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Dutch elm disease on the island of Gotland: monitoring disease vector and combat measures

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Dutch elm disease on the island of Gotland: monitoring disease vector and combat measures

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ABSTRACT
The island of Gotland (Sweden) possesses the largest (more than one million trees) wild population of elms in northern Europe, which until recently was not affected by Dutch elm disease (DED). In 2005, DED was observed for the first time in the northeastern part of Gotland, and in the following years, it rapidly spread in all directions, generally following the major distribution of elms. Implementation of intensive control measures including ground surveys and geographic information system mapping of DED-diseased trees, their felling and destruction, and stump treatment with the herbicide glyphosate allowed reduction of the source of infection and probably suppression of an otherwise very rapid spread of the disease. Monitoring the flying periods of Scolytus multistriatus vector beetles between the years 2007 and 2011 showed that the abundance of trapped beetles in most cases differed significantly among individual years. Over the entire monitoring period, 55.2% of the beetles were trapped in June, 31.2% in July and 13.5% in August (difference among individual months significant at p < .001). In conclusion, the study demonstrated the seasonal flying patterns of S. multistriatus, suggesting that the removal of trees attacked in the previous vegetation period as a combat measure should be completed before the beginning of the flying season of S. multistriatus, and that the application of the integrated DED management has the potential to arrest the development of the disease in a geographically isolated area such as Gotland.

Introduction
Gotland (N57°26′, E18°27′), with its total area of 2994 km2, is Sweden’s largest island and the largest island in the Baltic Sea (Statistics Sweden 2005). At present, Gotland possesses more than one million trees, which is the largest and most valuable wild population of elms (mainly Ulmus minor) in Europe, and which are of crucial importance for a number of NATURA 2000 habitats unique for the island (Östbrant et al. 2009). Until recently, the Gotland population of elms was not affected by the virulent form of the Dutch elm disease (DED), which arrived in the late 1960s (Brasier et al. 2004). Compared to mainland Europe, such form of the disease was not affected by the virulent form of the Dutch elm disease (DED). The Gotland population of elms in northern Europe, which until recently was not affected by Dutch elm disease (DED). In 2005, DED was observed for the first time in the northeastern part of Gotland, and in the following years, it rapidly spread in all directions, generally following the major distribution of elms. Implementation of intensive control measures including ground surveys and geographic information system mapping of DED-diseased trees, their felling and destruction, and stump treatment with the herbicide glyphosate allowed reduction of the source of infection and probably suppression of an otherwise very rapid spread of the disease. Monitoring the flying periods of Scolytus multistriatus vector beetles between the years 2007 and 2011 showed that the abundance of trapped beetles in most cases differed significantly among individual years. Over the entire monitoring period, 55.2% of the beetles were trapped in June, 31.2% in July and 13.5% in August (difference among individual months significant at p < .001). In conclusion, the study demonstrated the seasonal flying patterns of S. multistriatus, suggesting that the removal of trees attacked in the previous vegetation period as a combat measure should be completed before the beginning of the flying season of S. multistriatus, and that the application of the integrated DED management has the potential to arrest the development of the disease in a geographically isolated area such as Gotland.

Once within a tree, the DED fungi reproduce by a yeast-like budding process, and the bud spores are distributed in the sap stream and spread rapidly throughout the current xylem (Webber & Brasier 1984). The fungi cause wilting and death, both by the plugging of the conducting system and by the production of toxins. A typical internal symptom of the disease is the formation of a brown ring in the infected sapwood resulting from the formation of tyloses and gels in the xylem vessels (Santini & Faccoli 2015). In a severe attack, the entire tree is usually killed before the end of the summer, though in the event of tree survival, the tree is likely to die the following season (Phillips & Burdekin 1982). The aim of the present study was to investigate the yearly incidence of DED on Gotland in relation to the applied combat measures, and simultaneously monitor the phenology (flying periods) of the disease vector S. multistriatus, in order to provide certain implications for its control.

Materials and methods
Monitoring spread of DED
Ground surveys and (geographic information system) GIS mapping of the DED-diseased and the elm bark beetles-attacked trees were carried out during 2005–2013 by the Swedish Forest Agency. Elm inventory data from the previous years were used to find and inspect elms in the field. During
2005–2007, all elms larger than 10 cm in diameter in the DED-affected area, and also in the neighbouring areas, were visited and inspected. From 2008 onwards, surveys encompassed the entire area of the island. Each year, surveys were carried out between July and September, that is, in the period when the external symptoms of DED, for example, yellowing, browning and wilting (“flagging”) of the leaves in a single or multiple branches of the canopy, are typically recognizable. If external symptoms were not obvious, the presence of DED was confirmed by inspection of internal symptoms (see Introduction). Whenever possible, the entry holes of the elm bark beetles in the DED-diseased and in the neighbouring elms were checked and recorded. The GIS data were analysed and the maps were produced using ArcGIS v.10.2 (Esri, Redlands, CA, USA).

Combat measures against DED

During 2005–2009, DED-diseased trees were mapped, felled and destroyed. Destruction was done yearly between October and April. In 2009, a new combat strategy was adopted; not only DED-diseased elms were felled and destroyed, but also visually healthy elms growing in their vicinity, and thus in likely root contact with DED-diseased ones. Stumps of all felled trees were treated with the herbicide glyphosate aiming to kill root systems and to prevent further spread of the DED via roots and sprouting. The herbicide was applied in the form of Ecoplug plastic plugs (Ecoplug Sweden AB, Åtvindaberg, Sweden) that were hammered into the vicinity, and thus in likely root contact with DED-diseased elms. Stumps of all felled trees were treated with the herbicide killed infected vector beetles. The precise route of disease arrival was determined by inspection of internal symptoms (see Introduction). Whenever possible, the entry holes of the elm bark beetles in the DED-diseased and in the neighbouring elms were checked and recorded. The GIS data were analysed and the maps were produced using ArcGIS v.10.2 (Esri, Redlands, CA, USA).

Flight of the elm bark beetles

The flying periods of the elm bark beetles were monitored between 2007 and 2011 at Vallstena (N57°36′, E18°41′) and Hogrän (N57°31′, E18°18′). The sites were characteristic to Gotland in terms of landscape and trees species composition, and were areas characterized by high DED activity. At each site, 10 window traps with a P188 pheromone lure (Synergy Semiochemicals Corp., Burnaby, Canada) were placed at 200 m intervals and checked weekly during June–August each year. Traps were composed of a container, which was filled with a water/glycol mixture, and a vertically placed transparent plastic sheet (50 cm × 50 cm in size) above it. Traps were set on two sticks ca. 1.5 m above the ground. Lures were fastened to the plastic sheet, and the same lure was used during the entire season. Lures consisted of two semi-permeable plastic pouches containing a mixture of cubeb oil, 1-hexanol, multistriatin and 4-methyl-3-heptanol. The lure used attracts Scolytus spp. beetles, which while flying towards the lure, hit the plastic sheet, fall into the container with a water/glycol mixture and sink. For identification, trapped insects were examined with a magnification glass and the number ofelm bark beetles was recorded. Illustrations of S. multistriatus were used for identification.

Statistical analyses

The abundance of elm bark beetles trapped in different months and sampling seasons was compared by non-parametric chi-squared tests calculated from the actual number of observations (Mead & Cumow 1983). As the data sets were subjected to multiple comparisons, confidence limits for p-values of the chi-squared tests were reduced a corresponding number of times, as required by the Bonferroni correction (Sokal & Rohlf 1995).

Results

In 2005, the virulent form of DED, caused by O. novo-ulmi, was for the first time observed in the northeastern part of Gotland. In subsequent years, it rapidly spread in all directions, generally following the major distribution of elms (Figure 1). A rapid spread of DED was particularly notable during the first three years. Consequently, the area with DED-diseased trees in Gotland increased from 15.8 km² (0.5%) in 2005 to 1446.2 km² (48.3%) in 2008, and its diameter expanded from 5.5 to 85.6 km, respectively (Table 1, Figure 1). During 2005–2008, 4278 DED-diseased elms were felled and destroyed (Table 1). During the period between 2009 and 2013, the implementation of a new combat strategy resulted in the felling and destruction of 17,903 DED-diseased and visually healthy elms growing in their vicinity. The use of the herbicide killed stumps and root systems of harvested elms. Implementation of this control strategy resulted in the number of DED-diseased trees and the area of Gotland infected by DED remaining similar each year (Table 1, Figure 1). In 2013, however, both the number of DED-diseased trees and the area infected by DED slightly increased. Among the felled and destroyed elms, 77% were of the 10–30 cm in diameter trees, 15% of the 30–50 cm and 8% of those >50 cm. Elms less than 10 cm in diameter were not counted and were classified as scrubs.

During 2007–2011, 1121 beetles of S. multistriatus were trapped, or on average, 11.2 beetles per year per trap. Information on the beetles trapped (data pooled from both sites) during each season is shown in Figure 2. There were 36.8% of S. multistriatus trapped in 2007, 20.6% in 2008, 25.9% in 2009, 11.2% in 2010 and 5.5% in 2011. Chi-squared tests showed that the number of beetles trapped each year differed significantly (p < .0001), with exceptions in 2008 and 2009, which did not differ significantly from each other. In all seasons, 55.2% of S. multistriatus were trapped in June, 31.2% in July and 13.5% in August (difference significant at p < .0001).

Discussion

Despite the fact that the virulent form of DED was present for decades in mainland Europe (including Sweden), the elm population in Gotland remained unaffected. The geographical position of the island in the Baltic Sea (ca. 70 km east of the coast of mainland Sweden and ca. 150 km west of the coast of Latvia) has likely prevented natural dispersal of DED-infected vector beetles. The precise route of disease arrival is not known, but was probably brought to the island with DED-infected elm wood, which similarly occurred elsewhere.
before (Brasier et al. 2004 and references therein), and would corroborate Santini et al. (2013) that humans may strongly impact introduction of invasive alien forest pathogens to new areas.

After introduction, the spread of DED occurred very rapidly and over large distances (Figure 1, Table 1). Taking into consideration that an average flying distance of *S. multistriatus* is between 400 and 600 m (Wollerman 1979), and up to 5 or 6 km according to other reports (Wollenbarger & Jones 1943), it is unlikely that the beetles themselves could transmit the DED at such speed and over such a distance. For example, Craighead (1950) suggested that long-distance dispersal of DED may be associated with trade and transportation of infected elm wood – the situation that could occasionally occur in Gotland, and thereby contribute to more rapid spread of this disease. Nevertheless, a large effort was made by the Swedish Forest Agency to inform and educate society, land owners and local authorities, and to implement intensive control measures that all led to the stabilization of the incidence of DED in the following years (Figure 1).

In addition to increased awareness of landowners/end-users when handling DED-diseased elm wood, stabilized incidences of DED can also be explained by the shift in the applied control strategy. Before 2009, only DED-diseased

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*Figure 1. Maps of Gotland showing the natural distribution of elms (green circles) and the occurrence of Dutch elm disease-diseased elms (red circles) during the years 2005–2013.*
trees had been felled and destroyed, but numerous secondary infections likely occurred from root systems of their stumps to roots of adjacent healthy trees, resulting in the observed increase of DED incidence (without bark beetle attack). The new combat strategy resulted in not only DED-diseased elms being felled and destroyed, but also visually healthy elms growing in their vicinity, thus in root contact with DED-diseased ones. The herbicide treatment killed root systems and prevented further spread of the DED via roots and sprouting. Elms that were left growing at the site, but appeared to be in root contact with felled trees, were also killed by the herbicide in the following year.

The flying intensity of *S. multistriatus* in Gotland varied among different seasons (Figure 2), which can probably be explained by seasonal fluctuation of temperatures, as the emergence from the trees and the activity of *S. multistriatus* are largely temperature dependent (Bartels & Lanier 1974). While possessing a single generation in Gotland and in southern Sweden and it was interpreted as the first part of the season. However, in some years, the second peak of flying occurred later in the season (Figure 2). A similar pattern of flying was also observed for *Scolytus triarminus* (formerly *Scolytus scolytus*) in southern Sweden and it was interpreted as the emergence of the second generation of beetles (Anderbrant & Schlyter 1987).

In conclusion, the study demonstrated the seasonal flying patterns of *S. multistriatus*, suggesting that combat measures that include removal of trees attacked in the previous vegetation period should be completed before the flying season of *S. multistriatus* and that the application of the integrated DED management has the potential to arrest the development of the disease in a geographically isolated area such as Gotland.

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