Dissertationes Forestales 81

What was behind the bark?
– An assessment of decay among urban *Tilia, Betula* and *Acer* trees felled as hazardous in the Helsinki City area

Minna Terho

Department of Forest Ecology
Faculty of Agriculture and Forestry
University of Helsinki

Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in the auditorium 1041 at the Viikki Biocenter 2 (Viikinkaari 5, Helsinki) on April 3rd, 2009 at 12 o'clock.

Title of dissertation: What was behind the bark? – An assessment of decay among urban *Tilia, Betula* and *Acer* trees felled as hazardous in the Helsinki City area

Author: Minna Terho

Dissertationes Forestales 81

Supervisors:
Dr. Anna-Maija Hallaksela
Finnish Forest Research Institute, Vantaa Research Unit, Finland
Prof. Jarkko Hantula
Finnish Forest Research Institute, Vantaa Research Unit, Finland

Pre-Examiners:
Dr. Steve Woodward,
Institute of Biological and Environmental Sciences, University of Aberdeen, UK
Dr. Jonas Rönnberg,
Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Sweden

Opponent:
Doc. Heikki Kotiranta
Finnish Environment Institute, Finland

ISSN 1795-7389
ISBN 978-951-651-250-4 (PDF)

(2009)

Publishers:
Finnish Society of Forest Science
Finnish Forest Research Institute
Faculty of Agriculture and Forestry of the University of Helsinki
Faculty of Forest Sciences of the University of Joensuu

Editorial Office:
The Finnish Society of Forest Science
P.O. Box 18, FI-01301 Vantaa, Finland
http://www.metla.fi/dissertationes

Terho, M. 2009. What was behind the bark? – An assessment of decay among urban *Tilia, Betul*a and *Acer* trees felled as hazardous in the Helsinki City area. Dissertationes Forestales 81. 36 p. Available at http://www.metla.fi/dissertationes/df81.htm

ABSTRACT

Old trees growing in urban environments are often felled due to symptoms of mechanical defects that could be hazardous to people and property. The decisions concerning these removals are justified by risk assessments carried out by tree care professionals. The major motivation for this study was to determine the most common profiles of potential hazard characteristics for the three most common urban tree genera in Helsinki City: *Tilia, Betula* and *Acer*, and in this way improve management practices and protection of old amenity trees. For this research, material from approximately 250 urban trees was collected in cooperation with the City of Helsinki Public Works Department during 2001 - 2004. From the total number of trees sampled, approximately 70% were defined as hazardous.

The tree species had characteristic features as potential hazard profiles. For *Tilia* trees, hollowed heartwood with low fungal activity and advanced decay caused by *Ganoderma lipsiense* were the two most common profiles. In *Betula* spp., the primary reason for tree removal was usually lowered amenity value in terms of decline of the crown. Internal cracks, most often due to weak fork formation, were common causes of potential failure in *Acer* spp. Decay caused by *Rigidoporus populinus* often increased the risk of stem breakage in these *Acer* trees.

Of the decay fungi observed, *G. lipsiense* was most often the reason for the increased risk of stem collapse. Other fungi that also caused extensive decay were *R. populinus, Inonotus obliquus, Kretzschmaria deusta* and *Phellinus igniarius*. The most common decay fungi in terms of incidence were *Pholiota* spp., but decay caused by these species did not have a high potential for causing stem breakage, because it rarely extended to the cambium.

The various evaluations used in the study suggested contradictions in felling decisions based on trees displaying different stages of decay. For protection of old urban trees, it is crucial to develop monitoring methods so that tree care professionals could better analyse the rate of decay progression towards the sapwood and separate those trees with decreasing amounts of sound wood from those with decay that is restricted to the heartwood area.

Keywords: risk assessment, urban forestry, arboriculture, decay fungi

Mittaa tarkkaan
kahden puun välinen etäisyys,
kuuntele niiden
keskustelua, niin hiljaista:
ne puhuvat tulevaisuuden
epävarmoista tuulista.
Arvoituksellista on yhä kaikki.
Entä ihmiset?
He eivät ole täyteen mittaansa
vielä kasvaneet.

Kantautuuko
oppineisuuden kuurasta
elävä ääni?
Vai kertovatko puut,
yksinäiset puut
talven valossa,
lepattavan
sielun usvassa,
mahlasta,
näkymättömästä keväästä?

– Bo Carpelan –

ACKNOWLEDGEMENTS

This project was financed by the Finnish Forest Research Institute (METLA), the City of Helsinki and the Ministry of the Environment. The City of Helsinki provided all the help for collecting the study material. The analyses were carried out at METLA, where I started working in early 2001. At the later stage, the work was also funded by the Maiju and Yrjö Rikala Foundation, the Niemi Foundation, the Alfred Kordelin Foundation, and the Finnish Society of Forest Science. I want to express my gratitude to the financers, the staff of the Public Works Department of Helsinki City and the directors of METLA for providing all the facilities needed for this study.

The 'mother' of the project was Dr. Anna-Maija Hallaksela, who also became my supervisor, colleague and friend. Annu, I want to express my warmest thanks for these fine years, immemorial moments beside old trees, deep discussions of life and your loving support for my struggle to make this thesis come true.

I warmly thank Juha Raisio, Sampo Sainio, Sami Kiema, Kirsi Nyman, Antti Salminen and Hannu Kalaja for helping me to collect the study material. This work would never have succeeded without you, your patience, and positive attitude for this project! Luckily I have many photographs to cherish the memories of the days spent working with you.

Many people has helped me with various things during the project: Tuukka Heikura, Jari Perttunen and Risto Sievänen with the computer based decay analysis; Brita Aarnio, Annikki Viitanen, Hillevi Sinkko, Riitta Heinonen with the bureaucracy at METLA; Pentti Salonen and Olavi Kurttio with computers; Kerttu Rainio, Sonja Sarsila, Marja-Leena Santanen with the study material; William Roberts, Elina Peuhu and Liina Kjellberg with the fieldwork; Kari Korhonen for helping me with the manuscript II; and Anne Siika, Essi Puranen and Lotta Hardman with the layout of the thesis. My sincere thanks to all of you!

During the project I have come to know an anonymous group of Finnish arborists, and many of them have also been helping me to collect the study material. Thank you Teppo, Antti, Eeva, Marika, Aki M., Saija, Leena, Tapani, Päivi, Outi, Timo, Mare, Mika P., Tanja, Mika H., Aki T., Jussi including Hanna and Anu, the active members of the Finnish Tree Care Association. Your enthusiasm about trees has been 'infectious' and your spirit has fuelled my motivation!

I want to thank the reviewers, Dr. Steve Woodward and Dr. Jonas Rönnberg for their suggestions for improving this thesis. Prof. Jarkko Hantula and Prof. Fred Asiegbu are also acknowledged for their help in hurdling the final bureaucracy to become qualified.

I would like to thank my colleagues in METLA for all the different kinds of support during these years and also for all those coffee-table discussions of various subjects with a towards increase trend in absurdity from Monday to Friday. Henna and Ritva, I sincerely want to thank you for your time and presence, especially during 'the cloudy days'. Taina, Lotta, Eeva, Tiina and Heikki thank you for the special encouragement and advice for the final struggle.

My heartfelt thanks go to my dear friends, especially Katja, Eija, Paula, Johanna, Sari, Hanna, Minna, Marja-Leena, Anu, Sanna and Leena for their support. The very special ones I address to Virpi and Mikko. Virpi, you stood by me and pushed me at a time when my own strength was failing. Mikko, thank you for your excellent cookery, which I've enjoyed with hearty appetite so many times during this study project.

Finally, I would like to thank my family, the groundwork of my life. I sincerely thank my aunts Tuula and Anni for their interest and care together with the 'everyday luxury' of movies and family dinners. Anni, thank you also for those numerous transportation services between

Helsinki and the important cottage in Tammela. My sister and her family have provided me time and various kinds of help, from computer aid to relaxing times of just being together. Thank you Virva, Jaakko, Olli, Aino and Leo, you've been there whenever needed! My parents, Arja and Lauri, have always been willing to help me without question. This support has been irreplaceable, and especially during the last two years when financing was not always guaranteed. My sincere thanks to you, 'äiskä' and 'iskä', with big hugs!

Helsinki, January 2009

Minna Terho

LIST OF ORIGINAL ARTICLES

The thesis is based on the following articles that are referred to in the text by their Roman numerals:

I Terho, M. and Hallaksela, A-M. 2005. Potential hazard characteristics of *Tilia, Betula*, and *Acer* trees removed in the Helsinki City Area during 2001-2003. Urban Forestry & Urban Greening 3:113-120.

II Terho, M., Hantula, J. and Hallaksela, A-M. 2007. Occurrence and decay patterns of common wood-decay fungi in hazardous trees felled in the Helsinki City. Forest Pathology 37: 420-432.

III Terho, M. and Hallaksela, A-M. 2008. Decay characteristics of hazardous *Tilia, Betula*, and *Acer* trees felled by municipal urban tree managers in the Helsinki City Area. Forestry 81:151-159.

IV Terho, M. 2009. An assessment of decay among urban *Tilia, Betula*, and *Acer* trees felled as hazardous. Urban Forestry & Urban Greening (in press) (DOI 10.1016/ j.ufug.2009.02.004).

Some unpublished, concluding results are also presented and discussed.

AUTHOR'S CONTRIBUTION

I The main idea of the study, major part of fieldwork with identification of fungi by fruiting bodies, ideas of processing the analysis, interpretation of the results, and manuscript preparation was carried out by Minna Terho. Anna-Maija Hallaksela participated in the fieldwork and in editing the manuscript.

II The main idea of the study, ideas of processing the analysis, major part of field work, decay analysis, interpretation of results, and manuscript preparation was carried out by Minna Terho. Anna-Maija Hallaksela participated in the fieldwork by planning of the sampling for mycelia identifications, carried out the microscopical identification of the fungi, and participated in editing the manuscript. Jarkko Hantula conducted *Ganoderma lipsiense* identification by molecular methods and participated in editing the manuscript.

III The main idea of the study, ideas of processing the analysis, fieldwork, decay analysis, interpretation of results, and manuscript preparation was carried out by Minna Terho. Anna-Maija Hallaksela participated in the fieldwork by planning of the sampling for mycelia identifications, carried out the microscopical identification of the fungi, and participated in editing the manuscript.

CONTENTS

1 INTRODUCTION

1.1 Importance and problems of urban trees

Urban forestry has its roots in North America and Europe (Konijnendijk 1999, Konijnendijk et al. 2000). It is a relatively recent and rapidly developing field worldwide, into which are incorporated several disciplines: arboriculture, biology, forestry, horticulture, landscape architecture, social sciences, and ecology (Nilsson et al. 2000, Andersen et al. 2002). The diversity of green areas with trees ranges widely from forests to single urban trees. Three different types of urban trees can be defined, based on the conditions under which they grow: park trees, street trees and trees growing in urban woodlands (Nilsson et al. 2000).

The present study was focused on the care of park and street trees. These trees play a central role in built-up urban environments, creating pleasant and health-promoting neighbourhoods (Kuo 2003, Wolf 2003). Trees are, however, large organisms and their size causes problems in densely built-up residential areas. The room available for growth is limited, and trees become susceptible to many stress factors: stem- and root damage by traffic and excavation works, pruning wounds and soil compaction (Nilsson et al. 2000). Very often trees sustain injuries and usually their protective cortex layer is damaged. Trees become exposed to attacks of decay fungi and the decay process begins. The presence of decay does not mean the immediate death of the tree. The process extends over several years, but in urban areas the risk of accidents increases constantly.

1.2 Risk assessment - a management practice of urban tree care

According to the ‘European Tree Worker Handbook’ (2000), tree care comprises the planting, monitoring and maintenance of amenity trees. Tree care professionals take into account conservation matters, environmental protection and safety regulations. Diagnosis of ill health in trees and risk assessment are also included.

The purpose of risk assessment is to identify hazardous trees. A tree becomes hazardous if there is both a likelihood of failure and a potential target that could be damaged by it (Matheny and Clark 1994, Lonsdale 1999, Mortimer and Kane 2004, Ellison 2005). Liability aspects force councils to identify these trees and to treat them appropriately (Curle 1991, Mynors 1993, Matheny and Clark 1994, Mortimer and Kane 2004). The outcome is often that the entire tree must be felled. Public criticism is often directed against these actions. Therefore, good knowledge and sufficient justification are needed for management.

Risk assessments of trees are usually based on visual inspection of the current condition. One well-known procedure is the visual tree assessment (VTA) method, which is based on visual inspection for diagnostic symptoms of defects and tree vitality together with the residual strength of the tree (Mattheck and Breloer 1994a). This practice is commonly applied by tree care specialists working in Finland.

1.3 Decay as a potential cause for hazards in urban trees

1.3.1 Destruction of mechanical support

A tree crown is mechanically supported by the stem, which is anchored to the ground by roots. In general, this structure is mechanically 'optimized', and there are only two inherently major weaknesses in it, namely, weak fork formation and inability of roots to resist strong winds (Lonsdale 1999).

The major tissues of the stem are the outer bark, inner bark, cambium, sapwood and heartwood (Kramer and Kozlowski 1979). Of these tissues, sapwood and heartwood provide the main mechanical support for a tree stem. Sapwood conducts sap, strengthens the stem and, with the help of living parenchyma cells, stores food reserves. Heartwood is not involved in physiological processes. It consists of dead cells and provides only mechanical support for the tree. The anatomy of woody tissues and amount of heartwood differ greatly, depending on tree species and also individuals. The area of sapwood relative to heartwood is greater in the stem than in roots or branches of similar size (Shigo and Hillis 1973). In general, the structure is more homogeneous in gymnosperms than in angiosperms (Schwarze et al. 2000a).

The most important structure in wood anatomy is the lignified cell wall, which constitutes five cell-wall layers: middle lamella, primary wall and a three-layered secondary wall (reviewed by Schwarze et al. 2000a). The middle lamella contains pectin and lignin, and both primary and secondary cell walls contain cellulose, lignin and hemicellulosic polysaccharides. The largest part of the cell wall is the secondary wall that may contain up to 94% cellulose (reviewed by Schwarze et al. 2000a). Spatially, lignin forms a matrix surrounding the cellulose microfibrils. The amorphous structure of the middle lamella gives compression strength and stiffness to the cell wall. In contrast, structures formed from cellulose have high tensile strength (Blanchette 1991, Schwarze et al. 2000a).

Many organisms are involved in the decomposition of wood, but the transcendent role of decay fungi is based on their ability to decompose the lignified cell walls. The visible symptoms of wood decay vary from discolouration through partially broken structures and, finally to cavities. At the same time, wood gradually loses its mechanical strength. Several strategies have been proposed for this process, depending on the degradation order of different compounds. The degradation is enzymatic, but the enzymes that most saprophytic fungi produce do not degrade woody substrates effectively unless lignin is unbound, modified or removed (Blanchette 1991). The main types of decay are white rot, brown rot and soft rot (Table 1). In addition, two subgroups of white rot have been described (Table 1). The majority of decay fungi attacking broad-leaved trees cause white rot.

As a result of a different order in decomposition of wood structure, the consistency and mechanical strength of decayed wood have characteristic features, depending on the type of degradation strategy of the fungi involved (Table 1). In a simplified model of the mechanical effects of white rot on wood structure, lignin is broken down and soft, tough hollow ropes of cellulose remain (Schwarze et al. 2000a). This process particularly decreases the capacity of a tree stem to withstand compression loading compared with tensile loading (Mattheck and Breloer 1994b). A contrasting situation occurs with brown rot.

From the standpoint of stem breakage, knowledge of the lateral degradation rate towards the sapwood and stem surface is more crucial than the vertical spread of decay. For the likelihood of the tree to collapse two critical factors need to be considered: strength loss due to decay or defect, and the load required to cause a failure (Kane et al. 2001). In most of the thresholds applied, strength loss was the primary consideration (Kane et al. 2001),

Table 1. Characteristic features of different decay types (applied from Schwarze et al. 2000a). The characteristic features of each decay type are marked with x.

	Brown rot	White rot		Soft rot	
		Simultaneus rot	Selective lignification	Conventional picture	New information
Host					
Conifers	x (especially)	(seldom)	x	x	
Broad-leaved		x (especially)	x	x + wooden structures	x (especially)
Fungi					
Basidiomycetes	x (Polyporaceae)	x	x	x	
Ascomycetes		x	x	x	
Deuteromycetes				x	
Degradation					
Cellulose	x	x	x (later)	x	x
Hemicellulose	x	x	x (first)	x	x
Lignin		x	x (first)	slightly	x (strongly)
Consistency	fragile, powdery, brown, cracks, clefts	brittle	fibrous (stringy)	brittle	brittle
Strength	Drastic reduction of bending and impact strength	Less drastic than in brown rot, brittle fracture at the initial stage; great reduction of impact bending strength	Ductile fracture at initial stage; slight increase in impact bending strength	Between brown and white rot, high stiffness, brittle fracture	Between brown and white rot, high stiffness, brittle fracture

others, however, emphasized load (Wessolly 1995a). There was no consensus on any one single method (Wessolly 1995a, 1995b, Mattheck and Bethge 2005, Mattheck et al. 2006), but the importance of visual assessment of trees was stressed in studies and guides concerning the issue (Matheny and Clark 1994, Kennard et al. 1996). The strength loss estimation according to the VTA was based on the buckling strength of a cylinder more commonly known in engineering. It gives a critical threshold of 30% sound wood of the stem radius in hollowed trees (Mattheck et al. 2006). In practice, application of this guideline is depending much on the experience of the individual tree care professional.

1.3.2 Dynamic process

Trees are mainly exposed to decay fungi following wounding or through dead organs (Fig. 1). It was suggested that dysfunction of the current sapwood as a water-carrying tissue is the primary factor that creates the opportunity for fungal colonization (Rayner 1986). Very few fungi, e.g. some *Armillaria* species, are able to penetrate directly through the outer tissues, that are the bark, periderm and rhytidome of a living tree (Pearce 1996). Even after successful penetration, decay fungi must overcome the heterogeneous microenvironments within a living tree, e.g. unequal distribution of water between sap- and heartwood, high concentrations

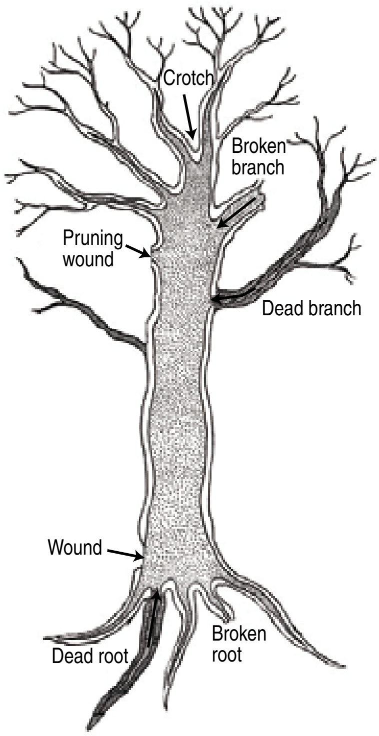


Figure 1. Routes for fungal infection (applied from Peace 1962).

of extractives in heartwood, active defence mechanisms in sapwood, and competition with other fungi (Rayner and Boddy 1988, Pearce 1996, Boddy 2000).

Several strategies were proposed for colonization of living trees by decay fungi (Rayner and Boddy 1986). Heart-rot fungi live in a microenvironment in which living cells are absent or rare and the gaseous phase may be extensive. Specialized opportunists exploit stressful conditions, e.g. drought stress, infection and internal competition. Active pathogens are those that are able to access intact sapwood by enzyme production, while unspecialized opportunists colonize sapwood via wounding or through dead bark. Individual fungi may be capable of combining several of these strategies.

Degradation in living trees is usually not caused by a single species of fungus (Shigo 1963, Shigo and Hillis 1973, Shortle et al. 1978, Rayner and Boddy 1988). Bacteria and organisms other than decay fungi were commonly observed in discoloured wood (Shigo and Sharon 1968, Tattar et al. 1971, Blanchette and Shaw 1978, Shortle et al. 1978, Blanchette et al. 1981, Parker et al. 1994). In addition, interspecific interactions occur between different decay fungi, as well as between different isolates of the same species (Rayner 1991, Owens et al. 1994, Boddy 2000). Competition is the most common of these interactions and can be divided into primary and secondary resource capture (Boddy 2000). In primary resource capture uncolonized resources, and in secondary, resources already colonized by other fungi, are colonized. As a result of these interactions, either replacement or deadlock follows (Boddy 2000). This process, however, may also be dependent on host vitality. Gramss (1992) showed that tree decline favoured unlimited mycelial colonization and survival. Therefore, it is important to consider whether the tree is colonized because it is dying or if it is dying because it is colonized (Rayner 1993).

Trees are protected from fungi by passive and active resistance. Passive resistance is formed by morphological and/or chemical barriers that prevent fungal penetration and colonization, including protective tissues such as bark and heartwood extractives (Biggs 1992, Merrill 1992, Woodward 1992). Unfavourable conditions for microorganisms in nonliving heartwood are based on the antimicrobial character of extractives accumulated in these tissues (reviewed by Pearce 1996, 2000). Active resistance, in contrast, involves induced morphological and/or chemical barriers to colonization by a pathogen (Bauch et al. 1980, Pearce and Rutherford 1981, Pearce and Woodward 1986, Pearce 1990). In wood, this activity occurs in living parenchyma cells. In general, sapwood is considered more resistant than heartwood. In addition to metabolically active defence responses, high water and low oxygen content are believed to restrict fungal growth (Rayner and Boddy 1988, Pearce 1996, 2000).

The walling-out response, which occurs in roots, stems and foliage, in the cortex-phloem and xylem, is the most common active but nonspecific resistance mechanism in woody plants (Merrill 1992). The principal function of this mechanism is to limit damage to the smallest possible volume of cells. One very well-known concept of compartmentalization is the model 'Compartmentalization of Decay In Trees' (CODIT). It was published in the 1970s as a result of increased understanding of the role of sapwood, succession of microorganisms, and differences between heartwood and discoloured wood in living trees (Shigo and Hillis 1973, Shigo and Marx 1977, Shortle and Cowling 1978, Shortle 1979). The CODIT model describes the importance of cell walls, which limit the vertical, parallel and perpendicular spread of decay fungi and other pioneer species (Shigo and Marx 1977, Shortle 1979).

The concept of compartmentalization is not universally accepted (Rayner and Boddy 1988, Pearce 1996, 2000, Smith 2006). Part of the criticism is based on the reasons for formation of boundaries. It is assumed that the reaction and barrier zones are formed to prevent aeration and drying of sapwood after wounding, and the restriction of fungal growth is more a consequence of this process (Rayner and Boddy 1988). In addition, decay processes in living trees could extend over several decades. It is a complex chain of environmentally influenced events driven by stress, competition and disturbance. Due to this complexity, no single theory alone can exhaustively describe either the progressive stages of degradation or the mechanisms that restrict wood-inhabiting microorganisms (Pearce 1996). However, even without a full understanding of decay processes, the principals of compartmentalization have helped to develop an understanding of some of the reasons why trees with extensively hollowed stems remain alive (Smith 2006).

In conclusion, our assumption on decay as a potential risk for stem collapse is based on extensive knowledge of scientific studies and practical experience. As a result, concepts of important fungal species, host-pathogen combinations and factors that should be noted in assessing the decay on urban trees are well developed (Mattheck and Breloer 1994b, Strouts and Winter 1994, Lonsdale 1999, Schwarze et al. 2000a). The problem is, however, how to digest all this information and adjust it in a local municipal risk assessment practice. There are various signs and symptoms, e.g. wounds, cracks, crown decline and fruiting bodies of decay fungi that help tree care specialists to recognize the presence of decay (Mattheck and Breloer 1994a, Matheny and Clark 1994, Lonsdale 1999, European Tree Worker... 2000). It is, however, impossible to predict exactly when a tree will fail or collapse, but the predictability of decay could be improved by observation (Lonsdale 1999, Kane et al. 2001), failure surveys after windstorms or other natural events (Burdekin 1977, Gibbs and Greig 1990, Kane 2008), and feedback from assessments after tree felling (Kennard et al. 1996).

2 AIMS OF THE STUDY

There are approximately 150 000 - 200 000 park trees and currently over 30 000 street trees in the Helsinki City area. The most common urban tree species are *Tilia* spp., *Betula* spp., and *Acer* spp. Approximately 18% of park trees are *Acer* spp., 14% are *Tilia* spp. and 11% are *Betula* spp.; these make up approximately 10%, 50% and 10% of street trees, respectively (I). The Public Works Department of the City of Helsinki is responsible for the management of most of these trees.

Since 1999 the parks in Helsinki have been undergoing an extensive restoration programme, including urban tree inventories with risk assessments. These inventories have shown that a large number of old park and street trees are in poor condition. This inventory work, together with strong public interest in the management actions taken, has made it necessary to define the timing of tree felling more carefully. The major motivation of this study was to specify the conventions of risk assessments used in the Public Works Department of the City of Helsinki, and in this manner to determine how these conventions could be improved to avoid premature removals without increasing the risk of decayed trees to people's health and property. To accomplish this task, the general hypothesis addressed below was tested with the more specific aims indicated by the numerals:

General Hypothesis:
Municipal practices of risk assessment and protection for mature urban trees may be improved by knowledge of specified failure profiles acquired by reassessment of decision making for tree removals after felling.

The specific aims of the study were to determine:

1. the importance of decay as a potential risk of stem breakage in urban trees (I, IV),

2. the decay fungi most hazardous to urban trees growing in Helsinki City (II),

3. the potential hazard characteristics of urban *Tilia, Betula*, and *Acer* trees (I, III, IV),

4. the defects that are the most probable indicators for hazardous decay (I, II, III, IV) and

5. how externally visible defects affect felling decisions (IV).

3 MATERIAL AND METHODS

3.1 Tree material

The study material comprised a total of 99 *Tilia* spp. (mostly *T. vulgaris* Hayne and *T. platyphyllos* Scop.), 77 *Betula* spp. (mostly *B. pendula* Roth and *B. pubescens* Ehrh.) and 89 *Acer* spp. (mostly *A. platanoides* L.) felled in the central parks and streets of the Helsinki City area (60°15'N, 25°00'E) during the period 2001 - 2004. The mean age of the trees was over 60 years, and the majority were old park trees (I). Approximately 70% of the trees were defined as hazardous (see definition in Table 2). A more detailed scheme of the tree material (I - IV) is presented in Fig. 2.

Tree care specialists from the Helsinki City Administration or private entrepreneurs assigned by the city examined the trees, and the Public Works Department of the City of Helsinki was responsible for the original risk assessment and decision-making and felling. For the present study, the condition of the trees before felling and decay analysis after felling were retrospectively investigated by the author after being informed that the trees were to be removed.

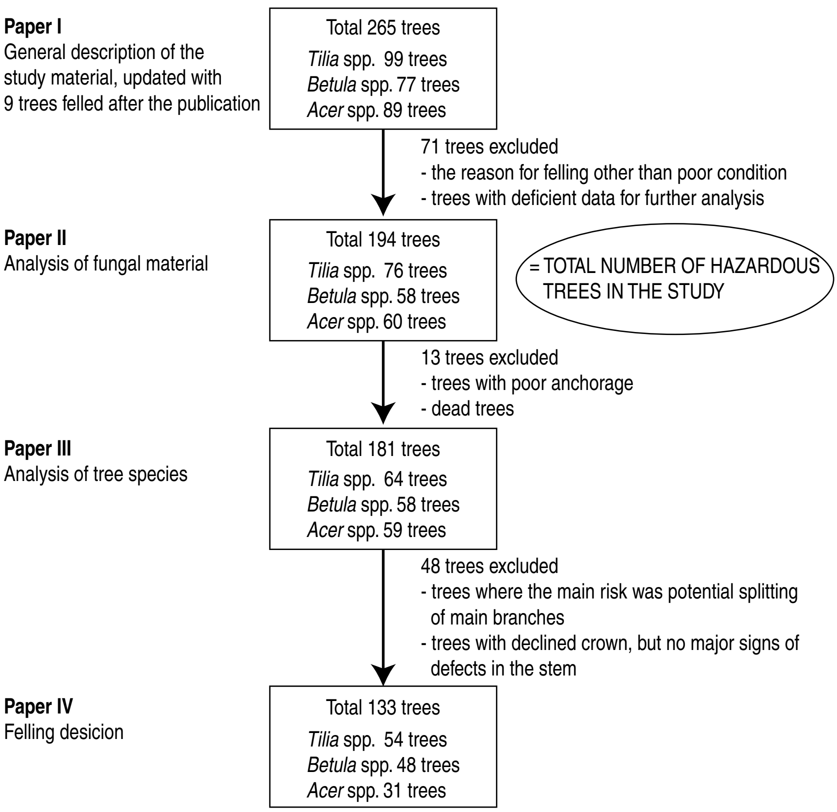


Figure 2. Scheme for preparing tree material used (I-IV).

Table 2. External variables used for defining the potential hazard characteristics of the trees felled as hazardous.

External variables	Reported in
Felling decision based on Tree AZ categories:	
Z removed based on external factors e.g. construction work	I
Z1 small or young (could be replaced like for like)	I
Z3 Dead, dying, diseased or declining trees	I, II, III, IV, Summary
Z4 Severe damage /structural defect e.g. decay	I, II, III, IV, Summary
Z5 Instability due to poor anchorage	I, II, Summary
Z10 Interfering trees	I
Z11 Poor trees occupying space for better ones	I
Hazardous trees = Z3 + Z4 + Z5	I, Summary
Potential failure points:	
Butt (& roots): Major defect located below 30 cm	I, IV, Summary
Butt & stem: Major defect located below 30 cm upwards	I
Stem: Major defect located in the vertical part of the stem	I
Stem & crotch: Major defect located in the fork area	I
Crotch: Major defect was splitting at a junction	I, Summary
Fungal fruiting bodies (see Table 3):	I, II, III, IV Summary
Damage Groups:	
Crack: Major external sign of a potential hazard was longitudinal crack(s)	IV, Summary
Pruning wound: Primary reason for main decay in the stem was a pruning wound	IV, Summary
Bruise: Primary reason for main decay in the stem was a stem bruise	IV, Summary
Roots: Only severe external sign of a potential hazard were *Ganoderma lipsiense* fruiting bodies in the butt	IV, Summary
Mixed: Several external signs of potential hazard, primary reason for the main stem decay could not been identified	IV, Summary
None: Declined trees with no major external sign of decay	Summary
Crotch: The major defect was splitting at a junction	Summary
Individual defects:	
Crack 1: Open, longitudinal crack with no rib formation	Summary
Crack 2: Open, longitudinal crack with rib formation	Summary
Crack 3: Closed longitudinal crack with rib formation	Summary
Pruning wound 1: Hollowed (exposed heartwood)	Summary
Pruning wound 2: Decayed (advanced decay)	Summary
Pruning wound 3: No decay	Summary
Pruning wound 4: Branch breakage	Summary
Stem defect 1: Wounds with exposed sap- and heartwood	Summary
Stem defect 2: Dents, bulges, and deformities with undamaged bark	Summary
Cavity: Openings with hollowed heartwood that could be observed externally	IV, Summary

3.2 Analysis of the study material

3.2.1 Sampling

The aim of the sampling was to determine the most likely point for stem breakage to occur. The critical points of tree breakage were estimated on the basis of decay extension and tree architecture. Analysis was carried out stepwise, as presented in Fig. 3. All the external variables used in I - IV and in the summary are listed and explained in Table 2. Two categorizations were used for external signs of defects: 'the potential failure points' (I), and 'the damage groups' (IV). Only the latter is used in the summary, because categorization into the damage groups was based on retrospective analysis after felling.

In the summary the number of the damage groups was complemented with the groups 'none' and 'crotch'(Table 2). In these trees decay was assumed to be a secondary cause for increased risk of hazard, which is why these data were omitted (IV). In addition, unlike in IV, more detailed categorization of cracks, pruning wounds and stem defects was added to the evaluation of external defects. These categories are described as 'individual defects' in Table 2. The complemented study material as a whole is presented in Table 3.

3.2.2 Fungal material

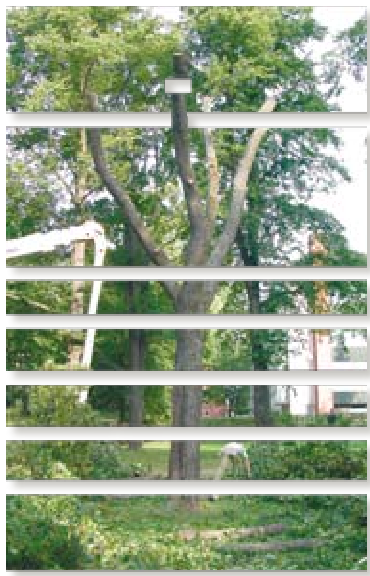
The list of decay fungi identified from the trees examined is presented in Table 3. Most of the decay fungi were identified on the basis of fruiting bodies, decay patterns and pure culture isolations. The following authorities were used for the identification of fruiting bodies: Jahn (1979), Breitenbach and Kränzlin (1984), Ryman and Holmåsen (1984), and Ryvarden and Gilbertson (1993). Microscopic identification of pure cultures was based on the results of Nobles (1948), Hallaksela (1977), and Stalpers (1978). Species of *Armillaria* were identified by means of mating tests (Guillaumin et al. 1991). The identification of *Ganoderma lipsiense* (Batsch) G.F. Atk. [synon. *G. applanatum* (Pers.) Pat.] isolates was verified by sequence analysis of internal transcribed spacer (ITS) regions as detailed (II).

3.2.3 Decay analysis

Analysis was based on the decay characteristics found at the point of the stem that was determined as having the greatest potential for breakage (see 3.2.1 Sampling). The risk caused by decay was assessed by examining two different aspects: decay stage (discoloured, advanced, hollowed) and decay profile by decay groups I - III (Table 4). The evaluations were made separately according to fungal species (II), tree species (III) and the major external defect (IV). The final evaluation of felling decisions was based on both external and internal assessments (IV). The importance of decay as a hazard factor is discussed in the summary.

Step 1
Measurements before the felling
- Photograph
- Evaluation of vitality
- Mapping all the main external signs of defects (height and location)
- Mapping the main branches and the height of crotches

Step 2
Sampling the cross-sections
- Crown elimination, only the main stem and branches were left up to about 8 metres
- Cardinal point was marked to the stem and main branches
- The cross-sectional sample discs were cut at the following locations:
  (a) lower-, middle-, and upper edge of defects
  (b) at the height of external signs of fungal fruiting bodies (or signs of infection)
  (c) under and above the crotches of main branches
  (d) upper edge of the main column(s) of decay
  (e) butt



Step 3
Study material for future analyses
- Height, top/bottom-side, and cardinal points were marked on the sample discs
- Photograph for future measurements
- Wood pieces from representative decay patterns for pure culture isolations of fungi

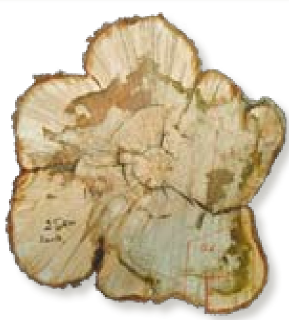


Figure 3. Stepwise analysis used for each tree to sample the decay fungi and to define the point of the stem at which breakage was most likely.

Table 3. Number of trees in the different damage groups and variable categories.

	Damage Groups							
	None	Crotch	Crack	Pruning wound	Bruise	Roots*	Mixed	Total
	Number of trees							
Group total	12	36	17	24	25	9	58	181
Betula spp.	4	6	15	-	6	-	27	58
Tilia spp.	4	6	2	21	9	8	14	64
Acer spp.	4	24	-	3	10	1	17	59
External variables:								
Declined trees	12	3	6	1	4	1	35	62
Butt (& roots)**	-	-	1	2	13	9	9	34
Crack 1 (open)	-	29	17	8	9	3	31	97
Crack 2 (open with rib)	2	12	3	7	1	-	13	38
Crack 3 (closed with rib)	-	7	-	9	2	-	11	29
Pruning wound 1 (hollowed)	-	7	1	16	7	-	19	50
Pruning wound 2 (decayed)	2	18	5	10	5	3	22	65
Pruning wound 3 (no decay)	4	19	7	9	9	5	24	77
Pruning wound 4 (dead/ broken)	1	4	8	2	3	-	25	43
Stem defect 1 (damaged bark)	8	12	8	10	25	1	38	102
Stem defect 2 (undamaged bark)	3	19	5	4	9	3	23	66
Cavitiy trees	-	11	4	12	11	-	19	57
Internal variables:								
Discoloured stage of decay	4	2	3	-	-	2	4	15
Advanced stage of decay	6	15	3	1	8	6	17	56
Hollowed stage of decay	2	19	11	23	17	1	37	110
Fungal species:								
Armillaria spp.	1	5	1	1	2	-	9	19
Chondrostereum purpureum	2	3	1	1	3	-	10	20
Climacodon septentrionalis	-	6	2	-	-	-	2	10
Cerrena unicolor	-	-	1	-	-	-	4	5
Ganoderma lipsiense	-	2	-	1	3	9	6	21
Hypholoma spp.	-	-	-	5	1	-	3	9
Inonotus obliquus	-	2	4	-	-	-	11	17
Kretzschmaria deusta	1	5	-	1	4	1	2	14
Piptoporus betulinus	-	1	4	-	1	-	12	18
Phellinus igniarius	-	1	-	-	-	-	6	7
Pholiota spp.	1	13	7	5	9	-	16	51
Pleurotus spp.	-	5	-	-	4	-	1	10
Rigidoporus populinus	1	15	-	2	5	2	8	33

*) *Ganoderma lipsiense* fruiting bodies observed in the butt of the stem

**) Primary damage was located below 30 cm

Table 4. Internal variables used for defining the decay characteristics of the trees felled as hazardous.

Internal variables	Reported in
Decay stage:	
Discolouration: Only discolouration in the main stem	II, III, IV, Summary
Advanced: Visible changes in wood structure, no hollow	II, III, IV, Summary
Hollow: Hollow formed in the main stem	II, III, IV, Summary
Proportion (%) of decay from the cross-sectional area: Included advanced decay and hollow	II, III
Extension of decay to disc margin (cambium)	II
Hazard profile of cross-sectional sample: Crack: Potential hazard factor is primarily a crack Hollow: Potential hazard factor is primarily a hollow Advanced decay: Potential hazard factor was advanced decay in >50% of the cross-sectional area, or affected the sapwood in >90° of the disc circumference Other: No potential hazard caused by decay	III
Decay Groups:	
Decay I Moderate type of decay: Still vital trees where the amount of decay was <70% from the cross-sectional area, in the part of the stem where breakage was most likely. In some of the trees decay was unlikely to cause a risk of stem breakage at the time of tree felling. In the others the critical threshold of Mattheck et al. (2006) could have been exceeded, but the sound wood cylinder was complete and/or the tree had responded to the injury by growth reactions. 	IV, Summary
Decay II Poor type of decay: Still vital trees where the amount of decay was <70% from the cross-sectional area in the part of the stem where breakage was most likely, but it clearly posed a potential danger of stem breakage e.g. decay located across the cross-section and decay extended severely to the disc margin. 	IV, Summary
Decay III Crown decline: Trees with declined crown and external signs of decay. This group also included 4 trees, where the amount of decay was >70%, although the crown was not declined. 	IV, Summary

4 RESULTS AND DISCUSSION

4.1 Potential hazards

In general there are three potential hazards for urban trees: uprooting, branch breakage and stem collapse. Poor anchorage is often the primary cause for uprooting and weak branch attachments for branch breakages (Mattheck and Breloer 1994b, Lonsdale 1999). In contrast, stem collapse could be caused by several factors, due to tensile and compressive loading of trees (Mattheck and Breloer 1994b). The loss of strength of wood structures caused by horizontal progression of decay is one of these factors.

Based on the present results (I - IV), it can be concluded that in 61% of the trees felled as hazardous (Table 2 and Fig. 2), risk of stem collapse caused by decay was the most crucial factor for decreased safety. This proportion consisted of trees included in the damage groups pruning wounds, bruises, roots and mixed (Table 3). Knowledge of horizontal progression of decay and crown vitality were crucial in assessing the safety of these trees.

In the other trees, factors other than horizontal progression of decay were evaluated more as the primary causes of decreased safety. This proportion consisted of trees included in the damage groups crotch (weak branch attachments), crack (disruption of the uniform distribution of mechanical stress) and none (physiological problems such as drought). In addition, uprooting caused by poor anchorage was the primary reason for the decreased safety of trees grouped in TreeAZ category Z5 (Table 2).

4.2 Potential hazard characteristics of *Tilia, Betula* and *Acer*

Based on the present results, the characteristic profiles for potential hazard characteristics were identified for each of the tree species studied. The species-specific characteristics were evidently already based on the external signs of defects and inventory of fungal fruiting bodies (I), but the internal assessment ensured these conclusions (II - IV). For *Tilia* spp. the most probable hazard was stem breakage due to large cavities or extensive cross-sectional decay caused by *G. lipsiense*. The primary defects for cavities were large pruning wounds, and root damage resulting from *G. lipsiense* infection (IV). *Betula* species were most often removed due to crown decline. In addition, for *Betula* spp. the risk of stem breakage hazard was most often caused by large cracks, and extensive degradation by *Inonotus obliquus* (Pers.: Fr.) Pilát, *Piptoporus betulinus* (Bull.: Fr.) P. Karst., and *Cerrena unicolor* (Bull.: F.) Murrill (I, III, IV). For *Acer* spp. the most probable hazard was branch breakage. Decay caused by *Rigidoporus populinus* (Schumach.: Fr.) Pouz. [synon. *Oxyporus populinus* (Schumach.: Fr.] commonly increased this type of risk (I, III). In addition, decay caused by *Phellinus igniarius* (L.: Fr.) Quél. sensu lato and *Kretzschmaria deusta* (Hoffm.: Fr.) P. Martin [synon. *Ustulina deusta* (Fr.) Petrak] increased the risk of stem collapse of *Acer* spp. (II).

Relatively limited research has been carried out on species-specific differences in the failure profiles of urban trees, and most of the information is based on practical experience and observations made during fieldwork (Lonsdale 1999). *Tilia* spp., *Betula* spp. and *Acer* spp. do not differ widely based on the list of tree genera most commonly recorded as wind-blown (Cutler et al. 1990). *Acer* spp. and *Tilia* spp., however, cause damage to properties more often than *Betula* spp. (Gasson & Cutler 1998), as also suggested by the present results. Because of the symptoms of decline in the most hazardous *Betula* spp. trees (I, III), they are usually felled due to the lowered amenity value before any damage could occur (II). With *Tilia* spp. and *Acer* spp. the symptoms were not as obvious, and the risk for unpredictable hazard was therefore higher than with *Betula* spp.

In many of the hollowed *Tilia* trees, successful compartmentalization of decay was indicated by low proportions of discoloured wood and low expression of decay fungi (III). These observations support previous proposals that *Tilia* spp. effectively compartmentalize around wounds (Dujesiefken et al. 1989, 1998, 1999).

Tilia spp. were mostly affected by *G. lipsiense* decay (III), partly due to the impact of human influence. Being the most common street tree species in the Helsinki City area (I), *Tilia* spp. are more frequently exposed to activities that damage their roots than are *Betula* spp. and *Acer* spp., and therefore are more likely to become colonized by *G. lipsiense*. Urban environments under extensive human influence are considered to favour the fungus (Erkkilä and Niemelä 1986, Niemelä and Kotiranta 1986). In forests, however, *G. lipsiense* is considered to be more of a saprophyte and is commonly found on *Betula* spp. and *Populus* spp. stumps (Erkkilä and Niemelä 1986, Niemelä and Kotiranta 1986, Lindhe et al. 2004).

The high proportion of declining *Betula* trees also supports previous descriptions of species-specific characteristics. *Betula* spp. are considered among the shorter-lived of trees (reviewed by Atkinson 1992), and comparatively early decline is a characteristic of this genus (Bennell and Millar 1984). *Betula* spp. tolerate drought poorly, especially during the summer (Phillips and Burdekin 1982, Peinado and Moreno 1989, Atkinson 1992). Dead branches act as infection routes for fungi, and the symptoms of infected roots are often observed as dead branches and declining crowns (Rayner and Boddy 1988, Hallaksela and Niemistö 1998). A low compartmentalization capacity contributes to the decay process and, as a result, old *Betula* trees in urban surroundings often become decayed (Bauch et al. 1980, Dujesiefken et al. 1989, 1999).

It is also commonly known that *Acer* spp. are susceptible to weak branch attachments (Gibbs and Greig 1990, Lonsdale 1999). The high frequency of *R. populinus* in the present study is, however, worth noting. Due to critical location it was considered one of the most problematic decay fungi from the standpoint of risk assessment. In addition, the role of *R. populinus* as a decay agent could not be comprehensively evaluated, due to the problems in isolating it in pure culture (II). It is known that *R. populinus* cannot invade intact wood before other organisms first alter it, but *R. populinus* is probably the organism that initiates degradation of the cell wall. It can effectively decompose both lignin and cellulose and hence reduce the stability of trees (Shortle et al. 1971, Tattar et al. 1971, Shigo 1974). In Canada, Nordin (1954) reported that fruiting bodies of *R. populinus* were frequently present in merchantable forest trees of *A. saccharum*, but usually this polypore is not emphasized in tree care references (Strouts and Winter 1994, Lonsdale 1999, Schwarze et al. 2000a), probably because it is not considered very aggressive.

4.3 Decay as a potential risk for stem collapse

4.3.1 Symptoms of decay - entry points for fungal infection and crown decline

Numerous scientific studies have dealt with the entry points in trees for fungal infection, many of them from the perspective of host-pathogen interaction (Rayner and Boddy 1988, Blanchette and Biggs 1992). Another alternative is to study wounds and defects in relation to the extent of decay in trees. This perspective is commonly used in studying logging damage in forest trees (Mäkinen et al. 2007). Both perspectives are important in risk assessments of urban trees. With old decayed trees, however, the variety of symptoms makes it sometimes difficult to detect which is the primary entry point for fungal infection.

Splitting of main branches (crotch) was the most common single risk for failure throughout the study material (Table 5). This type of risk is primarily structural and caused by the inherent weakness of the branch attachment. Due to injury or cracking in the crotch, the bark included is formed in between the branches or between the branch and trunk. This makes the cell arrangements in the branch attachment discontinuous. The sharp angles between the branches and accumulation of snow and ice increase this type of risk (Shigo 1985). In addition, failure may become more likely if each of the stems above the fork grow thicker than the main stem below the fork (Helliwell 2004). Storm surveys showed that branch breakages are, together with uprooting, the most probable type of failure (Burdekin 1977, Gibbs and Greig 1990).

The branch crotch is also a common infection route for decay fungi (Shigo 1986). This type of decay, therefore, increases the risk of branch splitting. Of the fungi studied *R. populinus* and *Pholiota* species were most frequently recorded in association with weak branch attachments (Table 3). In addition, 60% of the total records of *Climacodon septentrionalis* (Fr.) P. Karst., 50% of *Pleurotus* spp., and 36% of *Kretzchmaria deusta* were also detected in branch crotches.

Pruning wounds, stem bruises and cracks were in the present study almost equally common infection routes responsible for the amount of decay detected in the most likely point of stem breakage (Table 5). It should, however, be noted that as a primary defect, pruning wounds were almost solely characteristic for *Tilia* spp. and cracks for *Betula* spp. (Table 3). This affected the outcome of fungal species detected in these trees. With stem bruises the three tree genera were more equally represented (Table 3).

Table 5. Proportions of main defects found in the trees felled as hazardous.

Main defect	% of the total number of hazardous trees in the study
According to the primary defect:	
Mixed	30
Crotch	19
Pruning wounds	13
Bruise	13
Crack	9
None	6
Roots & *Ganoderma lipsiense*	5
Poor anchorage	5
According to the ground level:	
Below ground*	16
Above ground**	84

* Includes: None, Roots & *Ganoderma lipsiense*, and Poor anchorage

** Includes: Mixed, Crotch, Pruning wounds, Bruise, and Crack

There is variation in how different tree species react to pruning. Large pruning wounds should be avoided with species that have weak compartmentalization capability, as well as with those species that do not form branch collars (Dujesiefken et al. 1998, Eisner et al. 2002). As with pruning wounds, the main risk posed by bruising is the infection routes opened to decay fungi. In half of the trees, where bruises were evaluated as a major external defect, they were located on the butt (IV), and root damage, therefore, may also have been expected. Of the fungi studied, *Pholiota* spp. were most often recorded in such wounds (Table 3). In addition, 40% of the total records of *Pleurotus* spp., and 29% of *K. deusta* were detected in trees where bruising was evaluated as a major external defect.

Roots as entry points for fungal infection were not investigated directly in the present study. This was mainly due to the available resources used to obtain the root material. Sampling the roots would have been both expensive and laborious. However, based on the external and internal assessments, roots were assumed to be the primary route for *G. lipsiense* infection (IV). The main external signs of decay in these trees were the fruiting bodies of the fungus. Of the fungal species detected in the study, *K. deusta, Armillaria* spp. and some *Pholiota* species were also described as root and butt pathogens (Schwarze et al. 2000a). In addition, *Pholiota* species may play roles as predisposing factors to other decay-causing species (Ross 1976, Lonsdale 1999, Schwarze et al. 2000a). Severely pathogenic species of *Armillaria* [*A. ostoyae* (Romagnesi) Henrik, *A. mellea* (Vahl: Fr.) Kummer] were not found in the trees investigated (II). *Armillaria cepistipes* Velenovsky was the dominant species and *A. borealis* Marxmüller and Korhonen was also recorded. These are the most common *Armillaria* species in Finland and are mostly saprotrophs but also weak pathogens of coniferous and broadleaved trees (Korhonen 1978, Roll-Hansen 1985, Prospero et al. 2004).

Mixed signs of defects were observed in one third of the trees felled, due to poor condition. In 60% of these crown decline was recorded (Table 3), and therefore the diversity of decay fungi resembled the list of species that are commonly mentioned as appearing on environmentally stressed trees (Korhonen 1978, Seehan 1979, Niemelä and Kotiranta 1983, Erkkilä and Niemelä 1986, Rayner and Boddy 1988, Lonsdale 1999). In addition, the high frequency of *Betula* trees influenced the variety of fungal species detected in trees with mixed signs of defects in this study (Table 3). Species that were specialized for *Betula* spp. were pronounced, including *C. unicolor, P. betulinus* and *Inonotus obliquus* (IV).

Decline was also characteristic of the trees included in the damage group 'none' (Table 3). The only symptom of decreased safety in these trees was crown decline. Very often, defective soil conditions lead to decline and death of trees before any detailed risk assessment is performed. Growing conditions below the ground are harsh for trees in urban environments. Soil compaction by heavy machinery, excavation work, use of de-icing salts and restricted space for roots are all examples of issues that decrease the lifespan of urban trees (Nilsson et al. 2000). In addition, a limited water supply is one of the most important factors in urban environments (Sæebø et al. 2003, Holopainen et al. 2006).

4.3.2 Effect of fungal species

For making felling decisions on trees showing signs of decay, it is important to distinguish between two types of decay fungi: those able to cause progressive horizontal decay and those that are more stable in terms of horizontal spread of decay. Due to its ability to cause progressive horizontal decay, *G. lipsiense* was found in 10% of the trees felled as hazardous in the study and was the cause for increased risk of stem collapse. This increased risk occurred at the highest frequency of any fungus identified in the study (Table 6). In addition, *G. lipsiense* often appeared at the base of the trunk, resulting in a potential for the entire tree to collapse (II, IV).

The identification of *G. lipsiense* isolates was confirmed in a population study (II), which supported previous reports that the dominant species of *Ganoderma* spp. in Finland is *G. lipsiense* (Jahn 1979, Ryman and Holmåsen 1984, Niemelä and Kotiranta 1986, Ryvarden and Gilbertson 1993). In central Europe, however, several *Ganoderma* species are commonly known as harmful decay agents of many urban tree species (Strouts and Winter 1994, Schwarze et al. 2000a, Schwarze and Ferner 2003). Recent studies have shown variation between these species in their relative abilities to colonize sapwood (Schwarze and Ferner 2003). For the correct management of trees, it is therefore crucial to identify the particular *Ganoderma* species correctly. Due to very similar fruiting bodies and differences in their ability to breach the reaction zones formed by the trees, accurate identification is especially important with *G. adspersum* (Schulzer) Pat. and *G. lipsiense* (Schwarze and Baum 2000, Mattock 2001, Schwarze 2001, Schwarze and Ferner 2003).

Although *Pholiota* species were the most frequent decay fungi in terms of incidence, they were less commonly isolated than *G. lipsiense* at the points where stem breakage was most likely (II, Table 6). Similar results were obtained for other agarics (II). In contrast, *R. populinus, I. obliquus, K. deusta* and *P. igniarius* were among the species that had the greatest potential for causing stem breakage (II, Table 6). Of these species *R. populinus* was frequently present in weak fork formations, while the potential risk caused by *I. obliquus* and *P. igniarius* was relatively predictable by reliable appearance of fruiting bodies, well-delimited heart rot, or lowered vitality of the crown (II).

Table 6. Significance of the various decay fungi studied in hazardous trees. The percentages represent the proportion of trees in which each fungus was present at the point of the stem where breakage was most likely.

The cause for potential hazard at the point of stem where breakage was most likely	% of the total number of hazardous trees in the study
Advanced decay caused by:	
Ganoderma lipsiense	10
Rigidoporus populinus	7
Inonotus obliquus	6
Kretzschmaria deusta	5
Phellinus igniarius	4
Pholiota spp.	4
Armillaria spp.	3
Climacodon septentrionalis	3
Hypholoma spp.	3
Cerrena unicolor	2
Piptoporus betulinus	2
Pleurotus spp.	1
Chondrostereum purpureum	0
Other reasons*	50

* Includes: trees with instability or poor anchorage; trees where the potential risk was splitting of main branches (without fungal observation); and trees with no fungal observation (especially on *Tilia* spp.).

Kretzschmaria deusta could, in terms of diagnostics and brittleness of decay (cf. selective lignification of *Ganoderma* spp.), be considered more harmful than *G. lipsiense* (Schwarze et al. 1995). However, the appearance and abundance of *K. deusta* fruiting bodies correlated well with the advancement of decay (II). Therefore, it was suggested that the appearance of fruiting bodies of *K. deusta* better indicated a tree that had exceeded the critical threshold for felling than the appearance of fruiting bodies of *G. lipsiense*, which were detected on every infected tree, even those that were only at the discolouration stage of decay. In addition, the results obtained in the study suggest that *G. lipsiense* plays a more primary role in the decay process than *K. deusta* (II). Although bacteria and fungi were proposed as important predisposing factors for the invasion of *G. lipsiense* (White 1920, Ross 1976), *G. lipsiense* was also isolated from discoloured sample discs, whereas *K. deusta* was not (II).

4.4 Evaluation of felling decisions and future prospects for improving the risk assessments of urban trees

Risk assessments of urban trees are mainly based on symptoms of the current state of tree health. In terms of management actions, however, it is important how these symptoms are interpreted and which type of future prognosis is made for assessed trees. The two most potential hazard profiles of *Tilia* spp. identified here are good examples of this: trees infected by *G. lipsiense* and trees with cavities (III, IV). The difference between these profiles lay in the stage of the decay process at the time the trees were felled. The majority of *G. lipsiense* -infected trees were felled during the advanced stages of decay with strongly affected sapwood, whereas the trees with cavities showed signs of successful compartmentalization with sapwood less affected by decay (II, III).

Based on the present study it is suggested that a contradiction in felling decisions exist between trees with cavities and trees in the advanced stages of decay (II, IV). It is also suggested that it was easier to judge trees with external signs of heartwood cavities as hazardous and requiring felling than to make such decisions for trees with partially decayed wood, even though the latter already showed symptoms of crown decline (IV). Several factors illustrate this contradiction. Storm surveys showed that uprooting and branch breakages are apparently more frequent than stem breakage (Burdekin 1977, Gibbs and Greig 1990). The properties of partially decayed wood differ, depending on the combination of host and fungal species, but it has never been proven that a partially decayed tree is safer than a tree with a cavity (Schwarze et al. 1997, Lonsdale 1999). In contrast, a reduction in wood strength occurs in the early stages of decay (Henningsson 1967, Wilcox 1978), while only severe defects can alter the likelihood of failure (Kane 2008). In addition, cavities were especially pronounced in *Tilia* spp., which effectively compartmentalized decayed wood (Dujesiefken et al., 1989, 1998, 1999, III, IV).

Hollowed trees, especially those with cavities, are ecologically important in terms of protection. Cavities provide habitats for many living organisms, e.g. birds, insects and fungi (Newton 1994, Niemelä et al. 1995, Franc 1997, Ranius 2002, Jonsell 2004). In addition, the variety of host species among old urban trees is more diverse than in the natural forest, and therefore the habitats they provide may be very rare (Franc 1997). Cavities were observed in a total of 57 trees (Table 3), half of which were *Tilia* spp. (II). The origin of cavities was not always clear, but about 40% arose from pruning wounds, 30% from bruises, 15% from splitting at junctions between branches and 10% from cracks (data not shown).

The different criteria used in felling decisions may have differed, due to difficulty in diagnosing advanced decay. Several factors influence the resulting decay (Otjen and Blanchette

1986, Otjen et al. 1987, 1988), and strict assignment of fungal species to different decay types is difficult, because the same species may have different strategies in various hosts, while even different isolates of the same species can differ (Otjen et al. 1987, Schwarze et al. 2000b). Therefore, it is very difficult to estimate without testing the strength of partially decayed wood compared to sound wood in a living tree (Schwarze et al. 1997).

The major problem in assessing strength loss is that in most trees, the whole pattern of horizontal extension of decay does not show externally in the stem. Many devices are available to aid in the detection of decay in standing trees (Dolwin et al. 1999, Ouis 2001, 2003, Catena 2003, Nicolotti et al. 2003). There are often restrictions in the use of many of these devices, however, including wounding of the tree (Kersten and Schwarze 2005, Weber and Mattheck 2006), or the output provided may be too narrow to build up a reliable picture of the entire decay pattern in the cross-section of a tree (Dolwin et al. 1999). To date, the most promising nonwounding techniques are based on acoustic tomograms (Nicolotti 2003, Rabe et al. 2004).

To improve risk assessments for amenity trees, it would be crucial to develop monitoring methods that would include both improvements in detection devices and applications for reliable data storage. A wealth of valuable information, which is experimentally very difficult to obtain, would be lost if old hazardous trees are felled without storing data on them. Applications such as those presented in Heikura et al. (2008), make it possible to store comprehensive three-dimensional (3D) information on tree architecture together with injury and decay profiles of felled trees. If this type of application could be combined with a reliable nonwounding decay detection device, it would also be possible to study decay dynamics, thus enabling detection of trees at different stages of decay and improvement of protection in old trees.

Reliable data storage would also improve the ability to study symptoms of hazardous decay. It is known that various types of defects (Tables 2 and 7) should be interpreted differently. Lonsdale (1999) showed that special attention should be focused on cracks with rib formation, because ribs suggest that these cracks may open again. Cracks accompanied by dents and bulges should also be considered carefully, because they could be signs of decay (Mattheck and Breloer 1994a, Lonsdale 1999). In addition, better knowledge of fruiting body appearance would improve risk assessments. In the present study, the most extensive and hazardous decay was well indicated by fruiting bodies (II), but it should, however, be noted that the study material consisted of only those trees that were already assessed as hazardous and for which the decision to fell was already made. For better results of diagnostics, those trees that were not felled should also have been included.

4.5 Evaluation of the study material

The present study material accumulated as a result of municipal protocols for tree care and awareness of the value of old urban trees. The results of the inventories conducted in Helsinki since 1999 showed a large number of old urban trees in poor condition, and thus furnishing material for investigation. Only the three most common tree genera grown in Helsinki City (*Tilia* spp., *Betula* spp. and *Acer* spp.) were selected for the study (I), thus furnishing sufficient material for species-specific evaluation.

Due to available resources, the study material did not cover every tree felling in the Helsinki City area during the time period in which the material was collected (I). For example, in 2003 the material collected represented about 70% of the total number of fellings in the most

Table 7. Proportions of various defect types from the total number of external defects evaluated on the trees felled as hazardous.

Defect type:	% of the total number of defects
Pruning wounds total	41
Stem defects total	36
Cracks total	23
Crack 1 (open)	16
Crack 2 (open with rib formation)	4
Crack 3 (closed with rib formation)	3
Pruning wound 3 (no decay)	13
Pruning wound 2 (decayed)	10
Pruning wound 1 (hollowed)	9
Pruning wound 4 (dead or broken)	8
Stem defect 1 (exposed sap and heartwood)	19
Stem defect 2 (undamaged bark)	17

central district of the city (Sampo Sainio, district gardener, pers. comm. 2003). However, most cases not included in the study were of desiccated and dead trees (I). It is likely that inclusion of these trees would have increased the total number of trees in the damage group ‘none’. In addition, approximately 30% of the trees were felled for reasons other than poor condition or risk of hazard (I). The number of felled trees also varied in different years (I). Several factors affected this, including timetables for restoration programmes, the economy and the harsh weather conditions in Finland in 2002, 2003 and 2006 (I, Holopainen et al. 2006).

The selection of tree species affected the list of fungi analysed in the study. Including *Ulmus* spp., *Salix* spp., *Quercus* spp., and *Fraxinus* spp. in the study would have improved the analysis of decay-causing species in multiple host species, especially *G. lipsiense* and *K. deusta*, as well as completed the list of fungi with important species such as *Polyporus squamosus* (Huds.: Fr.) Fr. and *Laetiporus sulphureus* (Bull.: Fr.) Murrill.

The fungal observations in the study were made by identification of fruiting bodies, mycelia and decay patterns. Care should be taken in interpreting the results obtained from pure culture isolations grown *in vitro*, because the growth of mycelia and interaction between other fungi may differ considerably between agar culture and natural substrata (Boddy 2000). This problem may have affected the pure culture isolations made here. In addition, the number of fungal observations with *Armillaria* spp., *Ganoderma* spp., *Inonotus* spp., *Phellinus* spp., and *Pleurotus* spp. could have been improved, using a recent multiplex PCR-based method for early identification of common wood-rotting fungi (Guglielmo et al. 2007, 2008). However, the list of species obtained in the study resembled those in previous studies of species variation in decay fungi observed in the Helsinki City area (Erkkilä and Niemelä 1986).

One major weakness of the present study is that it lacks statistical analysis, due mostly to problems in designing the experiment. The most obvious experiment would have been to compare the trees chosen for felling with the trees still left to grow. The present study material, however, consisted only of felled trees, and since old urban trees are not removed only for scientific purposes, this type of comparison was not possible.

The highest value of the present work is in the study material collected. Europe has a long tradition of arboriculture, which becomes evident on viewing the diversity of references offered (Strouts & Winter 1994, Mattheck & Breloer 1994a, Lonsdale 1999). However, previous investigations and references mostly focused on describing individual cases of damage or symptoms, but the quantitative data concerning entire trees is often lacking. Furthermore, the data collected (injury and decay information) can presumably also be used to formulate study hypotheses for future investigations.

5 CONCLUDING REMARKS

Based on the present results, stem collapse due to horizontal progression of decay is the most common potential hazard among trees felled according to municipal risk assessments in Helsinki. The contradiction in felling decisions between hollowed trees and those in advanced stages of decay showed that assessments could be improved by a better understanding of decay processes in living trees, which could benefit protection of trees with cavities, especially *Tilia* spp. In contrast, care should be taken with the following host-fungi combinations: *Ganoderma lipsiense* on *Tilia* spp. and *Acer* spp.; *Rigidoporus populinus* on *Acer* spp.; *Inonotus obliquus* on *Betula* spp.; *Kretzschmaria deusta* on *Acer* spp., *Tilia* spp. and *Betula* spp.; *Phellinus igniarius* on Acer spp.; and *Cerrena unicolor* on *Betula* spp. These fungal species are all able to cause potential risk for stem collapse by extensive horizontal decay in the stem.

The present work also demonstrated the potential hazard characteristics of *Tilia* spp., *Betula* spp., and *Acer* spp. These characteristics resembled those commonly reported in European tree care references. However, the high frequency of *Rigidoporus populinus* on *Acer* trees, and occurrence of only one *Ganoderma* species differed from previous reports.

In general, more accurate risk assessments could be achieved by developing monitoring methods, especially by creation of databases containing various profiles of potential hazards. Defining a primary defect could be one way to input the database, which could enable storage of quantitative data frequently reported as problems in evaluating risk assessment of trees.

In conclusion, many of the potential risks reported in the present study could be avoided future use of programmes involving by professional pruning for young trees, and better planning of excavation and construction works. Perhaps there are no better means of motivation than to remember that in addition to creating pleasant environments, urban trees have great financial significance. Tree care is expensive; when all the equipment and labour are considered, simply planting a street tree can already cost 2000 - 3000 euros in Finland (Helsingin Sanomat 19.6.2008).

REFERENCES

Andersen, F., Konijnendijk, C.C. & Randrup, T.B. 2002. Higher education on urban forestry in Europe: an overview. Forestry 75:501-511.

Atkinson, M.D. 1992. *Betula pendula* Roth (*B. verrucosa* Ehrh.) and *B. pubescens* Ehrh. Journal of Ecology 80:837-870.

Bauch, J., Shigo, A.L. & Starck, M. 1980. Wound effects in the xylem of *Acer* and *Betula* species. Holzforschung 34:153-160.

Bennell, A.P. & Millar, C.S. 1984. Fungal pathogens of birch in Britain. Proceedings of the Royal Society of Edinburgh 85B:153-167.

Biggs, A.R. 1992. Anatomical and physiological responses of bark tissues to mechanical injury. In: Blanchette, R.A. & Biggs, A.R. (ed.). Defense mechanisms of woody plants against fungi. Springer-Verlag, Berlin, Heidelberg. p. 13-40.

Blanchette, R.A. 1991. Delignification by wood-decay fungi. Annual Review of Phytopathology 29:381-398.

— & Biggs, A.R. 1992. Defense mechanisms of woody plants against fungi. Springer-Verlag, Berlin, Heidelberg. 458 p.

— & Shaw, C.G. 1978. Associations among bacteria, yeasts, and Basidiomycetes during wood decay. Phytopathology 68:631-637.

—, Sutherland, J.B. & Crawford, D.L. 1981. Actinomycetes in discolored wood of living silver maple. Canadian Journal of Botany 59:1-7.

Boddy, L. 2000. Interspecific combative interactions between wood-decaying Basidiomycetes. Microbiology Ecology 31:185-194.

Breitenbach, J. & Kränzlin, F. 1984. Pilze der Schweiz. Band 1 Ascomyceten. Verlag Mykologia, Luzern. 313 p.

Burdekin, D.A. 1977. Gale damage to amenity trees. Arboricultural Journal 3:181-189.

Catena, A. 2003. Thermography reveals hidden tree decay. Arboricultural Journal 27:27-42.

Curle, M. 1991. Whose responsibility? Arboricultural Journal 15:235-241.

Cutler, D.F., Gasson, P.E. & Farmer, M.C. 1990. The wind blown tree survey: analysis of results. Arboricultural Journal 14:265-286.

Dolwin, J.A., Lonsdale, D. & Barnett, J. 1999. Detection of decay in trees. Arboricultural Journal 23:139-149.

Dujesiefken, D., Ebenritter, S. & Liese, W. 1989. Wundreaktionen im Holzgewebe bei Birke, Buche und Linde. Holz als Roh- und Werkstoff 47:495-500.

—, Stobbe, H. & Eckstein, D. 1998. Langzeitwirkungen von Astungen im Holz von Linde und Roßkastanie. Forstwissenschaftliches Centralblatt 117:305-315.

—, Rhaesa, A., Eckstein, D. & Stobbe, H. 1999. Tree wound reactions of differently treated boreholes. Journal of Arboriculture 25:113-123.

Eisner, N.J., Gilman, E.F. & Grabosky, J.C. 2002. Branch morphology impacts compartmentalization of pruning wounds. Journal of Arboriculture 28:99-105.

Ellison, M.J. 2005. Quantified tree risk assessment used in the management of amenity trees. Journal of Arboriculture 31: 57-65.

Erkkilä, R. & Niemelä, T. 1986. Polypores in the parks and forests of the City of Helsinki. Karstenia 26:1-40.

European Tree Worker Handbook. 2000. European Arboricultural Council (EAC). Patzer Verlag, Berlin-Hannover. 139 p.

Franc, V. 1997. Old trees in urban environments - refugia for rare and endangered beetles (Coleoptera). Acta Universitatis Carolinae Biologica 41:273-283.
Gasson, P.E. & Cutler, D.F. 1998. Can we live with trees in our towns and cities. Arboricultural Journal 22:1-9.
Gibbs, J.N. & Greig, B.J.W. 1990. Survey of parkland trees after the great storm of October 16, 1987. Arboricultural Journal 14:321-347.
Gramss, G. 1992. Invasion of wood by basidiomycetous fungi VI. Quantitative but not qualitative differences in the pathovirulence of pathogenic and saprophytic decay fungi. Journal of Basic Microbiology 32:75-90.
Guglielmo, F., Bergemann, S.E., Gonthier, P., Nicolotti, G. & Garbelotto, M. 2007. A multiplex PCR-based method for the detection and early identification of wood rotting fungi in standing trees. Journal of Applied Microbiology 103:1490-1507.
—, Gonthier, P., Garbelotto, M. & Nicolotti, G. 2008. A PCR-based method for the identification of important wood rotting fungal taxa within *Ganoderma, Inonotus* s.l. and *Phellinus* s.l. FEMS Microbiological Letter 282:228-237.
Guillaumin, J.J., Anderson, J.B. & Korhonen, K. 1991. Life cycle, interfertility, and biological species. In: Shaw, C.G.III. & Kile, G.A. (ed.). *Armillaria* Root Disease. Washington, DC: USDA Agriculture Handbook No. 691:10-20.
Hallaksela, A.M. 1977. Microbial flora isolated from Norway spruce stumps (English summary). Acta Forestalia Fennica 158:1-50.
— & Niemistö, P. 1998. Stem discoloration of planted silver birch. Scandinavian Journal of Forest Research 13:169-176.
Heikura, T., Terho, M., Perttunen, J. & Sievänen, R. 2008. A computer-based tool to link decay information to 3D architecture of urban trees. Urban Forestry & Urban Greening 7:233-239.
Helliwell, R. 2004. A discussion of the failure of weak forks (short paper). Arboricultural Journal 27:245-249.
Henningsson, B. 1967. Changes in impact bending strength, weight and alkali solubility following fungal attack on birch. Studia Forestalia Suecica 41:1-21.
Holopainen, M., Leino, O., Kämäri, H. & Talvitie, M. 2006. Drought damage in the park forests of the city of Helsinki. Urban Forestry & Urban Greening 4:75-83.
Jahn, H. 1979. Pilze die an Holz wachsen. Bussesche Verlagshandlung, Herford. 268 p.
Jonsell, M. 2004. Old park trees: A highly desirable resource for both history and beetle diversity. Journal of Arboriculture 30:238-243.
Kane, B. 2008. Tree failure following a windstorm in Brewster, Massachusetts, USA. Urban Forestry & Urban Greening 7:15-23.
—, Ryan, D. & Bloniarz, D.V. 2001. Comparing formulae that assess strength loss due to decay in trees. Journal of Arboriculture 27:78-87.
Kennard, D.K., Putz, F.E. & Niederhofer, M. 1996. The predictability of tree decay based on visual assessments. Journal of Arboriculture 22: 249-254.
Kersten, W. & Schwarze, F.W.M.R. 2005. Development of decay in the sapwood of trees wounded by the use of decay detecting devices. Arboricultural Journal 28:165-181.
Konijnendijk, C.C. 1999. Urban forestry policy-making: a comparative study of selected cities in Europe. Arboricultural Journal 23:1-15.
—, Randrup, T.B. & Nilsson, K. 2000. Urban forestry research in Europe: an overview. Journal of Arboriculture 26:152-161.
Korhonen, K. 1978. Interfertility and clinal size in the *Armillariella mellea* complex. Karstenia 18:31-42.

Kramer, P.J. & Kozlowski, T.T. 1979. Physiology of Woody Plants. Academic Press, INC., Orlando, Florida. 811 p.

Kuo, F.E. 2003. The role of arboriculture in a healthy social ecology. Journal of Arboriculture 29:148-155.

Lindhe, A., Åsenblad, N. & Toresson, H-G. 2004. Cut logs and high stumps of spruce, birch, aspen and oak - nine years of saproxylic fungi succession. Biological Conservation 119:443-454.

Lonsdale, D. 1999. Principles of tree hazard assessment and management. Forestry Commission Handbook, vol. 7. DETR, London. 388 p.

Matheny, N.P. & Clark, J.R. 1994. A Photographic guide to the evaluation of hazard trees in urban areas. International Society of Arboriculture, Urbana, Illinois. 85 p.

Mattheck, C. & Bethge, K. 2005. A critic of the static integrated analysis (SIA) method. Arboricultural Journal 28:191-199.

— & Breloer, H. 1994a. Field guide for visual tree assessment (VTA). Arboricultural Journal 18:1-23.

— & Breloer, H. 1994b. The body language of trees. A handbook for failure analysis Research for Amenity Trees No. 4 The Stationery Office. London. 240 p.

—, Bethge, K. & Tesari, I. 2006. Shear effects on failure of hollow trees. Trees 20:329-333.

Mattock, G. 2001. Notes on British *Ganoderma* species. Emphasising the annual species and *G. carnosum*. Field Mycology 2:60-64.

Merrill, W. 1992. Mechanisms of resistance to fungi in woody plants: A historical perspective. In: Blanchette, R.A. & Biggs, A.R. (ed.). Defense mechanisms of woody plants against fungi. Springer-Verlag, Berlin, Heidelberg. p. 1-12.

Mortimer, M.J. & Kane, B. 2004. Hazard tree liability in the United Sates: Uncertain risks for owners and professionals. Urban Forestry & Urban Greening 2:159-165.

Mynors, C. 1993. Trees and the law. Arboricultural Journal 17:413-423.

Mäkinen, H., Hallakesela, A-M. & Isomäki, A. 2007. Increment and decay in Norway spruce and Scots pine after artificial logging damage. Canadian Journal of Forest Research 37:2130-2141.

Newton, I. 1994. The role of nest sites in limiting the numbers of hole-nesting birds: a review. Biological Conservation 70:265-276.

Nicolotti, G., Socco, L.V., Martinis, R., Godio, A. & Sambuelli, L. 2003. Application and comparison of three tomographic techniques for detection of decay in trees. Journal of Arboriculture 29:66-78.

Niemelä, T. & Kotiranta, H. 1983. Polypore survey of Finland 3. The genera *Coltricia, Inonotopsis, Inonotus* and *Onnia*. Karstenia 23:15-25.

— & Kotiranta, H. 1986. Polypore survey of Finland 4. *Phaeolus, Fistulina, Ganoderma* and *Ischnoderma*. Karstenia 26:57-64.

—, Renvall, P. & Penttilä, R. 1995. Interactions of fungi at late stages of wood decomposition. Annales Botanica Fennici 32:141-152.

Nilsson, K., Randrup, T.B. & Wandall, B.M. 2000. Trees in the urban environment. In: Evans, J. (ed.). The Forest handbook Vol 1. Blackwell Science, Oxford p. 347-361.

Nobles, M.K. 1948. Studies in forest pathology: VI. Identification of cultures of wood-rotting fungi. Canadian Journal of Research 26:281-431.

Nordin, V.J. 1954. Studies in forest pathology XIII. Decay in sugar maple in the Ottawa-Huron and Algoma extension forest region of Ontario. Candian Journal of Botany 32:221-258.

Otjen, L. & Blanchette, R.A. 1986. A discussion of microstructural changes in wood during decomposition by white rot Basidiomycetes. Canadian Journal of Botany 64:905-911.

—, Blanchette, R.A., Effland, M. & Leatham, G. 1987. Assessment of 30 white rot basidiomycetes for selective lignin degradation. Hozforschung 41:343-349.
—, Blanchette, R.A. & Leatham, G.F. 1988. Lignin distribution in wood delignified by white-rot fungi: X-ray microanalysis of decayed wood treated with bromine. Holtzforschung 42:281-288.
Ouis, D. 2001. Detection of rot in standing trees by means of acoustic technique. Arboricultural Journal 25:117-152.
— 2003. Non-destructive techniques for detecting decay in standing trees. Arboricultural Journal 27:159-177.
Owens, E.M., Reddy, C.A. & Grethlein, H.E. 1994. Outcome of interspecific interactions among brown-rot and white-rot wood decay fungi. FEMS Microbiology Ecology 14:19-24.
Parker, S., Shortle, W.C. & Smith, K.T. 1994. Identification of gram-positive bacteria isolated from initial stages of wound-initiated discoloration of red maple. European Journal of Forest Pathology 24:48-54.
Peace, T.R. 1962. Pathology of trees and shrubs. With special reference to Britain. The Clarendon Press, Oxford. 753 p.
Pearce, R.B. 1990. Occurrence of decay-associated xylem suberization in a range of woody species. European Journal of Forest Pathology 20:275-289.
— 1996. Antimicrobial defenses in the wood of living trees. New Phytologist 132:203-233.
— 2000. Decay development and its restriction in trees. Journal of Arboriculture 26:1-11.
— & Rutherford, J. 1981. A wound-associated suberized barrier to the spread of decay in the sapwood of oak (*Quercus robur* L.). Physiological Plant Pathology 19:359-369.
— & Woodward, S. 1986. Compartmentalization and reaction zone barriers at the margin of decayed sapwood in *Acer saccharinum* L. Physiological Plant Pathology 29:197-216.
Peinado, M. & Moreno, G. 1989. The genus *Betula* (*Betulaceae*) in the Sistema Central (Spain). Willdenowia 18:343-359.
Phillips, D.H. & Burdekin, D.A. 1982. Diseases of forest and ornamental trees. The Macmillan Press Ltd, Hong Kong. 435 p.
Prospero, S., Holdenrieder, O. & Rigling, D. 2004. Comparison of the virulence of *Armillaria cepistipes* and *Armillaria ostoyae* on four Norway spruce provenances. Forest Pathology 34:1-14.
Rabe, C., Ferner, D., Fink, S. & Schwarze, F.W.M.R. 2004. Detection of decay in trees with stress waves and interpretation of acoustic tomograms. Arboricultural Journal 28:3-19.
Ranius, T. 2002. *Osmoderma eremita* as an indicator of species richness of beetles in tree hollows. Biodiversity and Conservation 11:931-941.
Rayner, A.D.M. 1986. Water and the origins of decay in trees In: Ayers, P.G. & Boddy, L. (ed.). Water, Fungi and Plants. Cambridge University Press, Cambridge p. 321-341.
— 1991. The Phytopathological significance of mycelial individualism. Annual Review of Phytopathology 29:305-323.
— 1993. New avenues for understanding processes of tree decay. Arboricultural Journal 17:171-189.
— & Boddy, L. 1986. Population structure and the infection biology of wood-decay fungi in living trees. Advances in Plant Pathology 5:119-160.
— & Boddy, L. 1988. Fungal decomposition of wood. Its biology and ecology. John Wiley & Sons Ltd., UK, Chichester. 587 p.
Roll-Hansen, F. 1985. The *Armillaria* species in Europe. A litterature review. European Journal of Forest Pathology 15:22-31.

Ross, W.D. 1976. Fungi associated with root diseases of aspen in Wyoming. Canadian Journal of Botany 54:734-744.

Ryman, S. & Holmåsen, I. 1984. Suomen ja pohjolan sienet (original Svampar en fälthandbok). Werner Söderström, Porvoo. 718 p.

Ryvarden, L. & Gilbertson, R.L. 1993. European Polypores. Part 1. Fungiflora, Oslo. 387 p.

Sæbø, A., Benedikz, T, & Randrup, T.B. 2003. Selection of trees for urban forestry in the Nordic countries. Urban Forestry & Urban Greening 2:101-114.

Schwarze, F.W.M.R. 2001. Development and prognosis of decay in the sapwood of living trees. Arboricultural Journal 25:321-337.

— & Baum, S. 2000. Mechanisms of reaction zone penetration by decay fungi in wood of beech (*Fagus sylvatica*). New Phytologist 146:129-140.

— & Ferner, D. 2003. *Ganoderma* on trees- differentiation of species and studies of invasiveness. Arboricultural Journal 27:59-77.

—, Lonsdale. D. & Mattheck, C. 1995. Detectability of wood decay caused by *Ustulina deusta* in comparison with other tree-decay fungi. European Journal of Forest Pathology 25:327-341.

—, Lonsdale, D. & Fink, S. 1997. An overview of wood degradation patterns and their limitations for tree hazard assessment. Arboricultural Journal 21:1-32.

—, Engels, J. & Mattheck, C. 2000a. Fungal strategies of wood decay in trees. Springer-Verlag, Berlin, Heidelberg. 185 p.

—, Baum, S. & Fink, S. 2000b. Dual modes of degeneration by *Fistulina hepatica* in xylem cell walls of *Quercus robur*. Mycological Research 104:846-852.

Seehann, G. 1979. Holzzerstörende Pilze an Straßen- und Parkbäumen in Hamburg. Mitteilungen der Deutschen Denrologischen Gesellschaft 71:193-221.

Shigo, A.L. 1963. Fungi associated with the discolorations around rot columns caused by *Fomes igniarius*. Plant Disease Reporter 47:820-823.

— 1974. Relative abilities of *Phialophora melinii, Fomes connatus*, and *F. igniarius* to invade freshly wounded tissues of *Acer rubrum*. Phytopathology 64:708-710.

— 1985. How tree branches are attached to trunks. Canadian Journal of Botany 63:1391-1401.

— 1986. A new tree biology. Sherwin Dodge Printers, Littleton, New Hampshire. 618 p.

— & Hillis, W.E. 1973. Heartwood, discolored wood, and microorganisms in living trees. Annual Review of Phytopathology 11:197-222.

— & Marx H.G. 1977. Compartmentalization of Decay in Trees. USDA Forest Service Agricultural Information Bulletin 405:1-73.

— & Sharon, E.M. 1968. Discoloration and decay in hardwoods following inoculations with Hymenomycetes. Phytopathology 58:1493-1498.

Shortle, W.C. 1979. Mechanisms of compartmentalization of decay in living trees. Phytopathology 69:1147-1151.

— & Cowling, E.B. 1978. Interaction of live sapwood and fungi commonly found in discolored and decayed wood. Phytopathology 68:617-623.

—, Tattar, T.A. & Rich, A.E. 1971. Effects of some phenolic compounds on the growth of *Phialophora melinii* and *Fomes connatus*. Phytopathology 61:552-555.

—, Menge, J.A. & Cowling, E.B. 1978. Interaction of bacteria, decay fungi, and live sapwood in discoloration and decay of trees. European Journal of Forest Pathology 8:293-300.

Smith, K. 2006. Compartmentalization today. Arboricultural Journal 29:173-184.

Stalpers, J.A. 1978. Identification of wood-inhabiting *Aphyllophorales* in pure culture. Studia Mycologica 16:1-248.

Strouts, R.G. & Winter, T.G. 1994. Diagnosis of ill-health in trees. Forestry Commission Handbook 2. DETR, London 334 p.

Tattar, T.A., Shortle, W.C. & Rich, A.E. 1971. Sequence of microorganisms and changes in constituents associeated with discoloration and decay of sugar maples infected with *Fomes connatus*. Phytopathology 61:556-558.

Weber, K. & Mattheck, C. 2006. The effects of excessive drilling diagnosis on decay propagation in trees. Trees 20:224-228.

Wessolly, L. 1995a. Fracture diagnosis of trees Part 2: Statics-Integrated methods - Statically-Integrated Assessment (SIA). Stadt und Grün 8:570-573.

— 1995b. Fracture diagnosis of trees Part 3: Boring is no way for reliable diagnosis. Stadt und Grün 9:635-640.

White, J.H. 1920. On the biology of *Fomes applanatus* (Pers.) Wallr. Transactions of the Royal Canadian Institute 12:133-174.

Wilcox, W.W. 1978. Review of literature on the effects of early stages of decay on wood strength. Wood and Fiber 9:252-257.

Woodward, S. 1992. Responses of gymnosperm bark tissues to fungal infections. In: Blanchette, R.A. & Biggs, A.R. (ed.). Defense mechanisms of woody plants against fungi. Springer-Verlag, Berlin, Heidelberg. p. 62-75.

Wolf, K.L. 2003. Social aspects of urban forestry: Public response to the urban forest in inner-city business districts. Journal of Arboriculture 29:117-126.