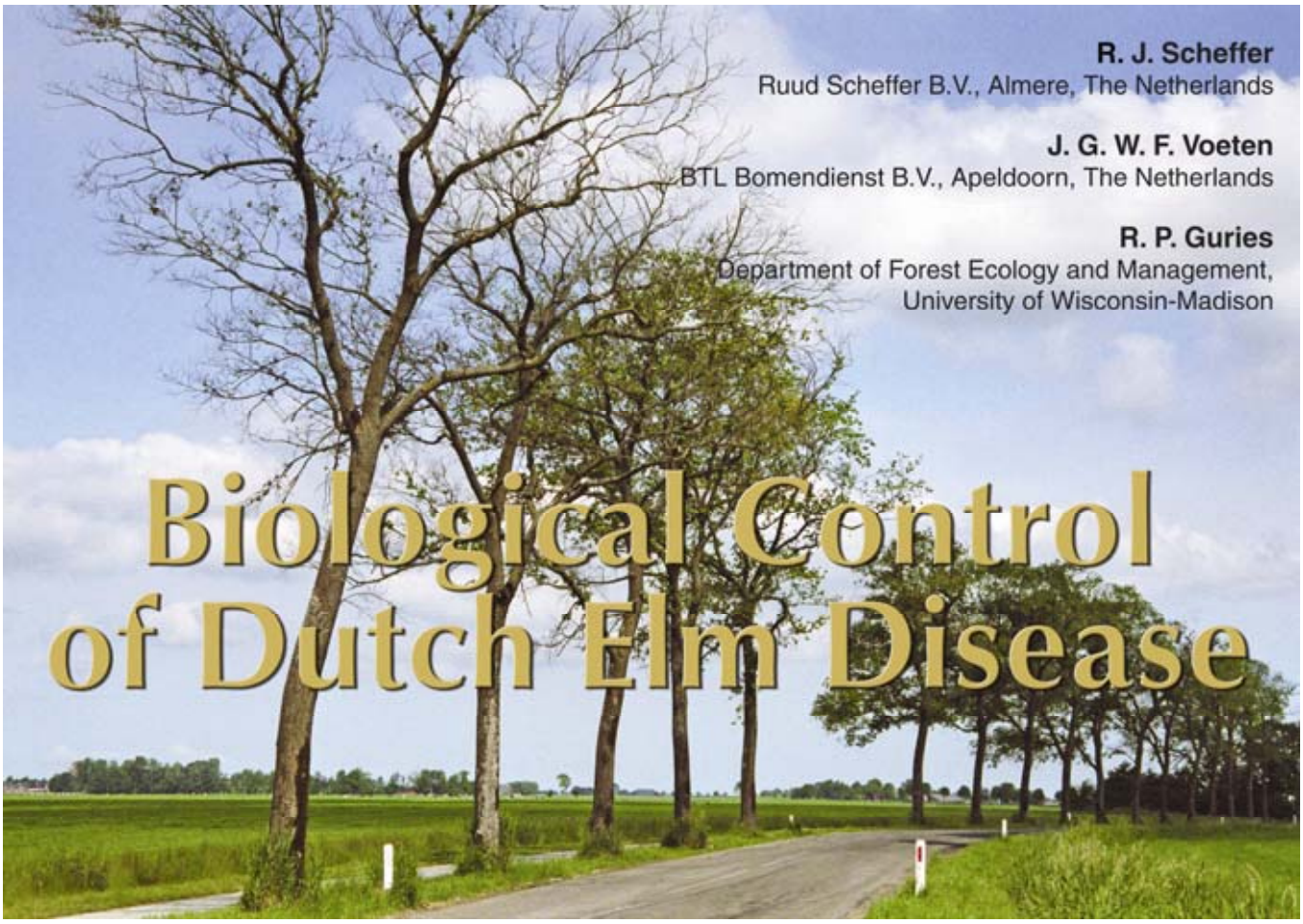

Elms have played a long and rich role in western cultural history, dating from the time when agriculture first appeared in European forests. The use of elm leaves for fodder, together with the many uses of elm wood and bark in a civilization built on wood, made elm an essential resource for several millennia. Elm appears in the myths of the Germanic people: the gods Odin, Lodur, and Hunir created the first man out of an ash and the first woman out of an elm. Elm was represented as a female in ancient German myths, but for the Romans elm was male because it was used to support grapevines. This marriage of tree and vine led to many metaphors on cooperation, from the poets of the Roman Empire to Shakespeare (18,21,38).

The long association between elm and humankind was based on the tree's useful properties. As a tree, elm survives harsh conditions, and many elms can cope with prolonged flooding even in summer, while in coastal regions elms survive salt and wind. This adaptability to stressful or harsh conditions, together with an attractive architecture, makes them favorites along roads and in urban environments (Fig. 1). Plantings along the canals of old cities such as Amsterdam were usually elms, owing to their ability to do well in the narrow spaces between water, pavement, and houses. In many respects, elms were ideal trees for our urban environments, with remarkably few pest and disease problems (53).

When Dutch elm disease was first identified in Europe during the 1920s and in North America by 1930, the potential impact on the long-term survival of elms was recognized. However, control of the new disease proved difficult, and Dutch elm disease developed into one of the most devastating tree diseases ever. Approximately 100 years after its first introduction into Europe, we want to review the options for biological control of Dutch elm disease as a component of an integrated control strategy for this disease.

The Host

Elms represent a large and important group of forest trees, primarily distributed in the north temperate regions, but also extending into subtropical parts of Central America and Southeast Asia. Approximately 45 species divided among 5 or 6 taxonomic sections are recognized (14,24,58) based on a variety of morphological and molecular criteria. Most elms naturally occur in Asia (25 to 28 species) and North America (9 species), but a few species pose taxonomic problems. Perhaps the most well-known of these problems concerns *Ulmus minor,* a complex of types that typically reproduces asexually and forms extensive clones in many parts of Great Britain and Western Europe, where its taxonomic status has been the subject of considerable and acrimonious debate (3,24,38). Interspecific hybrids also have been reported, and the general lack of incompatibility barriers between most species has facilitated the breeding of interspecific hybrids with varying levels of resistance to Dutch elm disease (47).

Selection and breeding activities, especially those aimed at Dutch elm disease resistance, occupied breeders for much of the twentieth century. Initial efforts to select tolerant individuals from within native European and North American populations ravaged by Dutch elm disease enjoyed some limited success (19,20), but the use of Asian species, especially *Ulmus pumila*, led to the development of more durable resistance (47). In general, the Asian elms are viewed as the most useful sources of Dutch elm disease resistance, but only a few such species—notably *U. pumila, U. japonica,* and *U. parvifolia*—

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have been evaluated systematically. In some respects, the use of Asian elms as a source of disease resistance genes has required that much more attention be paid to selecting for ornamentally attractive forms from among the diverse hybrid populations created. Unfortunately for Americans, the strong incompatibility barriers between American elm and other elms (1) has thus far precluded the creation of interspecific hybrids with an American elm (*U. americana*) that combine the classical vase-shaped architecture with Dutch elm disease resistance.

The Pathogen

By 1919, elms in the Netherlands were discovered showing symptoms of an unknown disease: a sudden wilting and dying of the leaves and branches. Some trees that appeared normal in early summer suddenly withered in full leaf, lost all their leaves, and died within weeks. In other trees, the leaves on a few branches in the crown turned yellow and fell, and by late summer these symptoms had spread throughout the canopy. On some shoots, the leaves at the end of withered and stunted tips often remained after the fully grown leaves had fallen off, thereby producing a characteristic "shepherd's crook" effect. In addition, diseased branches, when sectioned, always revealed dark discoloration in the most recent growth increment (Fig. 2). It was Spierenburg (50,51) who first described the disease and Schwarz (45) who isolated and identified the causal agent as *Graphium ulmi* Schwarz (Fig. 3). Others held different opinions (22), and debate continued on the cause of the disease. It was not until 1927 that Wollenweber (59) and Westerdijk (57) proved that *G. ulmi* was indeed the causal organism.

It is this early research, mainly carried out in the Netherlands, that gave the disease its name Dutch elm disease. Buisman (10) discovered the sexual stage of the fungus (Fig. 4) and changed the name to *Ceratostomella ulmi* (Schwarz) Buisman. Later, Melin and Nannfeld (32) classified the fungus as *Ophiostoma ulmi* (Buisman) Nannf. Between 1952 and 1981, several authors proposed *Ceratocystis ulmi*, but de Hoog and Scheffer (25) settled on *O. ulmi* as the correct name for the pathogen. In light of subsequent research, it is recognized that *O. ulmi senso lato* would have been more appropriate to encompass the entire group of Ophiostomas causing Dutch elm disease. More recently, Brasier (5) renamed the "aggressive strain" of *O. ulmi* as *O. novo-ulmi*, and in 2001, Brasier and Kirk (8) designated the two subpopulations of *O. novo-ulmi*, known as the Eurasian (EAN) and North American (NAN) races, into the subspecies *novo-ulmi* and *americana*.

O. ulmi sensu lato now is recognized as the pathogen, or the group of pathogens, causing Dutch elm disease in a variety of elms. *O. ulmi sensu stricto* caused the first pandemic in the 1920s to 1940s, while *O. novo-ulmi* is responsible for the current pandemic. A western Himalaya endemic species, isolated from breeding galleries of scolytid beetles in the bark of *U. wallichiana* in a geographic region where no disease symptoms were observed, was named *O. himal-ulmi* (9).

Vectors and Transmission

Transmission of the disease is mainly by the elm bark beetles *Scolytus scolytus* and *S. multistriatus* that breed in weakened and dead elms (Fig. 5). As the pathogen readily forms coremia in breeding galleries, the emerging beetles become contaminated with conidia. In the spring, newly emerged beetles feed on twigs and infect healthy trees by introducing conidia into the tissues of the tree they visit.

In North America, adults of the elm bark beetle *Hylurgopinus rufipes* can also transmit the disease. A related bark beetle, *S. schevyrewi*, was recognized as a potential vector in Asia (56). This species has been discovered in the United States, where it does attack elms; recently a role as Dutch

Fig. 1. Elms in Grant Park, Downtown Chicago on the lakefront of Lake Michigan.

Fig. 2. Discoloration in the growth rings in a cross section of a 5-year-old branch from a diseased elm tree. Discoloration is visible in the second, third, and (although less) fourth growth rings. Streaking of the wood under the bark was visible in the early spring wood as well. The tree was conditionally declining over the last years, but not yet dead, despite the existing Dutch elm disease infection. (Photo by J. G. W. F. Voeten)

elm disease vector has been suggested (36).

Unfortunately, elms often develop root grafts with neighboring elms. Dutch elm disease is often transmitted via root grafts (35), especially in the monoculture conditions created along boulevards and canals in urban areas. Control measures for root graft transmission focus on prevention by trenching and cutting roots between trees, but such treatments are expensive. Occasionally, killing roots using metam-sodium has been successful (13); experiments in the Netherlands with metam-sodium did stop root transmission, but registration of the product for this purpose was not feasible due to its unfavorable ecotoxicological profile, especially the potential for groundwater pollution (R. J. Scheffer, *unpublished results*).

Strategies to Control Dutch Elm Disease

Biological control. As early as 1933, Chester (11) claimed that "the fact of acquired immunity by plant vaccination has been satisfactorily proved" (p. 287). He used the term "vaccination" to include various methods of biological plant therapy. In his chapter on practical applications, Chester encouraged his reader to experiment with various methods of protection in situations where the individual plant is sufficiently valuable.

For elm, induction of resistance was shown 47 years later, in 1980 (44). In elms resistant to *O. ulmi*, but not to *O. novo-ulmi*, inoculation with a mixture of *O. ulmi* and *O. novo-ulmi* resulted in less symptom development than inoculation with only *O. novo-ulmi*. This was attributed to induction of resistance in the tree. Hubbes (26,27) and Hubbes and Jeng (28) explored this phenomenon to develop methods to control Dutch elm disease by inoculating trees with a strain of *O. ulmi* having low virulence, or by use of a glycoprotein isolated from the pathogen.

Scheffer (40), inspired by the promising results of Myers and Strobel (34), attempted to use antagonistic pseudomonads to control the disease. However, the lack of correlation with in vitro antagonistic properties of the bacteria led to the hypothesis that induction of resistance in the host, rather than antagonism, might explain the results. Because the elm clone or species distinctly influenced the effect of the bacterial treatment, induction of resistance became even more plausible (41). Induction of resistance was (again) shown for the elm clone 'Commelin', which is resistant to *O. ulmi*, but not to *O. novo-ulmi*. Very susceptible field elms could not be protected by a challenge inoculation with a strain of the pathogen with low virulence. However, one *Verticillium* isolate, WCS850, proved to effectively suppress disease development in both Commelin elms and susceptible field elms (42). The *Verticillium* isolate, which came from a potato field in Flevoland, the Netherlands, was chosen because *Verticillium* is a known vascular wilt pathogen, expected to increase the chance that the isolate would survive for some time within the tree and elicit a resistance response.

Recent results from Cornelissen et al. (12) showed that the *Verticillium* isolate WCS850 is a natural hyaline form of *V. albo-atrum* not producing resting structures and that it is not *V. dahliae* as originally stated. As *Verticillium* species can

Fig. 3. Coremia of *Ophiostoma ulmi* (=*Graphium ulmi*). The conidia (asexual spores) released by these structures are important for dissemination of Dutch elm disease by elm bark beetles. Beetles often carry such spores, and when they feed on young twigs, the disease may establish itself in the twigs. The typical symptoms of withered shoots with stunted tips relate to new infections by feeding beetles. (Photo by R. J. Scheffer)

Fig. 4. Scanning electron micrograph of a perithecium of *Ophiostoma ulmi*. Perithecia of *O. ulmi* release ascospores, which for years were thought to be less important because perithecia were not often observed. (Photo by R. J. Scheffer)

Fig. 5. Scanning electron micrograph of *Scolytus scolytus*, one of the major vectors of Dutch elm disease. (Photo by R. J. Scheffer)

cause vascular wilt disease in many plants, Mausel and Voeten (31) confirmed nonpathogenicity of *Verticillium* isolate WCS850 for 19 tree species in Seattle in 2001. *Verticillium* WCS850 was injected during the spring into mature trees, and these trees were monitored for any signs of wilt during the subsequent growing season. None of the trees, not even *Verticillium*-susceptible species like ash, showed any signs of wilt at any time during the growing season. Furthermore, Jacobs (K. Jacobs, Morton Arboretum, *personal communication*) confirmed limited spread and survival of *Verticillium* WCS850 in elms. *Verticillium* WCS850 could be reisolated from the injected tree, but only immediately beneath or above the site of injection in the trunk, and only up to 2 weeks after injection. Translocation of the isolate in the injected elm is minimal, confirming that there is no direct interaction between the injected *Verticillium* and *Ophiostoma*. *Verticillium* WCS850 could at no stage be recovered from root, branch, or petiole samples collected during the growing season of the injected trees.

In a study of another *Verticillium* isolate, *V. dahliae* isolate Vd-48, *Verticillium* could also only be isolated at the point of inoculation, or not at all (48). The isolate came from tomato, but led to severe *V. dahliae* disease symptoms in one of the three experiments. The prophylactic effect on Dutch elm disease symptom development was variable and seemed to be dependent on the interval between the inoculation with *V. dahliae* Vd-48 and the challenge with *O. novo-ulmi*. The authors concluded that strain Vd-48 did not offer a reliable option to control Dutch elm disease.

To further test the effect of *Verticillium* isolate WCS850, Guries (R. Guries, *unpublished data*) evaluated 17 American elm clones from the breeding program of the University of Wisconsin in a greenhouse experiment (Fig. 6). Two-year-old ramets, at least 8 per clone per treatment, were treated with water or WCS850 (one drop, 10^7 spores/ml injected at the base of the shoot) and 2 weeks later with either water or *O. novo-ulmi* (strain 18 or 32, both pathogenic, one drop of 10^6 spores/ml, also injected at the base of the shoot). Discoloration of cross-sections of the stem showed that both isolates of *O. novo-ulmi* were still pathogenic, except to the resistant clone 'New Horizon'. Discoloration in ramets treated with both WCS850 and *O. novo-ulmi* was greatly reduced in most clones, whereas ramets treated with only water or WCS850 showed little or no discoloration. The reduction of internal disease symptoms following inoculation with pathogenic strains of *O. novo-ulmi* was dependent on the clone, but preinoculation with WCS850 consistently reduced internal symptoms. As discoloration is a measure for severity of Dutch elm disease symptoms (16,47), this experiment showed not only differences in susceptibility of the clones tested, but also that preinoculation with WCS850 decreases such symptoms in every clone tested.

Based on the results of studies discussed in this section, the role of the tree in biological control of Dutch elm disease is emerging as the only key element of control by WCS850. We could reproducibly protect trees by preventive inoculations with WCS850. As the inoculant neither moves within the tree nor survives for a prolonged period, a physiological response of the tree remains as a plausible cause for the protective effect observed.

Field trials and evidence from preventive treatments with *Verticillium* WCS850. Upon registration of WCS850 in the Netherlands in 1992, large-scale application was initiated and 3,000 trees were treated. The numbers treated annually increased up

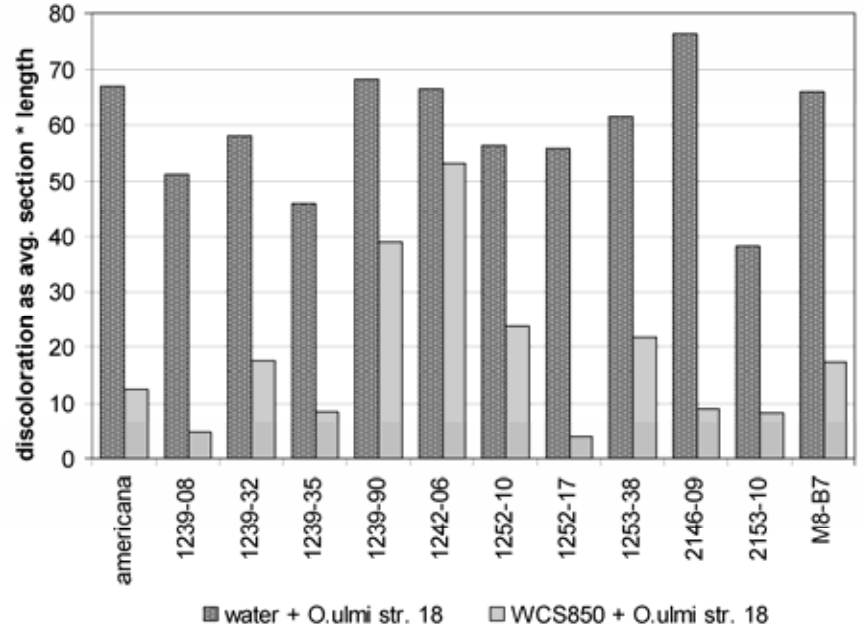

Fig. 6. Comparison of 2-year-old American elm ramets injected with water or *Verticillium albo-atrum* strain WCS850, followed by inoculation with *Ophiostoma ulmi* strain 18 two weeks later. Infection was measured by volume of discolored tissue (height of discoloration column by cross-sectional area of discoloration at several points along the stem), and the results plotted for the two combinations shown. (Data provided by R. P. Guries)

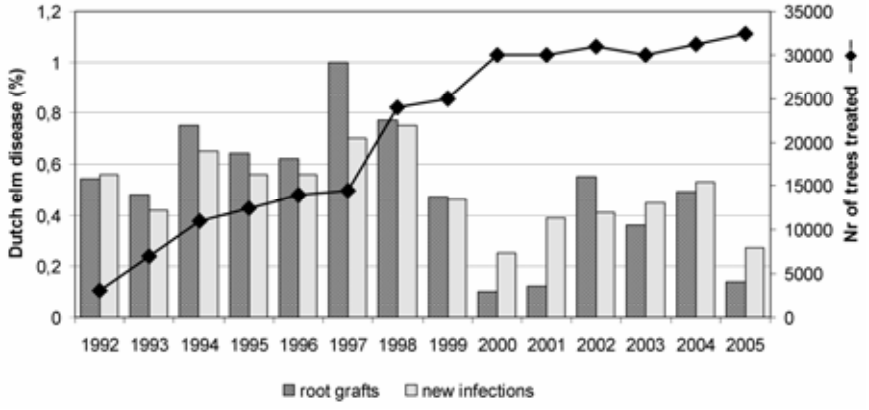

Fig. 7. Large-scale applications of *Verticillium albo-atrum* strain WCS850 in the Netherlands began in 1992. Total losses due to Dutch elm disease were on average 1%. Half of the losses represented infections via root grafts, against which treatment does not provide protection. In areas without treatment, estimates of losses ranged between 4 and 14%. The steep drop in new infections toward the year 2000, and the increase thereafter, may be a result of complex interactions among weather, vectors, and pathogen. Such undulating patterns were observed before, as in Brighton and East Sussex (17). In Brighton, losses went down to 0.14% in 1974, then up to 2.95% in 1977, and down again to 0.87% in 1981. In East Sussex, a drop of 56% in the number of felled trees also occurred (3,283 in 1979 to 1,844 in 1981) after a more or less gradual increase in the period 1971 to 1979.

to 32,380 in 2005 (Fig. 7). The methodology for treating trees was always identical. Elms were injected with Dutch Trig, an aqueous suspension of 10^7 conidia of WCS850 per ml, by means of the "Bomendienst" injection tool: 0.15 ml per injection with a distance between injections of 10 cm at a height of ca. 1.30 m. Treatment was in May or early June at the latest (Fig. 8). Occurrence of Dutch elm disease was registered as new infections and, separately, as infections via root grafts, because it was expected that the treatment would be ineffective for this category of infection. Other control measures, such as fungicides, did not protect elms when the pathogen infected the tree through root grafts. Trees found to be positive for Dutch elm disease were removed; therefore, all infections were reported as losses due to Dutch elm disease.

During the 14-year period (1992 to 2006), the combined losses averaged 1%. Half of the trees lost (0.5%) represented new infections and the other half (0.5%) root graft infections (Fig. 7). In areas without treatment, estimates of losses ranged between 4 and 14%. However, in a few programs, only part of the elm population in a city was treated, with registration of all trees lost to Dutch elm disease. We are reporting the cases for which we have full data, as these direct comparisons provide further insight on the efficacy of treatments with WCS850.

In The Hague, 28 to 48% of the municipal elms were treated between 1998 and 2001 in a Dutch elm disease prevention program (Fig. 9). Among treated trees, the disease rate fell in 4 years from 0.94 to 0.20%, while in nontreated trees losses ranged from 5.3 to 3.5%. Losses in the two tree groups differed significantly (*t* test, $P = 0.0001$). The total number of elms in the city decreased from over 37,000 in 1995 to 21,000 (11,000 untreated and 10,000 treated) in 2001. This fourfold decline in susceptible trees may explain the decrease in natural disease incidence in untreated trees.

In a similar 6-year experiment with *Ulmus americana* in Denver, CO, annual Dutch elm disease losses declined steeply after the first year from 7% to 0.4 to 0.6%; disease incidence in control trees slowly followed with a decrease from 5.2 to 1.1% (Fig. 10). In the first year (1998), more elms in the treated group succumbed to Dutch elm disease than in the nontreated group. This was partly attributable to a decision to visually select apparently weak elms to be treated. Many of these elms already had Dutch elm disease at the time of the first injection, and thus died despite the treatment. Once these diseased elms were eliminated from the treated group, disease incidence declined far below the disease incidence in the nontreated group (for 1999 to 2003; *t* test significant at $P = 0.05$).

Fig. 8. Injection of elms with *Verticillium albo-atrum* strain WCS850 by means of the 'Bomendienst' injection tool. In mature trees, 0.15 ml per injection is applied, and the distance between injections is 10 cm at a height of ca. 1.30 m. Treatment is in May or early June at the latest. The tool replaced the less convenient, but equally effective, inoculation of trees by means of a Stanley trim knife (The Stanley Works, New Britain, CT).

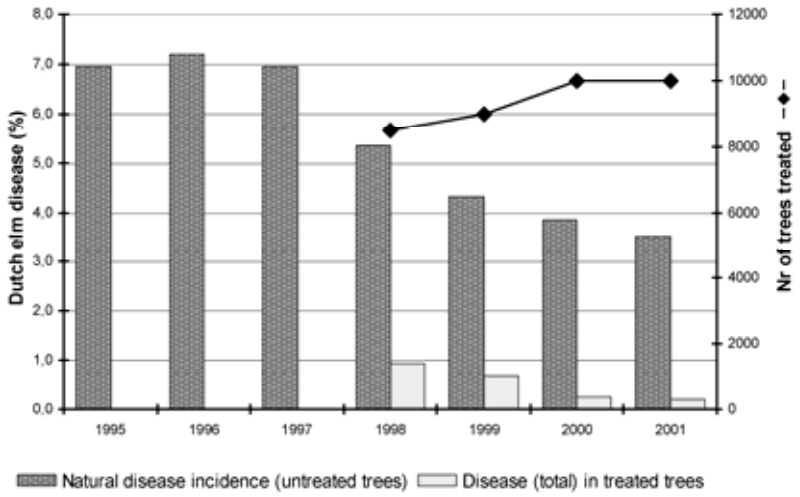

Fig. 9. Losses due to Dutch elm disease in The Hague 1995 to 2001. A large-scale prevention program started in 1998 when 8,500 trees were treated with *Verticillium albo-atrum* strain WCS850. The total disease rate in the treated trees dropped from 0.94% in 1998 to 0.20% in 2001. In the treated trees, new infections declined in 4 years from 0.53% to 0.22, 0.10, and 0.05%; root grafts counted for 0.41, 0.44, 0.15, and 0.15%.

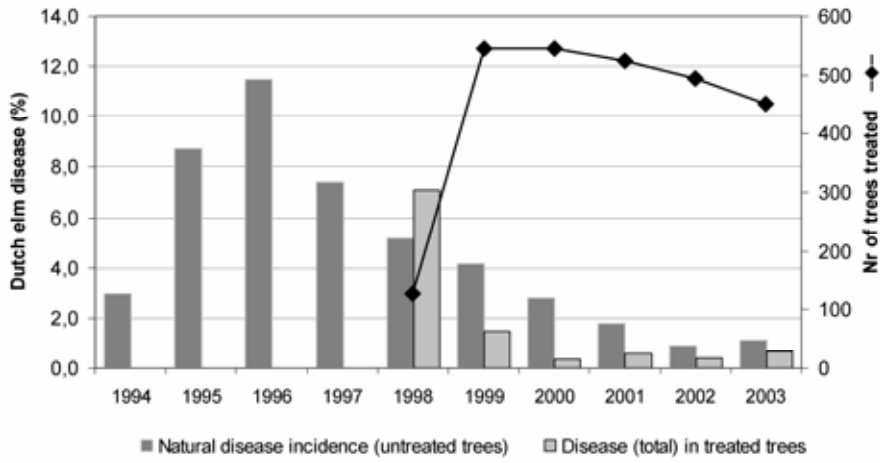

Fig. 10. Losses due to Dutch elm disease in Denver, CO, 1994 to 2003. A treatment program started in 1998 when 127 trees of a total of 1,967 elms were treated with *Verticillium albo-atrum* strain WCS850. In 1999, 545 elms were treated, with 1,318 controls; in 2003 the ratio was 450 treated to 1,282 controls.

Our experiments showed that a variety of elm species and clones respond to treatment with WCS850. In field trials we did not observe certain elms not to respond; in the greenhouse trial (Fig. 6) differences were clear, but all clones responded. The main mechanism we postulate for this biological control method is induction of resistance in the host. The induction has to take place before infection; apparently the tree needs time to build a resistance response. WCS850 could only be isolated from trees shortly after inoculation; this may explain why the treatment must be repeated annually. Based on the data presented here, and on a number of more limited field experiments, we conclude that injections with *Verticillium* WCS850 restricted new infections by the Dutch elm disease pathogen to less than 1% annually. However, infections through root grafts are not controlled and the treatment must be repeated annually.

Other control strategies: sanitation, fungicides, resistant elms, and devirulence factors. *Sanitation and beetle population control.* Eradication of Dutch elm disease has often been attempted, but without success. Eradication as a goal is unrealistic given the multiple pathways available for spread of the disease and the relatively susceptible populations of hosts that still occur, often in great abundance but with much reduced tree size. However, disease management is feasible, and efficacy depends on minimizing beetle populations. To achieve this, suitable breeding material must be destroyed. In practice, this means that all dying and dead elm wood should be promptly destroyed; at a minimum, the bark has to be pared from the wood. Success depends on vigilance and thoroughness. If some large branches are missed, or if some unbarked logs are kept for firewood, new beetles will emerge to sustain the epidemic. Effectiveness of a vigorous sanitation program was shown in the Netherlands during the years 1935 to 1944 and 1978 to 1988. The first program did reduce losses, but was curtailed during the Second World War. The later program quickly reduced losses to a stable 1.3% in clonal elms by 1984 and later (23). In wild populations of elm in fields and forests, losses remained high due to the problem of detecting and removing diseased trees in such complex environments. The national program itself fell victim to government budget cuts in 1988.

More recently, in New Zealand, an eradication program was initiated immediately upon discovery of the disease in 1989. In 2000, Gadgil et al. (15) concluded that eradication from New Zealand should be possible if the survey and removal program were continued. Indeed, losses were very small after 1995, but they did not further decline. In 2007, Biosecurity New Zealand, Wellington, NZ, still reports Dutch elm disease to be present and warns that it could wipe out elms in the country in 13 years if the program ends.

More success stories exist, such as the Integrated Elm Program of the City of Hamburg, Germany, which reports losses due to Dutch elm disease of less than 1%, and similar programs in a number of cities in North America. Such programs consistently show that, with sufficient vigilance, Dutch elm disease can be managed but not eradicated.

DDT (dichlorodiphenyltrichloroethane) once was used with success in Dutch elm disease control efforts, as it eliminated bark beetle populations, but it was banned during the 1960s for environmental reasons. Alternatives proved much less effective. Pheromone traps proved to be an effective monitoring tool for *Scolytus* beetle populations; they have been and still are used routinely in areas with sanitation programs in North America, Europe, and currently also in New Zealand. Pheromone traps can catch millions of beetles, but they have never proven effective in controlling Dutch elm disease (37).

Fungicide treatment. Control of the pathogen by fungicide treatment has focused mainly on benzimidazoles (benomyl, carbendazim, and thiabendazole) and sterol biosynthesis inhibitors. Of the benzimidazoles, thiabendazole was registered in the United States by 1977 for systemic injection into elm trees. Thiabendazole is currently registered in the United States as Arbotect 20-S (Syngenta Crop Protection, Inc., Greensboro, NC) for control of Dutch elm disease as well as sycamore anthracnose. When properly metered and injected in a timely fashion, Arbotect 20-S appears effective in protecting elm trees for up to 3 years. Injection of the proper amount of fungicide through drilled holes in the root flares requires several hours per tree, precluding the widespread use of this treatment on large numbers of trees, but it is feasible when used to protect relatively small numbers of the most valuable trees.

As it had been shown that hyphae are involved in the movement of the pathogen from one vessel to another (33), Kerkenaar et al. (29,30) hypothesized that fungal hyphae are necessary for transport of the pathogen from one vessel to another, and that sterol biosynthesis inhibitors can prevent the transformation from the conidial stage into the hyphal one through disruption of chitin deposition. Morpholines, especially fenpropimorph-phosphate and -sulfate, can be used effectively to control Dutch elm disease (43). The active ingredient could be detected by gas chromatography 2 years after treatment. No registration was obtained for tree injection, but another sterol biosynthesis inhibitor, propiconazole, was registered for use in the United States.

In a comparison of Arbotect 20-S (thiabendazole) and Alamo (propiconazole; Syngenta), Stennes (52) showed that both products could be useful in some cases as therapeutic treatments, but this is not recommended. Stennes notes that translocation of Arbotect to the new wood formed following treatment has been confirmed, but that this is not known for Alamo. Apparently propiconazole could not be detected in sapwood by means of traditional bioassay. Employing more advanced extraction technologies and gas chromatography/mass spectrometry (GC/MS), Armstrong (2) could not detect the active ingredient in four out of six trees treated with the recommended dose of 3.9 ml/cm diameter after 7 months. At four times the recommended dose, the active ingredient could be recovered after 7 months, but translocation into the new annual ring was deemed unlikely.

For newly infected elms, a systemic fungicide treatment plus eradicative pruning after the treatment can save some trees. The U.S. label for Arbotect 20-S cautions that treatment may not be effective when a tree shows more than 5% crown symptoms, and the Alamo label states that "trees in advanced stages of disease development may not respond to the treatment".

Elms resistant to Dutch elm disease. When Dutch elm disease threatened elm populations in Europe in the 1920s, breeding for resistance started as efforts to keep the elm as an important tree in urban and agricultural regions. The first program began in the Netherlands in 1928 and continued until about 1992 (19,20). Early emphasis was placed primarily on selecting for resistance within native species, especially *Ulmus glabra* and *U. carpinifolia* and their various hybrids. The second disease pandemic in Europe that peaked during the 1970s (6) decimated many surviving native populations and some of the early "resistant" cultivars (e.g., 'Commelin'). This led to more extensive use of Asian elm germplasm, particularly the Himalayan elm, *U. wallichiana,* as a source of resistance genes. More recent elm breeding efforts in Spain and Italy emphasize the native European species *Ulmus glabra* and *U. carpinifolia* (=*U. minor*) but rely on the Siberian elm (*U. pumila*) as the source of disease resistance genes (39,49). Siberian elm seems better adapted to the warmer, drier parts of the Mediterranean region than to the cooler, moister climates of Great Britain and the Netherlands where other diseases take their toll on *U. pumila*.

Similar breeding experiences took place in the United States beginning in the 1930s with early efforts focused on identifying resistant individuals in North American species, especially *U. americana* (46). Subsequent programs shifted to exploiting either selections within a resistant species, such as various cultivars of *U. parvifolia* developed by the U.S. Department of Agriculture (54) or released by private nurseries, or interspecific hybrids, mostly utiliz-

ing *U. pumila* and/or *U. japonica* as the source of resistance (47). Additional Eurasian materials, including selections of *U. glabra*, *U. carpinifolia,* and *U. japonica*, also were exploited to produce an array of inter-related and often complex hybrids now available in the U.S. nursery trade (55). A few partially resistant American elm cultivars continue to be marketed in the United States, but these are almost all selections identified in screening trials; efforts to select and breed more resistant American elms have been largely unsuccessful. Altogether, some 20 to 25 elm cultivars with a certain level of resistance to Dutch elm disease are now available in Europe and North America offering possibilities for replacement of elms lost to pandemics.

Devirulence factors impairing the pathogen. A radically different approach is mentioned in the work of Brasier (4), who found virus infections in *O. ulmi*, referred to as d (devirulence) factors that impair growth and viability of conidia. As a result, perithecial production is reduced, opening options for biocontrol of the pathogen through the release of d-factors. One strategy might be to release elm bark beetles that carry virus-infected spores compatible with the local dominant pathogen clone. If instead of one local dominant clone, many types of the pathogen are present in an area, genetic modification of the viruses was proposed (7). Brasier suggests that this could be part of an integrated control strategy. However, deploying pathogen-infested beetles might interfere with sanitation and with preventive biological or chemical control programs. How registration authorities are going to deal with these questions has not been resolved.

Disease Status after a Century and Outlook for the Future

Unnoticed due to the terror of the First World War, the pathogen must have had its first victims around a century ago in northwestern France or Belgium (22). Since then, millions of elms have succumbed to the disease. Many have been replaced by other species or by resistant elm clones. Various forms of chemical and biological control have been attempted with variable success rates, but in the past the cost of control has been prohibitive for many elm owners. Today's options for managing Dutch elm disease are limited. Vector eradication by chemical control measures has been banned for environmental reasons, and registration issues (in Europe) and costs limit the use of chemical control of the pathogen, although thiabendazole, propiconazole, and fenpropimorph have proven to be effective. Biological control, by means of *Verticillium* WCS850, has been developed into one commercial product, Dutch Trig, registered in the Netherlands (1992) and the United States (October 2005). Alternative biological control methods, including the use of antagonistic bacteria, strains of the pathogen with a low virulence, and viruses that impair growth and viability of conidia of the pathogen, have not yet been developed into commercial products.

Today in regions where elms are threatened by Dutch elm disease, a combined control strategy is feasible in those countries where registration allows use of the products. For existing elms, preventive biological control, preferably combined with a strict sanitation program, is possible. For especially valuable trees that are newly infected, a fungicide treatment (if available) plus eradicative pruning after treatment can save many such trees. Alternatively, preventive chemical control, also in combination with a sanitation program,

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can be employed. The "pros" of biological control, compared with the use of chemicals, are its environment-friendly character and the limited wounding necessary in comparison with fungicide injection. The "cons" are the need for periodic retreatment together with the costs of agents and equipment. Until such time as adequate resistance can be bred into ornamentally attractive and broadly adapted elms, biological control appears to provide the best method of retaining valuable trees in the landscape.

For replacements, resistant clones are worth planting in modest numbers. The long boulevards of monocultures that prevailed in the past should probably not be recreated. However, over 20 clones resulting from American and European breeding programs are available from nurseries on both continents for judicious use by the nurseryman and homeowner alike.

The uniformity of many tree plantings along roads and canals indicates that many designers and planners still place aesthetic interests above the need for genetic diversity in our urban and rural forests. Many of our agricultural practices similarly favor genetic uniformity. Such genetically uniform populations often provide an optimal environment for epidemics. Native populations of European and American elms were generally susceptible to Dutch elm disease. In combination with a few very popular clones in urban areas—all susceptible—Dutch elm disease provided a clear and continuing example that ecological accidents do happen. However, after approximately 100 years of Dutch elm disease experience, we now have tools to manage the disease.

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