motivated by a desire to keep trees safe and healthy.

Pruning is the selective removal of plant parts to meet specific goals and objectives. The main goal for many urban trees is a long lifespan and sustained stability, made possible by optimum trunk and branch structure. Poor structure, decay resulting from major wounds and cracks in forks and limbs all shorten the lives of trees (Fig. 42). Additionally, appropriate pruning requires knowledge of tree-crown architecture and the means of restoring crowns in mature trees. However, regular maintenance of trees can prevent premature tree failure, and extend lifespans. The making of corrections before problems arise, or even after a tree has developed slight to moderate defects, will prove a cost-effective solution that can be regarded as best practice for tree managers.

The last thirty years have brought detailed research on the pruning of deciduous trees in urban areas, and especially along streets or by the roadside. Today several pruning guides for trees and shrubs exist (e. g. Shigo 1989, Drénou 1999, Pfisterer 1999, Brown 2004, Gilman 2012), as well as relevant national or international rules and regulations (e.g. the European Tree Pruning Guide 2005, British Standard BSI 3998:2010 and ÖNORM L 1122 2011). In Germany, the state of the art as regards tree care is set out in the "Additional Technical Contractual Terms and Guidelines of Tree Care", or ZTV-Baumpflege (2006). This regulation applies to the implementation of measures including preventive maintenance, preservation, pruning for safety, and palliative care for trees in urban areas.

Fig. 41: In the days of tree surgery, it was customary to cut large branches flush to the stem. This often entailed leaving a pointed, elliptical shape that encouraged enlargement of the wound and decay in the wood.

Fig. 42: Poor structure, in this case a crack in the fork, shortens the lives of trees.

To avoid unnecessary interventions, it is important to inspect trees regularly, to see if measures are required. If possible, assessment of the need for tree care should be part of the inspections for traffic safety – "Guidelines for the Inspection of the Safety of Trees – Tree Assessment Guideline" (Baumkontrollrichtlinien 2010). Prior to the awarding of a contract and the commencement of tree-care measures, it is important that a clear, definitive diagnosis be made. Sufficient preliminary examinations are a prerequisite. These pertain to vitality and safety, undesirable developments in the crown, and possible infections with fungi or other organisms and their negative impacts on the tree. The principle means of diagnosis is a visual inspection by a professionally qualified expert.

The inspector must understand the goals, techniques, and limitations of the hazard evaluation process. The human eye is the most important instrument in diagnosis (Baumgarten *et al.* 2014, Fig. 43). Most defects can be detected visually, for example dead branches, cracks, hazard beams, or fruiting bodies of wood-destroying fungi (Dujesiefken *et al.* 2014). Knowledge of tree vigour and types of fungi can also be important. However, in some cases there is a need for special tools to confirm or detect the existence of defects, especially decay and internal cavities. In the last 25 years many tools with different operating principles have been developed, from the simple through to the very sophisticated. Detection strategies,

Fig. 43: Tree inspection: The human eye is the most important instrument in diagnosis.

for example, relate to resistance to physical penetration, the conductivity of sound waves, and the electrical resistance in wood. Extensive scientific work in recent years has led to the development of guidelines for further investigations of tree hazards (Matheny & Clark 1994; Wessolly & Erb 2014; Mattheck *et al*. 2015; Roloff 2015; Rust 2016).

3.2.2 Pruning

Pruning cuts and their implications

The procedure practised most commonly by arborists is pruning, to establish and maintain healthy, aesthetic and safe trees. This work requires a knowledge of tree biology, wound reactions and decay. Necessary pruning cuts should be made as early as possible in a tree's life, to keep wound size to a minimum. This prevents secondary damage like decay, and limits the need for subsequent mitigation measures. But even a correct cutting location can lead to extensive discolouration and decay inside the wood. According to the CODIT Principle (Dujesiefken & Liese 2015), essential parameters also include the diameter of the branch, and the ability of a tree to compartmentalise wounds.

Differences between tree species

Several investigations involving the compartmentalisation of similar wounds in different tree species reveal major differences. In general, there are two identified groups that differ in the strength of the compartmentalisation process. Weakly compartmentalising genera include *Aesculus, Betula, Malus, Populus, Prunus* and *Salix*, while effective compartmentalisers are in genera like *Carpinus, Fagus, Quercus* and *Tilia* (see Chapter 2.2.).

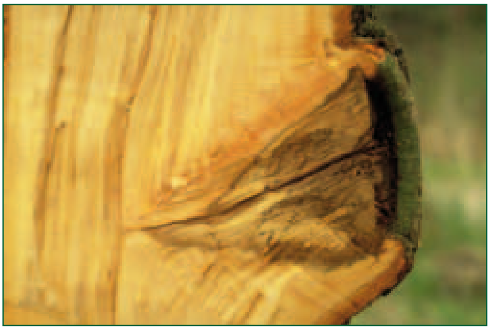

Fig. 44: Wound reactions after pruning: the older tissue at the wound centre compartmentalises more weakly than the tissue at the wound margin.

Fig. 45: If hyphae penetrate boundary layers and reach healthy and functional wood, the latter forms a new boundary layer.

Pruning wounds show an exponential increase in discoloration (and later on decay) with increasing branch diameter. The essential cause is most likely the age of the wounded tissue. Small pruning wounds only damage younger tissue, i.e. the increment of the last few years, which contains living parenchyma cells and the largest energy reserve. Major cuts also injure tissue at the (older) centre of the stem, which cannot react as effectively. The discolouration in the middle of the wound is shown to reach further into the stem than at the wound periphery, and the compartmentalisation of the older tissue near the pith seems weaker than the reaction of younger tissue (Fig. 44). After several years, the reaction zone forming immediately after wounding may be penetrated by microorganisms, with the result that further new discolouration surrounding the initially discoloured wood sets in (Fig. 45).

When to prune?

Tree pruning is often carried out in winter, because structural and wood defects are more visible then. There might also be less risk of damaging underlying vegetation. Traditionally, tree-care work is carried out in the winter, when there was an excess of labour. However, the mechanisms of compartmentalisation within deciduous trees depend on physiological activity of the parenchyma cells, as well as on the availability of stored material. For these reasons, time of year has an influence on the wound reactions of trees. This not only affects the expansion of discoloration in wood, but also the dieback of the cambium, and callus formation at the margin of the wound. To minimise possible damage and promote compartmentalisation and callus growth, pruning should be done during the growing season (see also Chapter 2.2.).

The so called "bleeding trees" (e.g. birch, maple and walnut) should not be pruned during times of high vascular pressure. However, while the draining of sap ("bleeding") from the wounds can be unsightly, it is not in general considered damaging.

The maximum wound size which will be compartmentalised effectively

According to the Hamburg Tree Pruning System, all pruning wounds of diameters less than approx. 5 cm are compartmentalised effectively (Fig. 46). Strongly compartmentalising trees also react similarly to cuts of diameter up to about 10 cm. In all species, larger wounds can lead to extensive discolouration and decay in the stem (Fig. 47).

Regardless of the time of year and tree species, it can generally be said that radical tree pruning, e.g. a drastic removal of crown parts or whole crowns, should not be a common practice. If possible, branches of more than 5 cm in diameter in weakly compartmentalising trees, or of more than 10 cm in strongly compartmentalising trees, should only be reduced, if necessary, rather than removed completely.

Fig. 46: An example of effective compartmentalisation following pruning of a lime tree.

Fig. 47: Weak compartmentalisation following pruning of a horse chestnut tree. Discoloration has already spread into the trunk, having started at the wound site.

Locating the right spot to make a cut

Pruning cuts should be made in such a way that branch tissue alone is removed, while stem tissue is left undamaged. At the point where the branch attaches to the stem, branch and stem tissues remain separate, but are contiguous. If only branch tissue is cut in the course of pruning, the wound is then as small as possible, and will close more rapidly. A summary of proper pruning cuts in line with the attachment of branches to the stem is given subsequently. It is based on the Hamburg Tree Pruning System (Dujesiefken & Stobbe 2002). Various branch attachments occur in nearly every tree species, so this framework is regarded as applicable irrespective of species and site, or cause or aim of treatment.

How to cut branches with a branch collar?

Slow-growing branches in the lower part of the crown mostly have a branch collar at the base. This swelling belongs to the stem and has to remain with it. To find the proper place for a removal cut, look for the branch collar that normally grows on the underside of the base of the branch. On the upper surface, there is usually a branch bark ridge that runs more or less parallel to the branch angle, along the stem of the tree. A proper cut begins just outside the branch bark ridge, and angles down away from the stem of the tree, thereby avoiding injury to the collar (Fig. 48). The cut is to be made as close as possible to the stem, in the branch

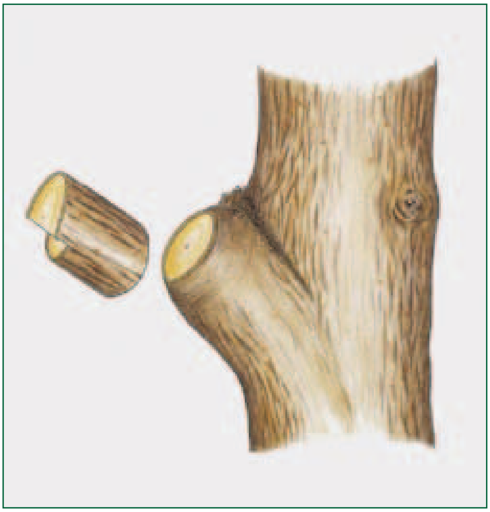

Fig. 48: If a branch collar is present, a cut must be made far enough away from the trunk that only branch tissue is removed, while the collar remains. The cut must also be made outside the branch bark ridge and, depending on the shape of the branch collar, must slant downwards.

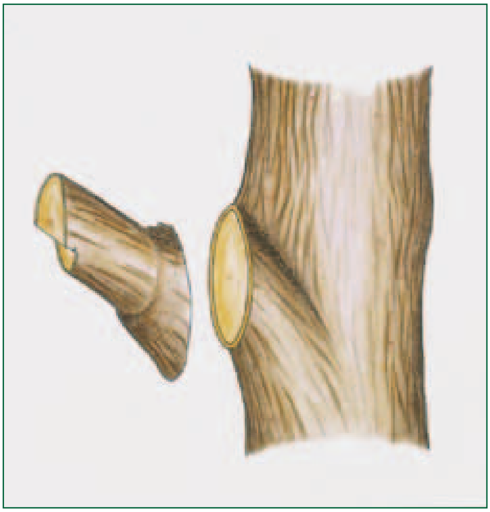

Fig. 49: Flush cuts made inside the branch collar or branch bark ridge lead to larger wounds, and to more discolouration and decay in the wood.

axil, but outside the branch bark ridge, so that stem tissue is not injured and the wound can be encapsulated in the shortest time possible.

If the cut is too far from the stem, leaving a branch stub, the branch tissue usually dies and wound wood forms from the stem tissue. Wound closure is delayed, because the wound wood must grow over the stub that was left.

Flush cuts made inside the branch collar or branch bark ridge lead to bigger wounds (Fig. 3.9) and more discoloration and decay in the wood. The larger size of the wound will ensure that encapsulation happens later than after a proper cut. Flush cuts are therefore unfavourable to trees.

How to cut branches lacking a collar?

Many branches, especially in the upper crown, do not have a branch collar. If a branch without a collar is pruned at a slanted angle to the stem, the cambium at the lower margin will die back several centimetres (Fig. 3.10). Therefore wound size increases, and at the lower margin of the wound, little dead stub will develop. The wound wood grows only partially over the cut surface, so that the wound closures slow down.

Branches with a branch collar normally form a funnel-shaped reaction zone in the area of the swelling called the branch collar. The wound wood develops on the outer margin of the

Fig. 50: Branches lacking collars at the base are often found in the upper crown.

Fig. 51: An S-shaped reaction zone is developed in branches without a branch collar.

branch collar, where the reaction zone contacts the cambium. In branches without a branch collar, the shape of the reaction zone is often different. Instead of a funnel-shaped reaction zone, an S-shaped one is developed (Fig. 51). On the upper side of the branch, the reaction zone is formed near the branch bark ridge, as in branch stubs with a branch collar; but on the lower side, the reaction is located closer to the stem.

The points at which the reaction zone contacts the cambium on the upper and lower sides of the branch bases (as in Figs. 52 and 53) suggest the locations for pruning cuts: branches with collars should be removed beyond the swelling at the base of the branch (mostly by way of a slanted angle to the parent stem), while branches without a collar should also be removed outside the branch bark ridge, but with a more parallel cut to the stem to avoid the formation of a dead stub at the lower margin of the wound. This cut is not a flush-cut, because the branch bark ridge remains at the stem, and the cut is more beyond it. The wound is also far smaller than the flush-cut, and oval-shaped. Although the initial cut surface may be slightly larger than where branches are cut beyond a branch collar, the ultimate wound will be smaller, due to reduced dieback from the cut. The cambium at the wound edges is supplied with assimilates, therefore the tree can wall off the wound directly from the wound edges. With this cut, the smallest possible wound and best closure are possible.

Fig. 52: When a branch lacking a branch collar is cut in the same way as one with a collar – in other words at a slant – the lower wound margin dies off. A dead stub may be partially formed and callusing of the wound will be delayed. As a result, the wound remains in Phase 3 for longer.

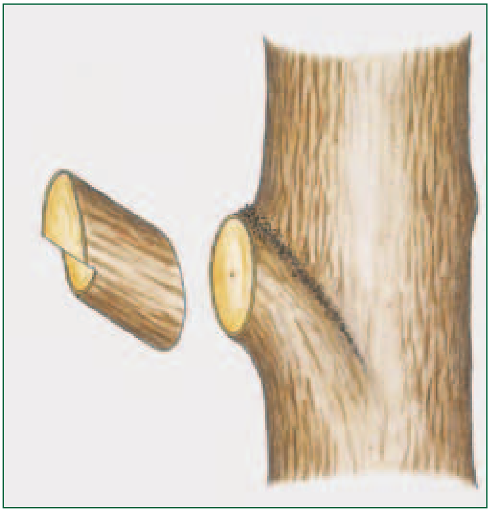

Fig. 53: If there is no discernible branch collar, a cut must be made outside the branch bark ridge, but parallel to the trunk, rather than at a slant, as with a stub cut. This prevents both the formation of a nourishment blind spot at the lower wound margin and dieoff in the area generally.

How to cut branches with included bark?

Included bark occurs in nearly every tree species, but very often in beech and robinia trees; and is one of the most common structural defects present in trees. In general, it develops frequently in branches without a branch collar and in V-shaped forks and between codominant stems (Fig. 54). Included bark is the condition whereby inner and outer bark forms between the branch and the trunk. Narrow-angled branch configurations are pre-disposed to included bark, because as each stem continues to grow in diameter each year, there is a competition for space in between at some point. The vascular cambium turns inward within the branch crotch, then the branch bark ridge also turns inward, forming 'lip-like' ribs (double ridge bark inclusion). Branches with included bark in the union are attached less strongly to the stem, and normally have no visible collar. Such branches should be removed from the tree at the nursery, or during formative pruning while the tree is young (Fig. 55).

Cuts made too close to the trunk usually result in a heart-shaped wound. Despite correct cutting, wound wood will often fail to form at the upper wound margin, because this area is not supplied as a result of the included bark. Before any tree care measures on stronger branches are performed, it must be considered whether the objective could also be achieved by, for example, reducing or cabling the crown, in order to prevent the complete removal of the branch.

Fig. 54: Many branches without a branch collar have forks with included bark.

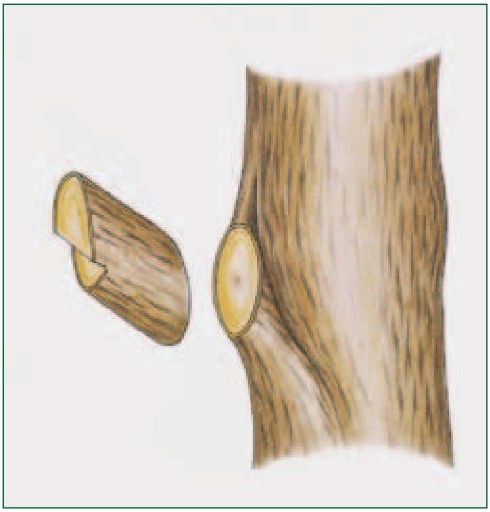

Fig. 55: If included bark is present between branch and stem, a cut must be made as close as possible to the latter, though without stem tissue above the branch base being injured.

How to cut codominant branches?

Codominant branches also occur in all tree species, but most often in e.g. ash and maple (Fig. 56). Making a cut at dominant branches is unproblematic if the branch to be removed is small (up to 5 cm in diameter). This also applies to larger branches (of up to 10 cm) in effectively compartmentalising tree species (see page 35). In both cases, the cut must be made outside the branch bark ridge (Fig. 57). If large branches (limbs) or even codominant stems are removed, the tree loses a significant amount of crown volume. Furthermore, cambial dieback arises (as well as dieoff of bark and wood), and the risk of breakage may increase below the cut wound because of intruding decay. In such cases, consideration must be given to the possibility of crown reduction as an alternative to the complete removal of a branch or codominant stem. The installation of tree-crown stabilisation (see page 91) constitutes another alternative to cutting forks at risk of failure.

Fig. 56: Codominant branches or stems can occur in all tree species.

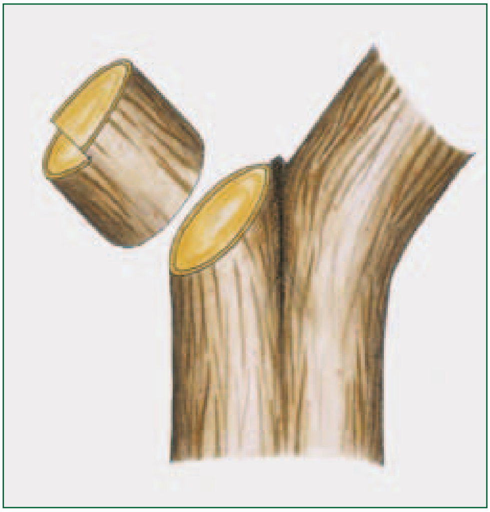

Fig. 57: The removal of one or two codominant branches is always a major intervention, given the considerable loss of crown volume and the size of the wound inflicted. Thicker branches (exceeding 5-10 cm in diameter) should be reduced, rather than removed completely. If complete removal is unavoidable, the cut must be made outside the branch bark ridge. When large cuts are made, a nourishment blind spot often arises at the lower wound margin.

How to make a reduction cut?

A reduction cut reduces the length of a branch or part of a crown by removing the terminal portion back to a living lateral branch of equal or smaller diameter. If branches are to be shortened, they must also be cut at a slant, outside the branch bark ridge, in the area of the remaining lateral branch (Fig. 58). Whenever possible, thicker branches (over 10 cm in diameter) should not be cut at all. If this is unavoidable, cambial necrosis will develop at the lower wound margin, and decay may occur as after large removal cuts.

If the cut is set further beyond the branch bark ridge, a dead stub will develop as after heading cuts. A heading cut reduces the length of a branch without regard to the position of nearby lateral branches. The term heading has also been used to describe topping or rounding over. Cutting between nodes normally results in dead stubs when the nearby buds fail to sprout. Heading of older trees is not recommended, because it initiates decay and cracks in the cut branch or stem, ruins their structure, and causes uncharacteristic upright growth.

Fig. 58.: If thick branches must be reduced, they must be cut at a slant, beyond the branch bark ridge, in the area of the remaining lateral branch. Branches over 5–10 cm in diameter should not be cut as, should this prove unavoidable, the inevitable consequence will be the formation of a nourishment blind spot at the lower wound margin.

How to cut dead branches?

Dead branches usually have a swelling of living tissue at the base - like a collar - formed by the stem (Fig. 59). The trunk nourishes this ring-shaped tissue. It encloses the dead wood, which has been colonised by various wood-decay fungi (Fig. 60). Wood decomposition is particularly intense at the branch base and, in this way, creates a predetermined breaking

Fig. 59.: A dead branch with a collar-like swelling of living tissue at its base, formed by the stem.

Fig. 60.: Wood destroying fungi create a predetermined breaking point close to the stem.

Fig. 61: A wound following breakage of a dead branch.

Fig. 62: The removal of dead branches should only involve the deadwood itself. The distinctive collar on the trunk is to remain uninjured, and decayed wood must not be coated with any wound dressing.

point close to the stem (Fig. 61). Decay does not usually penetrate through the boundary layer into the stem, as a result of this process, known in forestry terms as "self-pruning". After the breakoff occurs, the often cone-shaped discolouration and decay is grown over.

Just as branch collars should not be cut as live branches are pruned, so the swollen area of living tissue at the bases of dead branches should also be left intact (Fig. 62). Unlike with living branches, decayed wood is usually still present at the centre of the cut surface after the removal of a dead branch. Since decayed tissue should not be covered with any sort of wound dressing, the application of a sealant should also be avoided when a dead branch is removed.

Insufficient compartmentalisation in the stem is usually only observed in large-diameter dead branches and unhealthy trees. In these cases, neither a visible branch collar nor a swelling at the base can be found. Pruning wounds after removal of dead branches should always be monitored – especially on trees in urban areas – for safety reasons.

Pruning types (methods) for established trees

Established trees are pruned in urban areas primarily to reduce risk, provide clearance and preserve tree health, as well as for aesthetic reasons. These objectives lead to pruning strategies for trees of all life-stages and sizes. Trees can also be pruned for ornamental reasons. Crowns can be shaped in many ways. Trees respond differently to this kind of pruning, and great care must be taken to select the right genera or species tolerant of ornamental pruning methods. Ornamental pruning like topiary, pollarding or espalier should start when the tree is young.

This chapter describes the pruning methods for mature trees. In the ZTV- Baumpflege (2006) the main types noted for older trees are crown lifting, deadwood removal, crown maintenance, and crown reduction.

Crown Lifting

The only purpose of crown lifting is to provide necessary clearances (Fig. 63). To achieve these, pruning must be commenced with at a juvenile stage. In trees requiring future clearance pruning, pre-emptive action should be taken to prevent branches on the stem from reaching more than 5 cm in diameter.

The height of the crown base is dependent on species, form, topography and land use in the surrounding area, and must be considered when establishing the height of the lowest branches to obtain and maintain the necessary clearance. For example, if a stem height of 4.5 m is required, then it should be attained over four or five pruning cycles. Pruning should be carried out in a regular cycle of 2 to 3 years.

Fig. 63.: Clearance along a road in The Netherlands. Work on crown lifting began here at the juvenile stage.

Deadwood Removal

The only purpose of deadwood removal is to keep trees in a safe condition. In this case it is normally only dead and broken branches larger than 3 cm in diameter that should be removed.

Crown Maintenance

The purpose of crown cleaning is to keep trees in a safe and healthy condition (Fig. 64). Crown maintenance is the removal of dead, dying, diseased, crossing, hanging, and weakly-attached branches, in order to prevent poor crown development, e.g. co-dominant stems. As clearances for trees by a road are determined, consideration must be given to the site requirements, and to the effect of pruning on surrounding areas.

Crown Reduction

Crown reduction is used to reduce the size of the entire crown in height, and/or its lateral extension, in accordance with safety requirements and/or in line with the needs of the environment surrounding the tree. A reduction cut reduces the length of a branch or a part

Fig. 64.: A mature tree following crown maintenance. Dead, dying, diseased, crossing, hanging and weakly-attached branches have all been removed.

Fig. 65.: A mature tree following crown reduction. Crown length has been reduced through removal of the terminal portion back to a living lateral branch of smaller diameter.

of the crown by removing the terminal portion back to a living lateral branch of equal or smaller diameter (Fig. 65). At the time reduction cutting is engaged in, the diameter of the remaining branch should be at least 1/3 of that of the branch that is removed. If possible, the remaining crown should maintain its habit, or at least be able to regenerate it with new shoots. No more than 20% of the total foliage volume should be removed at any one time.

3.2.3 Tree Crown Stabilisation

Cables and braces are to be installed only when defects and risks of failure have been identified (Smiley & Lilly 2014). Consideration must be given, as a cabling system is installed, to the question of whether required pruning measures, resulting damage, long-term reaction of the tree and ongoing maintenance are more advantageous to tree health and safety. The question to be considered is whether the desired results can be attained either by crown pruning or by installing a tree crown stabilisation, or alternatively by a combination of both. In line with the German ZTV-Baumpflege 2006, the recommendations given are described as follows.

Advantages (Examples)

Pruning
- No engineered systems in the tree;
- No restriction of natural movement;
- Other pruning work in the crown can be done at the same time.

Cabling
- Preservation of the habit and no loss of crown volume;
- No effect on the natural energy balance;
- Immobilisation of branches susceptible to failure;
- No or minimal pruning required.

Disadvantages (Examples)

Pruning
- Pruning wounds;
- Possible reduction of vitality:
- Altering of habitus;
- Ongoing maintenance requirements due to changes in growth.

Cabling
- Possible hindrance of natural movement;
- Engineered system in the tree;
- Future maintenance due to cabling material requirements;
- Regular inspection and maintenance required;
- Installation is dependent on/limited to stable climbs and branches.

Examples where pruning is preferred to cabling:

- In general, on younger and mature trees;
- When the required pruning does not produce significant wounding and;
  – the habit/appearance of the tree is not altered substantially;
  – a cabling securing system is not to be installed for aesthetic reasons;
  – where corrective pruning of the crown is necessary;
  – if the ongoing inspection and maintenance is cost-prohibitive;
- If suitable limbs/stems for securing the compromised limbs are not available, or if the available supporting limbs/stems are compromised (e.g. due to cavities).

Examples where cabling is preferred to pruning:

- If the habit/appearance of the tree is to be preserved;
- Where there is a high risk of decay developing in wounds inflicted by pruning, and/or a resulting significant decrease in vitality, especially with older trees;

- In species that are known to have weak compartmentalising capabilities;
- If the tree may react adversely to the required pruning (e.g. missing supporting limbs, prone to sunburn, less able to build new shoots(reiteration) after pruning);
- If, as a result of pruning, the ongoing inspection and maintenance is cost-prohibitive (change of growth habit, formation of a secondary crown);
- In case of an acute risk of failure (e.g. split forks).

Examples of combining pruning and cabling:

- When there are substantial advantages to using both measures that outweigh the disadvantages.

If a cabling system should be used, the installation height depends on the type of hazard (e.g. crack in the fork, cavity in a limb). Normally, the cable is installed on one level, but it can under certain circumstances be installed on two. The cabling system reduces the forces acting in the crown by utilising the leveraging effect of branches. If the system cannot be installed at 2/3 of the total length of the limb/stem, then stronger cables should be used (Fig. 66).

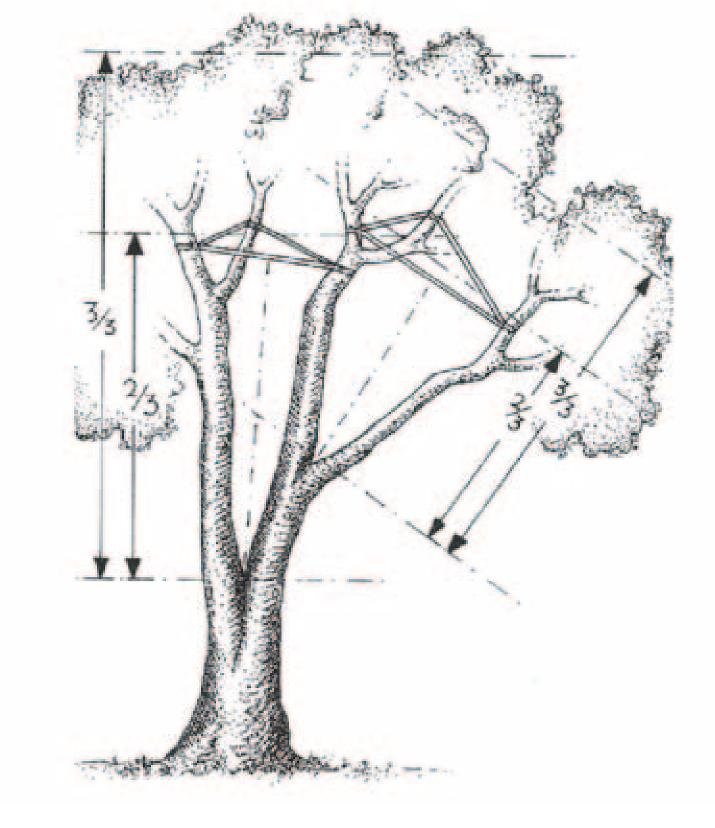

Fig. 66.: The height of installation for a single-level fracture prevention system (ZTV-Baumpflege 2006).

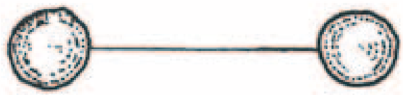

Fig. 67: Direct connection between two limbs/stems. Lateral swaying of secured crown parts is not obstructed (ZTV-Baumpflege 2006).

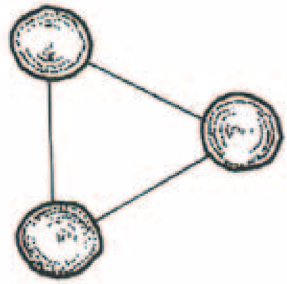

Fig 68: Where three limbs/stems are to be connected, a triangular connection has to be installed to reduce swaying in all directions (ZTV-Baumpflege 2006).

Cabling systems can be installed:

- to secure individual limbs/stems (single-limb securing system, Fig. 67);
- to secure several limbs/stems (Fig. 68);
- in special cases with connection to neighbouring trees.

The elastic property of the cabling system is determined by the type of material and its strain limitation. The material's elongation is primarily determined by the length of the connection, and can also be increased by installing shock-absorbing components. The effect of a shock-absorber on the elongation is independent of the overall length of the connection. In situations where the cabling system allows for too much elongation, excessive movement of the secured limbs may result in failure before the cable is loaded. Cable connections spanning long distances require greater stiffness. The minimum breaking strength of the system depends on the diameter of the limb/branch at the time of installation of the limb/branch base. The breaking load values in Table 1 for dynamic cabling systems are based on years of practical experience. These are minimum values for each component installed in the respective crown-securing system.

Depending on the manufacturer, cabling components made of synthetic fibres may be of varying physical properties and life expectancies. Some may not therefore be suitable for supporting heavy, permanent loads.

Attachment loops must be formed and positioned in such a way that:

- damage to rope and tree resulting from chafing, girdling and slipping is prevented permanently (e.g. through the use of protective sheathing);
- the loops can be adjusted to accommodate secondary growth of the stems to prevent girdling.

Installation in the summer requires that cables be installed without tension, but not be sagging either. Installation of cables in the winter requires that the cables sag slightly in the middle of the connection to prevent the system being permanently loaded when the tree is in full leaf.

Table 1: Empirical values for the dimensioning of dynamic cabling systems (from ZTV-Baumpflege 2006)

Diameter of limb/branch Measured at time of installation at limb/branch base	Minimum breaking strength of system For stated product service life, installation at minimum of 2/3 of length of limb/branch to be secured (tonnes)
40 cm (up to 15”)	2.0 t
40-60 cm (15-24”)	4.0 t
60-80 cm (24-32”)	8.0 t
80 cm (over 32”) special measures depending on individual case	

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3.3. Ancient trees and their value

Neville Fay, Nigel de Berker

"10,000 oaks of 100 years old are not a substitute for one 500-year-old oak."
(Rackham 1986).

3.3.1. Introduction – the path towards conservation arboriculture

In the UK the focus on ancient trees is recent. Over two decades the study of ancient trees as survivors, habitats, ecosystems and structural models has evolved into a discipline.

The United Kingdom has the largest concentration of ancient trees in Northern Europe. However, this is not a stable position as various studies in recent years show high rates of loss for many reasons, including neglect, misguided policy and inappropriate arboricultural management (Read 2000; Fay & de Berker 2000; Fay & Rose 2004; Bengtsson & Fay 2009; Bengtsson & Bengtsson 2011). This led to the conclusion that, while there may be large numbers of ancient trees, they are being lost at unsustainable rates and the often rare habitats they provide are also under threat (Fig. 69).

In recent years, tree and nature conservation specialists worked together to develop a more multi-disciplinary approach to the study and management of ancient trees. In the 1990s, concerns about the unsustainable loss of ancient trees in the UK resulted in the formation of the Ancient Tree Forum (ATF), which advocates that there should be no avoidable loss of ancient trees. This in turn has led to non-governmental organisations and citizen science approaches to the gathering of data on the quality, condition and distribution of ancient trees throughout the UK. The accumulated evidence has contributed to the development of conservation management and, over recent years, has led to a number of influential publications on principles and new practice guidance (Fay and de Berker 1997; Davis et al. 2000; Read 2000; National Tree Safety Group 2011; Lonsdale 2013b).

The definition of arboriculture has changed over time and may still be evolving. Since before medieval times, the Latin term arborator referred mainly to a tree orchard worker, while arboriculture referred to a broad discipline that covered management of trees principally for timber and orchard produce. Not until the mid-nineteenth century, with the development of urban parks and planting of street trees, did a separate cultural discipline begin to emerge on a significant scale. As those nineteenth century urban plantings began to mature, their care and repair increasingly became a municipal responsibility that called upon a set of professional tree management skills that were distinct from previous forestry and horticulture experience (Le Sueur 1949; Johnston 2015).

Arboriculture, as we know it today with its emphasis on amenity trees, is a young discipline. The UK Arboricultural Association dates from 1964[1]. 1966 brought BS 3998 'Recommendations for Tree Work' the first arboricultural British Standard, which provided practical guidance on tree work procedures. Most of the reference materials in all these developments have related to the tree from the nursery through to the mature state.

Present day arboriculture has undergone a character reassessment driven by the study of ancient trees. This focuses on the life cycle and natural history of the tree, which encompasses a much wider set of circumstances than those provided by the previous conventional arboricultural paradigm. In this new context account is taken of natural processes over extended periods of time, and of the plant, wildlife and other communities that surround the tree.

Borrowing from observations of ancient trees and natural processes suggests a 'lens' through which trees of all age classes may be viewed. This, together with observing natural-process mimicry, has contributed to the development of*conservation arboriculture* as an emerging discipline; one that today is influencing mainstream theory and practice worldwide.

Until recently conventional arboriculture adopted the view that dead wood was harmful to the parent tree indicating decline, weakness and the presence of hazards. This was reflected in industry practice through to the 1990s.

A sanitised approach required 'crown cleaning' with emphasis on dead wood removal, and cavity and decay treatment. Practices outlined in the original 1966 British Standard included the use of wound sealants, concrete cavity filling and the drilling and drainage of cavities and water pockets. The prejudice against dead wood remained and the subsequent British Standard (1989) persisted in recommending removal of dead, dying and diseased wood.

Wood decay has long been studied by naturalists, including entomologists and mycologists and under the influence of the Ancient Tree Forum, the study of ancient trees called into question previously accepted practices. This in turn led to a comprehensive reappraisal of the sanitisation approach to tree management, such that the current British Standard represents a paradigm shift. Practical guidance today recognises the fundamental importance of dead and decaying wood and the irreplaceable value of ancient trees (BSI 2010; BSI, 2012; ATF, 2014) and the importance of developing innovative practices under the auspices of conservation arboriculture.

[1] The UK Institute of Chartered Foresters (ICF) which was founded in 1925 also extended chartered status in 2008 to professional tree specialists who qualified as chartered arboriculturists.

Ancient and other veteran trees, their importance and vulnerability

In general what makes ancient and other veteran trees special is the biological, aesthetic and cultural interest that comes about through their age, size or condition (Read 2000). Fundamental to the biological aspect of these qualities is the habitat that derives from ageing and decay (Fig. 69). While the terms 'ancient' and 'veteran' are often used interchangeably, there is an important distinction to be made. Veteran is in a sense a metaphor that conveys the notion of the tree as a battle-scarred survivor. It describes a condition with signs of ancientness that may be present, irrespective of age that typically arise from wounding and natural decay processes. 'Ancient' on the other hand describes a life stage. While all ancient trees are veterans, not all veterans are ancient.

Veteran trees may also be described as 'ark trees' (from the biblical Noah's Ark), reflecting how such trees may function as a rare vessel with precious cargo, carry colonising species through space and time, providing *refugia* for potentially rare and endangered species[2]. Whereas it is not possible to recreate an ancient tree (due to the time entailed in ancientness), it is possible to create conditions that can precipitate veteran, ark-type habitats.

The term 'ancient' is in contrast an arboricultural age classification that reflects a life stage in the ageing process. An ancient tree is one that is old for its species and often displays large species-girth (Lonsdale 2013)[3]. The ancient *phase* includes early-, middle- and late-ancient *stage* (characterised in the morpho-physiological model (see Chapter 2.1, Figs. 1 and 2) as life Stages 8-10. The ageing process is a function of time. The larger a tree grows in size and in complexity, the greater its potential to provide saproxylic habitat interest. However, size alone is an unreliable indicator of ancientness as it varies considerably according to species and growing conditions.

Ancient trees are few in number compared to the abundancy of trees other age classes. By definition, they are true survivors for their species and some exceptional trees may live for thousands of years and may even carry the gene for longevity. Due to their rarity and habitat continuity, they play a special role in the European cultural landscape and as *keystone species*[4] have exceptionally high conservation values. Given that over their lifetime they are host to thousands of colonising, sometimes rare, species, when such trees are lost there are dramatic effects on inter-connected ecosystems. While tens of thousands of ancient trees are found in Britain, the rates of decline and loss are so substantial as to threaten and fragment valuable habitats with rich biological diversity (Fay & de Berker 1997; Fay 2002).

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2 Over 2,000 invertebrate species (six percent of British invertebrate fauna) depend upon ancient tree habitat (Alexander 2012).

3 In many circumstances the largest trees are not necessarily the oldest. Within a woodland setting the tallest trees may simply be benefiting from the most favourable growing conditions with smaller older trees nearby better adapted for longer life. Also trees growing in extreme conditions (e.g. on cliff faces) or under persistent acclimatised water stress (e.g. desert and tundra conditions) may reach exceptional ages whilst remaining diminutive.

4 Keystone species is one whose loss would result in collapse of habitat with severe harm to connected ecosystem and related biodiversity.

While dead wood and decay are *veteran features*, in themselves they may not be sufficient for a damaged mature tree to qualify as a high quality veteran specimen. Such features become valuable saproxylic habitat when their size, number and extent increase over the passage of time. Veteran habitat is a function of the physiological effects of damage, shading, drought and storms and can occur 'pre-maturely' in a non-ancient tree that mimics qualities of its older counterpart.

The body of the veteran tree becomes a record of the life experience of the tree reflected in its 'body language' - its morphology therefore is a record of its physiological history (Arber 1950; Del Tredici 2000; Mattheck, Bethge & Weber 2015). Through fine tuning our senses to tree morphology, we gain insights into the history and sequence of growth patterns associated with an individual tree's life stages (ontogeny). With experience this provides us with a norm and a diagnostic tool, against which physiological perturbations may be interpreted (Raimbault 1995).

The fourth dimension – the test of time

The function of time is a crucial factor in the evolution and development of the tree, in the formation of saproxylic habitats and the dynamic interactions with the environment. Species diversity requires continuity of habitat. For this to be optimised, a treescape (trees, their landscape and soil-root ecosystem) needs to be sufficiently stable for their connectivity to be maintained.

The greater the length of time a tree or groups of trees exist on a site, the greater the possibility not only for species diversity, but also for the colonisation of decaying woody habitat with rare species. As the continuity of ancient or veteran ark trees on a site supports the development of diverse and rare woody habitats, the vulnerability of old trees on sites with long continuity elevates their conservation importance[5]. This in turn places greater importance on ensuring their longevity through conservation arboriculture.

Recognising the vital significance of time, the *fourth dimension* of the tree, helps to overcome the limitations imposed by static, one-off observations (like a single photograph) or from conclusions that assume the trajectory of the ageing process as if it is one-directional. The fourth dimension also accounts for the ebb and flow between stress and response, apparent traumatic impacts of events that over time may become rejuvenating, transformative and promote longevity. Features that are at first seen as expressions of weakness or deterioration may be a phase of transition, nascent growth leading to adaptations destined over time to become mechanically strong and physiologically functional.

[5] The UK 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 (reflecting 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.

Developing a sense of the ebb and flow of the fourth dimension of the tree gives a perspective on the processes and time-scales by which trees operate. These function beyond our everyday common and professional perceptions, and the imagination required to recognise such processes is not unlike the conceptual steps that early biologists had to make in order to appreciate the reality of geological time.

The hidden nature of ancient tree soil – implications for conservation arboriculture

Above ground we see a fraction of the whole-tree-organism. Below ground, the hidden aspect encompasses a myriad of soil and root borne microorganisms, of fungi, bacteria, protozoa, nematodes and arthropods. Together the tree, its surrounding soil-food-web and its living soil serves as a functional entity.,

Beneath an ancient tree is an ancient soil system that is intimately connected and bonded with tree roots, microbiota and macrofauna communities. The closer to the ancient tree, the more stable and less disturbed are these microbial communities that have synergistically interacted, in some cases over centuries and millennia. In landscapes where there are matrices of ancient trees within networks of other veterans and age classes, their associated soils and organisms are interwoven with mycorrhizal networks so extensive that, if unravelled, 1cm^3 of top soil would contain hyphae extending to 8km in length if placed end to end (Stamets 2005).

For trees, bacteria and fungi, particularly mutualist mycorrhizas, are among the key drivers of soil ecology. These and non-beneficial microbes are in constant 'communication' through chemical signalling with the tree. Roots are neither static nor passive. Beneath the ageing tree, generations of exploring roots are in intimate contact with microorganisms and the soil which together constitute the *rhizosphere*. Roots are constantly tip-exploring and sensing, secreting sugars, proteins, root border cells and other chemicals, interacting within the soil host-space *and* microbial populations.

Root activity (mediated by the transition zone behind the meristem) reflects sensory behaviour that responds to favourable stimuli. The rhizosphere is a busy interface of chemical exchange between roots of the individual and other trees, fungal associates and other surrounding microorganisms (Baluška 2009). The rhizosphere soil may contain orders of microbial numbers such that 1g of soil hosts in the region of 10^6 fungi, 10^7 actinomycetes, 10^9 bacteria and 10^3 protozoa. This is up to 100 times richer in microbial numbers than further away and is the '*rhizosphere effect*' (Dix & Webster 1995). Root secretions signal, attract, repel and regulate microbial communities that are fundamental for growth, health and viability (Whitfield 2007; McNear 2013, Vieria et al. 2016). Exudates also initiate mycorrhizal associations, 'manage' root herbivores (nematodes) and mediate water relations. Root secretion has evolved to control biological associations through chemical signal mimicry that attracts mutualistic microorganisms (Badri & Vivanco 2009). Exudates are carbohydrate-rich and bound together with cast-off root cells within the fine, slime layer that stimulates bacteria to migrate

Fig. 69: *Ancient* tree with wounds, decay, trunk hollowing, branch cavities, broken branches, damaged bark, fungal fruiting bodies. All these wounds and colonisable *saproxylic* habitats are *veteran* features. There are many more habitats out of sight, internal and below ground.

to and forage around the zone surrounding the root surface. As microbes are consumed, digested and excreted by other soil food web organisms, nutrients are unlocked and released for recycling. Around 10-20% of photosynthetic assimilates are allocated to the rhizosphere; a sacrifice that emphasises the value that root exudates deliver to the tree (Walker *et al*. 2003).

Taking a holistic view, the ancient tree and its ancient soil and all the organisms therein might be considered to represent a 'superorganism'[6], in which all the interacting compo-

6 Under certain circumstances collections of interactive organisms are more than the sum of their parts and can be regarded as an *integrated superorganism*; i.e. they represent high levels of co-evolved inter-species mutualism and reciprocal antagonisms (Seal & Tschinkel 2007).

nents function as a whole (Molloy 2006; Buchen 2010), such that local effects interact at an inter-species level and influence subtle systemic changes that protect the whole. Despite the lack of depth and breadth of literature and empirical study of below ground ecosystem processes in general (and particularly with regard to mature and post-mature trees) there are emerging investigations at a whole tree level (Čermák *et al*. 2010) as well as trials involving soil amendment applied to ancient trees showing signs of stress. Studies point to practical measures to restore soil ecological function and condition to a model attempting to mimic a more natural, evolved state.

We have little knowledge of what is a natural root-soil system if our experience is limited to pre-ancient growth phases. The ancient tree rooting zone might be considered to have equivalent status to that of a soil reserve; a largely undocumented ecosystem that yet awaits study.

3.3.2. Ancient tree survival strategies

Wound response and the original compartmentalisation (CODIT) theory

The CODIT model was originally conceptualised to explain the way trees respond to wounding and damage through compartmentalisation. It operates in the proximity of wounding and damage and its significance varies according to the life-phases of the tree. The CODIT model of compartmentalisation concerns evolved responses to injury. Since the introduction of the model to modern arboriculture in their paper (Shigo & Marx 1977), beautifully illustrated by Carroll, the CODIT concept has driven developments in practical management and pruning. It builds upon the earlier work of Hepting (1935), who observed that mechanisms within trees restrict the development of decay to those tissues already present at the time of damage.

CODIT identifies three boundaries that function through the structure of normal wood anatomy and that are present as *axial, radial* and *tangential* compartmentalisation regions. Together, these form the *reaction zone* (Shigo & Marx 1977) and may be referred to individually as Walls 1-3 (or more generally as boundary layers) (Dujesiefken & Liese 2015). Following wounding, a tree has the capacity to harness these natural boundaries in the pre-existing wood, as an evolved containment strategy, to maintain its vital conductive functions. These three-dimensional arrangements and other properties resist and inhibit microbial proliferation and decay progression. Upon wounding, the reaction zone becomes reinforced with chemical inhibitors and may be additionally supplemented with sub-compartmenting plugs within conductive vessels (Dujesiefken & Liese 2015).

Qualitatively and biologically different from the reaction zone is the *barrier zone Wall 4,* i.e. the fourth wall and the strongest CODIT component. The barrier zone has no pre-wound history, being a wound-triggered cambial response that produces *de novo* a layer of modified protective cells that develop *between* pre-existing wood tissue and new wood formed subsequent to the damage. Critically, the barrier zone contains chemically modified, suberised lignin-enriched cells, resistant to microbial activity. Beyond the barrier zone, the new tissue that is laid down has the potential to occlude the wound (as *woundwood*). A significant aspect of the barrier zone is that it *protects against water loss and air ingress* (Biggs 1986), key factors in vascular function.

With the ageing process the original Walls 1 – 4 become increasingly distanced from the outer living wood. Although with time the barrier zone may be breeched by decay, more generally it survives as an intact, more or less resistant *demarcation layer* (often seen when trees are dissected) that records the origins of outward growth beyond the original wound event and may also support rejuvenescent development of functional columns.

Decay versus damage

When considering the tree over its entire life cycle, it is relevant to distinguish damage from decay. From this perspective, while 'wound' is synonymous with 'damage', 'damage' is not synonymous with 'decay'. The original model focused on the tree's survival strategy, which is organised to compartmentalise against 'infection' from micro-organisms leading to decay. More recent developments have recognised that the tree's primary strategy is to exclude air from functional tissue (rather than being targeted against decay progression per se).

Damage responses relate to the processes within the tree that react to the loss or disruption of living tissue. Since early investigations (Hepting 1935; Shigo & Marx 1977; Shigo 1984; Shigo 1989), the CODIT model has been extended beyond the primary concern of decay. Instead, tree wound responses are seen as triggered by damage to living conductive (functional) sapwood, to primarily protect the living inner bark, cambium and water conducting cells (i.e. those in the phloem, cambium, and sapwood) that perform a role in active defence (Dujesiefken & Liese 2015).

Safeguarding hydrological efficiency is a common feature of compartmenting strategies, central to which is the exclusion of air from vascular tissue (Pearce 2000; Dujesiefken et al. 2005; Dujesiefken & Liese 2015). The original compartmentalisation of decay theory was later revised as an *air-exclusion hypothesis,* a survival strategy to ensure that following damage, water-conducting functions essential to health and photosynthesis are not compromised through air embolism (Tyree & Ewers 1991; Tyree & Cochard 1996; Dujesiefken & Liese 2015).

The air-exclusion hypothesis is consistent with research confirming that endophytic fungal communities are present within hydrated sapwood irrespective of wounding (Rayner & Boddy 1988; Rayner 1996). These endophytes are typically dormant and under normal water-stress tolerances large populations co-exist as fellow travellers, along with other microorganisms, without detriment to tree physiology. From this perspective, in addition to its morpho-physiological colonial properties the tree is also a composite ecosystem. While relationships between the tree and its associated microorganism communities may remain in balance over long periods of time, they are subject to dynamic change in response to environmental influences (Rayner 1993). Endophytes interact hydro-dynamically with the tree and are influenced by aerobic conditions. The tree in this view is not a polar component in a victim–aggressor relationship (Shigo & Marx 1977). Rather, it is argued that it is the product of coevolution with colonising microorganisms including endophytic, wood decomposing and mycorrhizal fungi. Of the vast number of fungal species only a few are strong pathogens that harm living tissue[7].

Compartmentalisation responses at different age phases

In the ancient tree we see an organism predisposed to a range of evolved expressions of compartmentalisation. The study of wound damage responses has been largely focused on the young and mature phases. There is relatively little study charting the progress of CODIT and other decay processes beyond peak maturity. The abundance in the European landscape of hollowing in old healthy trees with a history of centuries of decay not all derived from physical injury suggests there are age-related processes in play in addition to damage-initiated compartmentalisation. With ancientness, decay progressively occurs internally, through the roots from the base up and in old branches from the top down. Ancient phase decay processes are centrifugal dominated (from the inside out) rather than centripetal (from the outside in), the latter being more characteristic of the CODIT model.

In the young developmental phase (Stages 1-5), during which the tree functions as a unitary organism, damage-inducing decay threatening a part of the tree can potentially affect the survival of the entire organism. As wounding includes the trauma inflicted by pruning, minimising impacts from pruning to support the natural capacity for compartmentalisation is a key aspect of tree management and practices need to limit the effects of wounding.

In younger trees, due to wound size and rapidity of the growth response, we are able to witness CODIT in action. In mature trees this is more difficult and we rely on the few relatively short term studies (compared with the lifespan of the tree) as well as attempts to predict outcomes on the basis of retrospective CODIT examples from younger trees. The ageing process represents time, the fourth dimension of the tree, which far exceeds the human scale and as such, observation of these natural events associated with the CODIT model is inevitably *retrospective*. The assumption that compartmentalisation is essential for inhibiting decay progression or that extensive decay necessarily critically weakens the tree structure as a whole is undermined by the reality of the ancient tree. Ancient trees show copious evidence of decay associated with large old cavities and hollowing, including from historic damage to which trees have adapted and which they have incorporated on their

7 In this sense wood decay organisms are not strong pathogens as compared with active and acute pathogens that affect the functions of living sapwood, such as *Ophiostoma novo-ulmi*, *Heterobasidion annosum* and, under certain conditions, some *Armillaria* species.

journey through to great age. The CODIT response has a transient role and serves to *delay* fungal-induced changes in wood condition. Tempering of decay and hollowing processes thus allows time for the stimulation of new outer living, cambial-mediated tissue to become biomechanically adapted. This *'tempering strategy'* enables growth adaptations to the hollowing and general morpho-physiological changes that are intrinsic to the ageing process to be read in the body language of ancient trees.

In the formative juvenile and mature phases (Life Stages 1 – 7) external wounding and damage create circumstances where decay operates from the outside to the inside; a decay process that works *centripetally* as described by Dujesiefken & Liese (2015). The most likely widespread incidence of major decay and hollowing in older trees (from around Stage 7 onwards) arises from causes other than physical damage. The die back and death of deep roots paves the way for *root retrenchment,* which coincides with and initiates *crown retrenchment*. Thus the tree retrenches both at crown and root levels and in the fullness of time it will undergo organisational change and further pulses of expansion.

With the death of large components of the primary root system, decay follows that typically ascends in one or more internal columns that rise within the non-living wood within the core of the trunk. Here, decay resistance operates passively, determined largely by the anatomy and the pre-conditioned chemical properties of the wood.

Basal trunk decay that develops from age-mediated root die-back is of *non-traumatic* (wounding) origin *from* fungal activity that, while constrained by the pre-existing conditions within the heartwood (or ripewood), operates *centrifugally* (from the inside to outside) until it encounters the hydrated, oxygen-impoverished conditions of the inner aspect of living sapwood.

The tree defence system is more complex than it might at first appear. Interactions between fungi themselves and between fungi and the tree generate responses that we might consider part of the range of tree defences. We cannot be sure that what we see as a tree response in this context is in fact attributable only to the agency of the tree.

The factor of time (the 'fourth dimension of arboriculture') is fundamental to the decay and self-recycling processes that create the soil upon which the ancient tree stands (*ancient soil medium*). In this sense, the ancient tree acts as both beneficiary and protector of its soil environment. The decay processes favour rejuvenescence while enriching the ecology.

As already discussed, in CODIT terms ancient tree fungus-host interactions tend to be observed long after original wounding, when an established Wall 4 is breached by attrition and decay. The tree may respond by producing a secondary barrier zone serving to re-seal and protect the living sapwood hydrology and maintain vascular integrity (Dujesiefken & Liese 2015). Over time this process can be repeated serially. The example of ancient hollow trees in which the fungal wood decomposing agents eventually reach the inner face of the sapwood and are faced with resistance is analogous to the fungus-host-interaction associated with the breach of Wall 4 described above.

As the non-sapwood components of the trunk are fungally decomposed, a substrate is created for microorganisms and macrofauna that live, die and are recycled within the tree. Ultimately this hollowing creates soil-like moist, mycorrhizal-rich humic habitat ('mulm') within the ancient rotting trunk and large branches, which when accumulated facilitates the development of internal adventitious roots that in turn descend into and occupy the decay medium. Adventitious roots forage for and recycle nutrients previously locked in the body of the tree that have been released from decay processes. These roots secrete chemicals that interact with bacteria and fungi and promote conditions not only conducive to tree growth but also to the support of the tree in the face of stresses and biotic threats, while reciprocally favouring beneficial fungal species while inhibiting harmful species.

In the long journey from the young solid trunk to the ancient hollow state, multiple successions of fungal communities occupy the tree as host-space. The evidence of fallen and felled trees that have been dissected and show black zone lines (the 'spalted wood' prized by wood turners) and pseudosclerotial sheets within the wood (active even long after tree death) confirms the presence of territorial boundaries that are established by fungal communities. These control the tissue hydration and defend nearby wood-spaces against competing fungi. Antagonist communities act to control segregate adjacent populations (Schwarze 2008). In this sense the fungi may be the causal agent of compartmentalisation and may not need the active participation of the tree in the process of fungal containment (Rayner 1993; Rayner 1996).

As distinct from traumatic wounding (that induces centripetal decay) centrifugal decay does not normally initiate callus formation, at least not until the status of internal decay has become so far advanced that it is capable of influencing a cambial response, around expanding vascular bundles within the functional sapwood. Within the old trunk callus formation may arise along with adaptive growth as a (secondary) biomechanical response to micro-fissures and other topical changes leading to the formation of conductive functional columns within the sapwood. Perhaps the strongest influence on the development of discrete functional vascular channels is the requirement for hydraulic efficiency and the capacity for effective vertical compartmentalisation. In old trees, aerial reiterations exploit nearby channels within the symplast descending through the trunk and, while initially dependent on the parent tree, may be considered a hemi-parasite until reaching independence when supplied with an autonomous root system (Lonsdale 2013b). This time-mediated compartmentalisation differs in scope from the CODIT model and is an evolved survival strategy not triggered by damage.

With the complexity of ancient trees the survival of the '*tree-as-colony*' does not rely on individual components. In the course of rejuvenescence, with the emergence of unitarian components that become independent as young trees, compartmentalisation again takes on a greater role for individual survival, and CODIT again assumes significance in the course of injury and damage – the mystery as ever is in the cambium.

The ageing process and annual increment patterns

The dynamic relationship between the tree and its growing circumstances over decades or hundreds of years is recorded in the laying down, year on year, of woody tissue. The variable nature of the annual growth of a tree as expressed in tree rings and its relationship with climate and hydrology were noticed as far back as the 16th Century by Leonardo da Vinci. The fact that trees record the impacts of their environment in their wood anatomy is the foundation, not only of tree morphology but also of *dendrochronology* (chrono-sequencing), which translates annual ring growth patterns of the tree in terms of '*a natural clock*' (Baillie 1995) and may be used to study the pattern in growth of individual and groups of trees[8].

Growth in any specific year in the tree's history is the Current Annual Increment (CAI) of new wood that is laid down in any particular year by the tree, above and below ground. With regard to individual trees, the CAI is conventionally represented and measured by the width of the annual ring on the main stem. The CAI varies from year to year under the influence of seasonal and other conditions. Weather, hydrology, light and soil conditions together with the influence of life stage are all factors that affect the size of annual rings.

Over the passage of the ageing process, the CAI broadly follows patterns that reflect the young, mature and ancient life phases (see Chapter 2.1, Figs. 1 and 2). In the young maturing phase of the ageing process the annual increment of new wood laid down each year is more or less constant. During the mature phase, as the crown foliar volume changes little and the volume of new wood remains the same, ring width reduces, being spread over the still-expanding tree.

With the onset of the ancient phase (Stage 8) the CAI decreases in volume and ring width. With successful crown retrenchment, CAI may increase in local sectors of the main trunk and around developing functional, cambial columns as they increasingly individuate about the hollowing core. This pattern continues and rings tend to become discontinuous in circumference. Locally, CAI may increase as juvenescence promotes cambial resurgence and the formation of new individual trunk columns connected to crown and trunk reiterations. In the ancient phase (Stages 8-10) senescence may increasingly dominate with a trend towards accelerated decline reflected in diminishing CAI. However, if the rejuvenescence counter-trend is sufficiently strong, vigorous reiterations and individual columns may continue to develop either as independent clonal units with phoenix potential, or as contributors to the growth of the parent tree.

Retrenchment and ageing

Natural crown retrenchment is thought to be initiated when the root system is unable to further 'finance' crown expansion, having reached the ontogenetic limits of its life history

[8] Over recent decades dendrochronology has been applied to heritage dating, climate change history and forecasting, environmental forensics and even reconstruction of river stream-flow (Grissino-Mayer 2007; Berger 2011).

and species characteristics. The natural limits on continued tree growth are imposed by the laws of physics and biology which determine the functional range for energetic efficiency for the organism. Beyond peak maturity, these natural determinants initiate retrenchment about the tree as root and crown impose mutual regulatory constraints that reduce continued rates of growth above and below ground. Over a protracted period of time this is accompanied by increasing levels of redundancy, the shedding of parts and the accumulation of dead and decaying wood along with gradual die back. This process overall is referred to as natural retrenchment (Figs. 70a and 70b).

The processes that precipitate natural, age-related retrenchment start to take hold in the later stages of full-crown maturity, as new sapwood is spread more thinly year on year about the expanding body of the tree. This lessens the efficiency of storage and supply of photosynthetic assimilates to the crown, trunk and roots, and reduces the capacity of the tree to maintain previous levels of growth. Along with these changes, the mature-state height and complexity of xylem and phloem pathways impose levels of hydraulic resistance (Tyree & Ewers 1991; Rust & Hüttl 1999; Mencuccini *et al.* 2005). Together, these constraints create a tipping point seen in the contraction of the crown with consequent below ground influences. In comparison with animal ageing, cellular senescence in the 'tree-plant' is not considered a significant aspect of natural age-related crown decline (Thomas 2013).

Hydraulic and energetic equilibria (Clair-Maczulajtys *et al*. 1999) above and below ground are gradually re-established through a shortening and general simplification of pathways for water, nutrients and photosynthate (Mencuccini *et al*. 2007). As canopy light conditions change, internal crown growth is stimulated with the resurgence of new shoot generations including reiterations.

Fig. 70a, 70b: Natural crown retrenchment: a) roadside Penduculate oak, b) Spanish chestnut.

Fig 71a, 71b: Stress induced retrenchment - mature oak trees with impacted roots.

While age-related crown retrenchment is naturally benign, the condition may be misdiagnosed as symptomatic of irreversible ill-health. However, where natural retrenchment is successful, resilience and longevity are favoured and this phase of growth can be the longest in the life of the tree (Read 2000; Lonsdale 2013b).

Naturally occurring crown retrenchment is mostly only discernible in retrospect. The transition occurs gradually and slowly over long periods of Tree-Time and therefore is not readily observed in Human-Time. On the other hand, *induced crown retrenchment* is more readily observable as it affects significant portions of the crown relatively rapidly and under stress conditions, such as drought or root damage. These symptoms may be observed at any life stage (Figs. 71a and 71b). Induced crown retrenchment simulates advancing of the age-clock (Del Tredici 2000), and may be considered to *mimic* natural retrenchment. Stress induced changes are expressed in crown architecture and configuration of the twig structure, and can be more readily interpreted in pre-ancient age classes.

Natural crown retrenchment results in the establishment of a crown with reduced height, initially also with reduced foliar mass, leading to increasing morpho-physiological complexity in the overall ageing tree organism. At this stage, the tree is no longer an expression of a single trunk with a unitary crown but increasingly assumes a devolved 'colonial' condition, which

Fig. 72a, 72b: Colonial systems operating in a semi-autonomous stage.
A): an ancient Cretan olive tree showing complex, braided inter-woven vascular strands connecting as functional units between roots and crown.
B): A beech (*Fagus* s.) forming cambial columns from roots into the trunk. The emerging cambial columns are younger and subordinate to the parent trunk. The columns contribute to structural support and are influenced by wood decay fungi.

confers the potential for extreme longevity. Under the stimulation of hollowing and fungal interactions, these processes are amplified by the differentiation of the trunk into functional vascular connections (cambial columns) capable of developing individual linkage between parts of the retrenched crown and root system. Ancient phase decay and hollowing additionally enhances resilience to the extent that the tree evolves from a solid state to a light-weight structure reinforced by biomechanical adaptation. Crown retrenchment also contributes to the static safety factors through reducing crown mass, lever-arm and mechanical loading.

Modular ageing – reiteration and other expressions of the colonial tree

While trees appear to be individual plants, they are structured as populations of repetitive, homologous units *(phytomers*) (Thomas 2016). Relationships between these units are complex and not necessarily fixed, operating at fluctuating levels, and ranging from mutually supportive to competitive, depending upon the growth circumstances and life stage. In a sense, all these phytomers that are endowed with self-replication are expressions of *reiteration* or *reiterative growth*. Reiteration is fundamental to rejuvenescence potential in trees and occurs not only about the crown and on the main stem but also in the root system.

Conceptually and biologically, *Reiteration* in its fullest expression is a complete new tree, with stem, leaves and flowering potential, growing on the parent plant and sharing its genetic programme (Oldeman 1974).

Total reiterations faithfully represent the original young tree form and where physiologically adapted and conditions permit, may go on to recreate the parent as a clonal successor (Hallé 1999; Hallé 2001). Reiterations that repeat the growth pattern of the species without being a replicate of the parent tree in its juvenile state are *partial reiterations*. An adult tree comprises thousands of partial reiterations and relatively few total reiterations. Partial reiterations do not complete the morphological blueprint of the parent but essentially service the physiological functions of the tree.

The phyllotaxic expressions of most species of trees have recognisable underlying reiterative characteristics that do not normally develop beyond the partial stages. Partial reiterations that develop gradually without trauma beyond their primordial (fractal) state are termed *adaptive reiterations*. These develop in response to changes brought about by gravity and light and are characterised by the presence of third- and fourth-order branches that morpho-physiologically assume the role of the trunk and begin to mediate this through the vascular system of the original parent trunk.

By the time of full maturity, a number of reiteration sequences is likely to have occurred. During ancient Stages 9 and 10, adaptive reiterations that have evolved from natural crown retrenchment will likely develop into total reiterations, mostly originating from upper-surface dormant buds. These reiterations are the mainstay of the rejuvenescent crown architecture.

Thus through the process of reiteration the tree replicates its architecture with new copies of its basic architectural signature. While reiteration emerges from branches, these in fact function as entire mini-trees, growing on a parent-tree as if growing on a 'simulated ground level'. Reiterations, according to Hallé (2007), not only comprise trunk, branch and crown but also contain prototypic root organs that engage with the parent branch's vascular system.

The superabundance of meristems in a mature tree is borne upon the multiplicity of partial reiterations. This provides a potent generative store for new growth which is organised to accommodate damage, deterioration and senescence of individual parts and to promote longevity of the entire organism.

Alongside gradual adaptive reiterations, others may be induced in response to wounding or other damage events and are referred to as *traumatic reiterations* and that develop to replicate the young parent form. Examples of traumatic reiterations include epicormic sucker growths arising from storm damage, pruning and pollarding, which, given that these are mutually competitive, are subject to high levels of initial loss leading to a few dominant successors capable of expressing full reiterative potential.

Trees are colonial plants with the capacity to generate replicates, such that trees in the mature phase accumulate new architectural units on already-existing units, forming a colony (as with a coral reef). Certain types of unit are truly *reiterative in that* these are, in effect, young, clonal trees growing on an old tree. Reiterative units replicate the parent, when it was a young tree with a single, monopodial architecture.

Total reiterations from dormant buds evolve towards independence through proto-root systems with the existing vascular system potentially forming discrete root traces that may ultimately provide autonomy. In a sense, until entirely united with their independent root system, these units in morpho-physiological terms may be paradoxically thought of as parasitic upon the parent tree (Hallé pers. comm. 2016).

Phoenix reiteration

Phoenix reiteration is an important tree survival strategy that reflects the evolved capacity of a parent tree to regenerate vegetatively. This may occur as a result of traumatic failure followed by rooting of the fallen part (layering) (73a) or from adaptive reiteration through adventitious rooting, including through the old trunk to ground level (Fay & de Berker 1997) (Figs 5,6a). The latter may arise within the enriched medium of the ancient hollow trunk or as part of individuating sapwood cambial columns (Lonsdale 2013b).

Fig. 73a, 73b: Evolved vegetative phoenix survival strategies
A): *Tilia cordata* at Buckinghamshire, UK showing adventitious root grown from pollard crown through hollow trunk to the ground. It is now functional and structurally self-supporting. The original trunk has since decayed and fallen away.
B): Phoenix trunk layering of collapsed *Fagus sylvatica* at La Tallaie, Fontainebleau, France

3.3.3. Conservation management

Principles of Conservation Management

A fundamental principle in conservation management is that there should be no avoidable loss of ancient and other veteran trees. Furthermore, the Ancient Tree Forum UK considers that current guardians of ancient trees have a duty to protect them for future generations (Lonsdale 2013b).

This is in part attributable to the fact that ancient trees and their biodiversity are inherently valuable and irreplaceable. Also, even on sites where there are currently large populations of old trees, rates of decline and losses are commonly unsustainable.

Conservation management takes a number of forms. These include maintaining existing trees and their environment, and restoring deteriorating and declining trees and their habitat. Restoring individual ancient trees following trauma, disturbance and decline involves techniques that aim to re-establish functional balances in physiology and structure, essential to the conservation of old tree habitat. Management should also aim to protect against loss, and create future veteran trees and bridge habitat.

Whereas modern arboriculture emphasises crown management typically in light of amenity and safety (Gilman 2012), conservation arboriculture, in considering the tree as an ecosystem, aims to take account of the dynamic interactions between the tree and its surrounding habitat when managing the crown, the soil-root system and associated biodiversity (Lonsdale 2013b).

Conservation management needs to assess the status of individual trees and populations. This typically requires specialist training so that the vulnerabilities and priorities for inter-

Fig. 74:
Ancient tree showing time-driven vegetative responses to wounding and decay including processes subsequent to CODIT, pollard traumatic reiteration and subsequent phoenix rooting and stem regeneration

Ancient *Carpinus betulus* pollard crown with traumatic reiterations. Following pruning and decay and subsequent to the breaking down of the reaction zone (Walls 1 - 3) the cambial response has generated adventitious aerial roots, which have over decades grown down through the decaying trunk, nutrifying the crown. Adventitious roots have reached the ground and developed autonomous root systems.

Ageing adventitious roots have anastomosed above ground to form stem vascular columns within the ancient shell, which can replicate the function of the parent trunk. The successor root system and regenerated above ground parts have 'phoenix' potential.

vention may be understood. It is important to evaluate the risk *to the tree* from structural failure or physiological decline. It is additionally important for tree-related habitat quality to be assessed for tree management to be able to take this fully into account (Fay & de Berker 1997). From such assessments *individual tree management plans* (ITMPs) can be formulated to guide long-term conservation strategy. A tree viability scoring system can also be used to aid the implementation of the ITMP by helping to define conservation objectives, treatment priorities and the phasing of intervention (Figs 75 and 76) (Lonsdale 2013b).

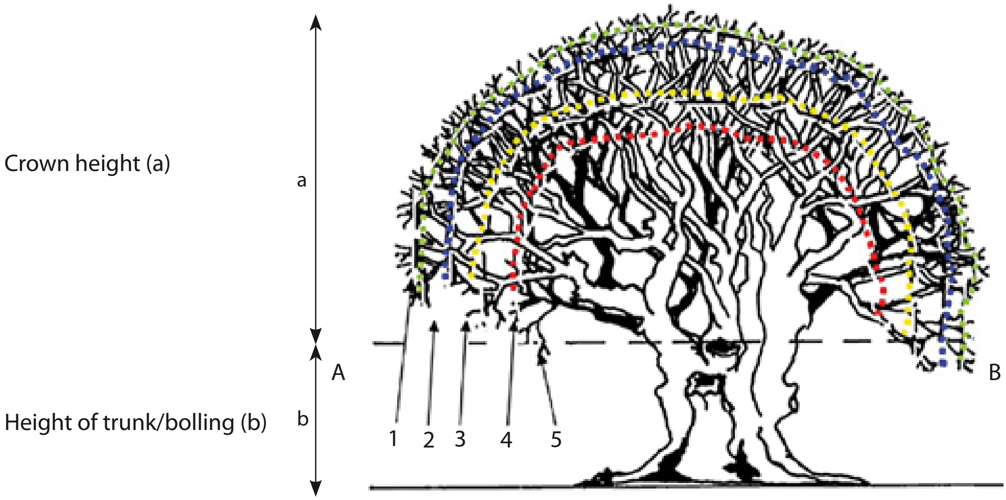
Retrenchment pruning

Retrenchment pruning is a technique used for veteran tree restoration. It has been developed and trialled in the UK over recent decades and has been adopted by conservation arborists elsewhere in Europe, as well as Canada, Australia and the US. The technique mimics the process of natural retrenchment of the crown as it gradually contracts when entering the ancient phase. Though as yet unproven, theoretically the technique imitates the way the root and crown systems interact in the ageing process and through the use of certain crown pruning techniques, the intention is to reciprocally influence root growth, with a view to restoring physiological balance both above and below ground.

Retrenchment Pruning is today accepted by the UK British Standard (BSI 2010). In this document it is defined as "*a phased form of crown reduction, intended to emulate the natural process whereby the crown of a declining tree retains its overall biomechanical integrity by becoming smaller through the progressive shedding of small branches and the development of the lower crown (retrenchment). This natural loss of branches of poor vitality improves the ratio between dynamic (biologically active) and static (inactive) mass, thus helping the tree as a whole to retain good physiological function*". The British Standard acknowledges that as old trees are sensitive to change, they require well-considered, planned and subtle treatments, sometimes extending over periods far in excess of those conventionally applied - *"Subsequent pruning treatments should take place only when newly developed branches suitable for retention have become strongly established. After the final phase of progressive reduction, a cyclic pruning of new growth should continue, so as to avoid the excessive loading of extensively decayed branches. If there is a need to encourage the production of a dense lower crown, the development of shoots from dormant and/or epicormic buds should be stimulated by retaining stubs when branches are pruned...*" (BSI 2010, Annex C.2).

Decisions on restoration

In order to implement these techniques successfully the arborist needs to be familiar with ancient trees and to have an understanding of tree rejuvenation processes, specifically the dynamics of vegetative growth and strategies to stimulate these processes (Hallé *et al*. 1978, Hallé 2001). The decision to initiate retrenchment pruning draws on an appreciation that ageing is not a one-way process in trees, and may affect different parts at different rates (Del Tredici, 2000). The selection of trees suitable for treatment and the type and dosage of pruning is informed by the morpho-physiological state of the particular tree, as well as an



Neville Fay (2008) *Treework Enviromental Practice*

Ratio Crown height (a) : Trunk height (b)	**Total number of years to carry out reduction**	Number of stages: To carry out phased reduction (including first stage)	Period between stages (no of years)*
4:1	36	6	6
3:1	25	5	5
2:1	20	5	4
1:1	16	4	4
Example for tree with crown/trunk/ ratio 1:3			
Stage 1 (year 1)	**Intervention stage**	Typically involves fine pruning (<10%) targeted reduction of end-growth (degree will depend on current vitality)	
Stage 2, 3 & 4 (years 5, 10, 15)	**Intermediate stages**	Typically five years later, in sequence (preceded by re-inspection, moderated if necessary in responce to vitality indications)	
Stage 5 (year 20)	**Final stage**	Preceded by re-inspection & carried out to achieve target height (expected to be five years after stage 4)	
*This may be reduced or extended depending on the vitality of the tree and its response to intervention and later stages of treatment			

Fig. 75:
Model Guidance example for phased retrenchment pruning based on individual tree management plan (ITMP)

assessment of tolerance to change and the long term prospects for restructuring the crown architecture. The latter includes strategies for working with reiterative units (Raimbault 1995, see also Chapter 2.1. Fig. 2), including phoenix growth (Fay 2002). Light demanding or shade bearing, branch-shoot (phyllotaxic) arrangements, sprouting (epicormic) tendencies are all important factors to be taken into account when considering the likely tolerance of the tree to intervention.

By observation the arborist can distinguish between natural and stress-induced processes and determine the basis for intervention. Restoration strategies may require that remedial measures should focus first on the soil and root system. In other cases restoration measures will be concentrated on crown rejuvenation through retrenchment pruning, or in extreme cases more major crown management to avoid structural failure.

Arborists need to be aware that when natural crown retrenchment is observed, this does not necessarily indicate decline in condition or health. In addition when decline is observed in post-mature trees, this is not necessarily irreversible. Before undertaking conservation techniques there is a need to gain competence in distinguishing between natural age-related retrenchment and stress-induced crown retrenchment (such as may be caused by root damage, excessive pruning or other trauma). It is also important to 'read' the tree's self-pruning trends, referring to the size of parts that are shed through natural pruning and cladoptosis (Rust & Roloff 2002).

Retrenchment pruning aims to achieve a reduced crown over the long term, while avoiding inducing trauma, using techniques sensitive to inherent rejuvenating processes. Treatment is *phased*. *Small-dose* pruning (e.g. typically less than 10% of foliar mass) is typically undertaken using predominantly small-diameter cuts (e.g. 25-50 mm diameter) focused on peripheral growth to stimulate internal epicormic development and other future orders of growth. The work is mostly carried out with hand tools, typically from mobile elevated work platforms (MEWPs).

The future programme of works will involve return treatments based on assessment of response. Important features of return treatments include continuing management of conductive pathways and of selected reiterative architectural units. Peripheral 'mosaic thinning' may also be required to address the effects of earlier pruning that has stimulated a marginal 'umbrella thatch' that restricts light penetration and impairs internal crown growth.

Old hollow trees with severe mechanical faults and old lapsed pollards that are prone to structural collapse require priority treatment. Where tree stability is already heavily compromised, reduction needs to be sufficient to reduce the crown load centre and lever arm to an acceptable level, and reduction in such cases will likely exceed retrenchment guidance..

Conservation soil management

When trees show signs of *low vitality*, pruning should be deferred until the *soil-rooting environment is assessed and its condition and biology improved*. Soil should be assessed for structure, aeration and, where practicable, biology and chemistry, to establish remedial specifications and a baseline against which to monitor change. Measures for improving compacted ground include introducing woodchip mulch and reconditioning soil.

Ancient phase rooting is highly variable due to historic below-ground changes and local influences on root mortality and rejuvenation. The pulses of root contraction and expansion are influenced by fluctuating conditions. Contracting and expanding root zones are typically eccentric and erratically distributed, sometimes with high levels of growth close to the trunk and distal roots exploring regions beyond the crown spread.

As the ancient tree is vulnerable to change, the root environment should be protected from disturbance. Best practice guidance with regard to the protection of ancient trees is that, where practicable, a protected zone should be maintained, extending radially from the trunk centre to a distance 15 times the trunk diameter (dbh) or 5 m beyond the crown, whichever is the greater. While such separation may not always be achievable, expert ancient tree guidance should be obtained to assess potentially harmful impacts and provide recommendations to safeguard tree viability (Read 2000; Lonsdale 2013b).

Where ancient trees exhibit abnormal stress symptoms, decline may be attributable to impaired soil conditions due to poor porosity affecting aeration, impaired drainage and in extreme cases, waterlogging. These factors influence soil biology, shifting microbiological balances away from benign to more pathogenic influences, also affecting root respiration and other functions (Popoola & Fox 2003; Roberts *et al*. 2006).

Introducing woodchip mulch is a generally effective non-technical treatment, used for some years at UK veteran tree sites (Himelick & Watson 1990; Lonsdale 2013b). Woodchip specifications are normally prescribed at 100 mm depth, applied as a blanket layer, radially or as a mosaic within the crown spread to the dripline, avoiding contact with the trunk and replenished annually to maintain cover. Woodchip should, if possible, be of similar species to the tree being treated.

Habitat creation, veteranisation and dead wood management

Natural events, including storms and drought, can create saproxylic habitat, as does tree surgery. The ancient practice of pollarding is a common treatment that accelerates habitat creation and veteranisation while incidentally contributing to longevity. The creation of decaying woody habitat in trees by deliberately inducing damage runs against the grain of amenity arboriculture. Nonetheless, the practice can be invaluable when there is a need to create *ark trees* due to serious loss and discontinuity of saproxylic habitat. Veteranisation methods include mimicry of natural damage processes that induce decay through e.g. natural fracture, 'coronet cutting' and other wound techniques (ATF VETree 2014) to create *bridge habitat* where deficits exist. Such strategies include recruitment of young trees, some of which may be deliberately planted as sacrificial candidates while others may be selected from existing stock for their long-term bridging contribution. Population analysis helps to determine succession planting when strategies are designed to ensure the presence of ancient trees into the future.

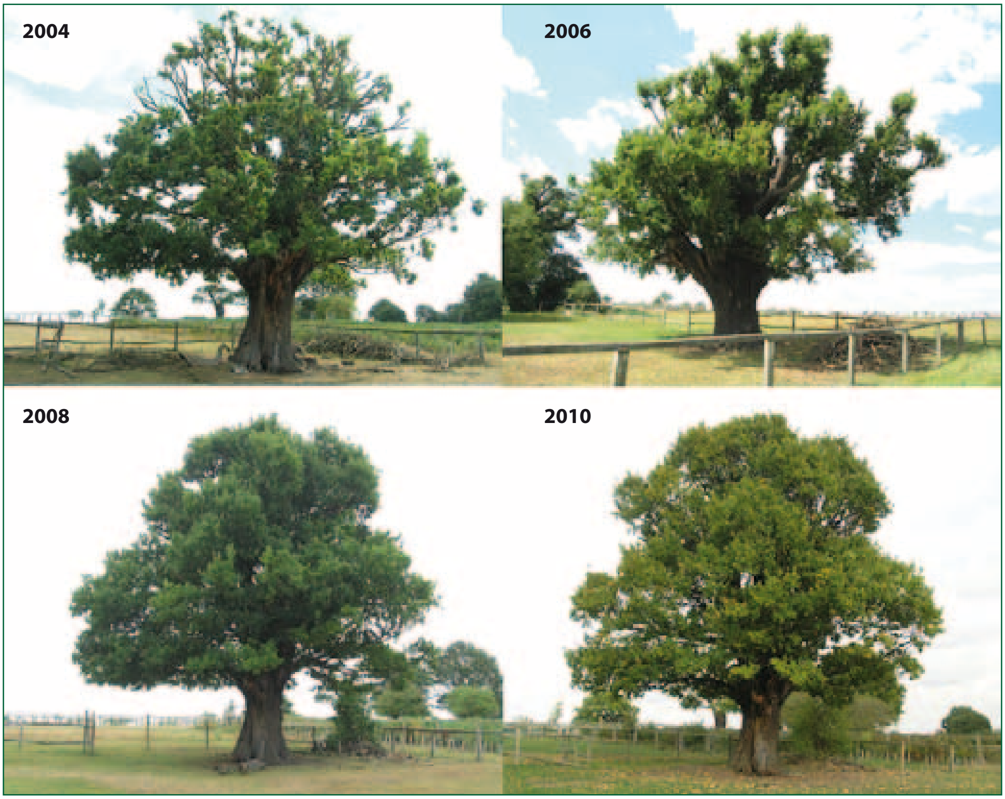


Fig. 76: Ancient pollard oak (*Quercus robur*) at Richmond Park National Nature Reserve, London included in the *Millennium Oak Study* carried out by Treework Environmental Practice. It is one of 835 veteran oaks and was identified to be high risk of mechanical failure. The photographs illustrate the retrenchment pruning and subsequent monitoring. It is due for a second phase treatment in 2016–17. Soil-rooting area management should partner crown treatment.

The UK British Standard for tree work – recommendations (BSI 2010) – recognises the value of dead wood as habitat and advises that "unnecessary loss of deadwood habitats should be avoided when specifying pruning or other works, particularly if legally protected species are using the tree". It further recommends that, rather than being automatically removed, dead branches and dead trees should be assessed and managed to meet a reasonably acceptable level of risk to people and property.

Notes on ancient trees and safety management

Over-reaction to perceived 'defects' in veteran trees has led, as a result of risk-aversion, to the loss of many irreplaceable ancient specimens and their associated habitat – in the perceived interests of meeting duty of care. Ancient and ark trees need to be inspected without

The Arthur Clough Oak

1910 1920 1950 1981 2009

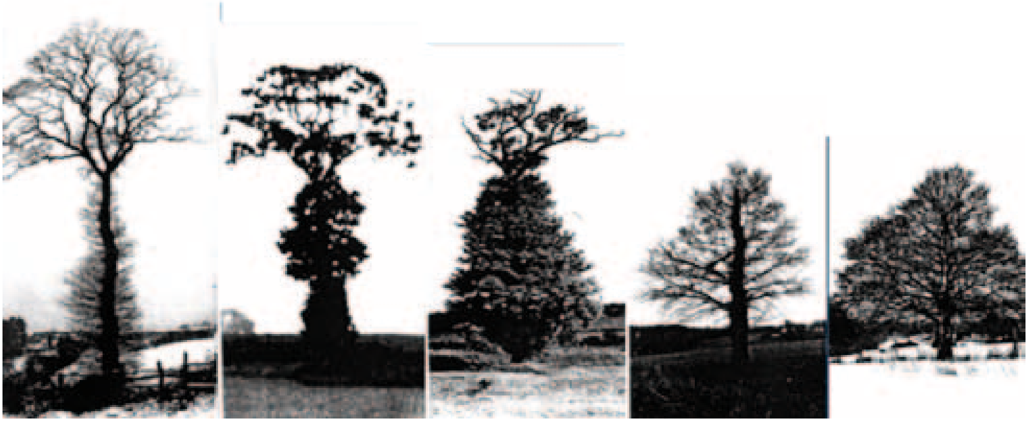


Fig. 77: The Arthur Clough Oak – a hundred years of ageing
It is hard to believe this is one and the same tree. We are limited in our understanding of 'tree time'. Probably most of us would neither have anticipated the next stage of growth nor foreseen the tree's rejuvenation response. Observing the ageing process helps us to understand the age clock and how it may be reversed when attempting to enhance tree longevity.
Thanks are due to Philip Stewart, Boars Hill for these images.

prejudice with the same level of diligence as applies to any other class of tree. While veteran features do not conform to the ideal of the solid utility tree, they need to be intelligently assessed in the context of their hazard status and, more importantly, distinguished from *risks* that may be posed. This is fundamental to risk assessment, as it is the risks that require reasonable management, not the hazard *per se* (Davis, Fay & Mynors 2000). Risk decision- making needs to determine the *real risks* posed by trees and respond appropriately to this (National Tree Safety Group 2011).

Tree habitat qualities and values need to be taken into account when managing risks. This requires that assessment be made in order to determine the type and level of management needed to achieve an acceptable level of risk. Risks are not required to be removed entirely; only that they be reasonably controlled. Thus *non-tree management* risk control should be explored, for example moving the target beyond the falling distance of the hazard before considering measures that may reduce the habitat value.

3.3.4. Conclusion

The developmental stages that accompany tree ageing from pre-juvenile to late ancient are generally poorly understood even in arboriculture, and this has led to the loss of a great number of ancient and other veteran trees. Part of the problem derives from the discrepancy between human-time and tree-time, which, when tested in retrospect, leads to hasty decisions and intervention based on often erroneous forecasting of tree responses. Fig. 9 illustrates a rarely-captured sequence of growth and retrenchment spanning a century – a relatively brief period, when measured against the scale of tree-time. Radical changes have occurred in the pulses of growth, during which time had intervention taken place, natural adjustments would have been distorted and we would have been none-the-wiser. We should bear in mind that the ages of a great many ancient trees far exceed that age of the tree in this example.

It is hard to find examples of the ancient tree paradigm in non-natural settings, particularly in the built environment where most arborists acquire their skills and experience. In such settings the arboricultural norm is determined by a modern, cost-benefit model that is mostly short-term and based on a concept of the 'useful life' of the tree, principally driven by requirements for safety and visual amenity. As a consequence, until relatively recently the value of tree habitat and biodiversity has had little place in the useful-life concept. However, we now know from studying the ancient tree that biodiversity and ecosystem values increase with tree age and that safety risks are frequently misunderstood and overstated.

Conservation arboriculture looks beyond the useful-life concept. Informed by experience of the ancient tree, it provides a lens, through which to view the archive of the tree's experience and a means by which to conceptualise the tree throughout its lifespan. Thus the paradigm of the ancient tree adds considerably to the use-value concept and opens up the prospect that future management planning will not only include an improved understanding of the young and maturing phases, but will also determine models to ensure that current young tree populations will provide the ancient trees of the future.

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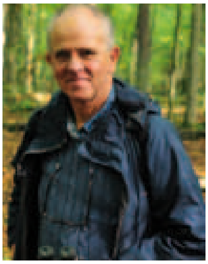


Nigel de Berker, B.A. (Hons), N.D.Arb. F.Arbor.A.

Since the early 1970s, Nigel de Berker has spent his working life involved with trees. Initially as a young man with the Royal Parks, National Trust and Royal Botanic Gardens, then developing his own arboricultural operational and consultancy practice with an emphasis on the management of veteran and ancient trees.
Over many years with his friend and colleague Neville Fay, he has worked to achieve a better understanding of the processes of trees, particularly in the ancient phase and has collaborated in the production of guidance on tree surveying, safety and conservation. He has been a Fellow of the Arboricultural Association since 1989.

Prof. Dirk Dujesiefken

Dirk Dujesiefken is „Diplom-Holzwirt" (Diploma in forestry and forestry products) and was a research fellow for the Chair for Wood Biology of the University of Hamburg (now: Center of Wood Science) from 1980 to 1991. In 1990 he founded the "Institut für Baumpflege Hamburg" (Institute of Arboriculture) and is working there since then. He is a consultant for wood biology and tree care and additionally the Organiser of the "Deutsche Baumpflegetage" (German Tree Care Conference) in Augsburg. He teaches at the University of Applied Science (HAWK) in Göttingen/Germany, at the Swedish University of Agricultural Science (SLU) in Alnarp/Sweden, and at the University of Natural Resources and Life Sciences (BOKU) in Vienna/Austria. The main subject of his research is tree biology and wound reactions. He is author of several books. Together with Prof. Dr. Walter Liese he wrote the book "The CODIT Principle – Implications for Best Practices", it was published by the International Society of Arboriculture (ISA), Champaign, Illinois/USA in 2015.

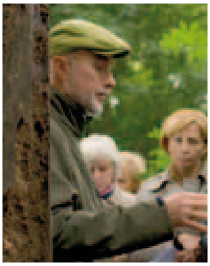
Jan-Willem de Groot

Jan-Willem de Groot (1975) was born in Ede and is owner of Boomadviesbureau De Groot from Veenendaal, The Netherlands. Ever since he was young, encouraged by his father, he developed a passion for nature and in particular trees and birds. In 1996 he graduated in forest- and nature management at Helicon in Rheden. An internship at Pius Floris Boomverzorging Veenendaal resulted in a job as a European Tree Worker. In the next ten years he learnt the profession of tree care and developed himself into a consulting arborist. In 2005 Jan-Willem de Groot founded Boomadviesbureau De Groot. His company provides professional and independent tree consulting services. He is the organiser of the Nederlandse Boominfodag (Dutch Tree Care Conference) at University of Applied Sciences Van Hall Larenstein in Velp. In 2011 he wrote an article about the concept of pruning young street trees in The Netherlands. It was published in Germany in Jahrbuch der Baumpflege 2011 and presented at the Deutsche Baumpflegetage 2011 in Augsburg and at the ISA international conference 2013 in Toronto.

Neville Fay MA (Hons), MICFor, MArborA, FLS, FRGS, FRSA

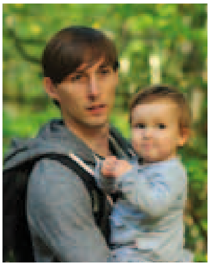
Neville Fay is a chartered arboriculturist with the Institute of Chartered Foresters and is principal consultant at Treework Environmental Practice, a leading UK multi-disciplinary consultancy. He is an expert witness for environmental claims and personal injury cases. Neville has co-authored with his colleague Nigel de Berker, The Specialist Survey Method (the national standard for surveying veteran trees). He has studied the tree ageing process and managed ancient and other veteran tree populations, working collaboratively with colleagues, pioneering ventures including soil and root studies in relation to tree health.

He is past chairman of the Ancient Tree Forum and founded the charity Tree Aid. He chaired the National Tree Safety Group (NTSG) drafting subcommittee. He is a professional member of the Arboricultural Association and in 2009 was granted its Award for Services to Arboriculture. He is a Fellow of the Linnean Society and of the Royal Geographical Society. He lectures internationally and writes on Conservation Arboriculture, ancient trees and tree management, public safety and policy. He co-authored Tree Surveys: a guide to good practice. He runs Innovations in Arboriculture, a seminar, study and educational series inspired by tree and ecological knowledge.



Piotr Tyszko-Chmielowiec PhD

Piotr Tyszko-Chmielowiec - director of the Tree Institute, conservationist and arborist, initiator and leader of the "Roads for Nature" programme. Co-author and editor of publications on management, assessment, and conservation of trees. Forester by education, graduate of Warsaw Agricultural University (M.S., silviculture) and Virginia Tech in Blacksburg, Virginia, USA (Ph.D., tree ecological physiology). Deputy president of the Foundation for Sustainable Development in Wrocław, Poland.



Kamil Witkos-Gnach BSc (Hons), TechArborA

Kamil is deputy Director and co-founder of the Polish Tree Institute, arboricultural consultant. He studied forestry at the University of Aberdeen. He then moved to Bialowieza National Park where he worked as Recreation Forester. Later Kamil joined the Roads for Nature programme as project manager and trainings coordinator. He is editor and author of books and articles on tree assessment, management and conservation. Kamil is a member of the Arboricultural Association and the Polish Dendrological Society.