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Declining incidence of multi-trunking over time in a Scottish plantation of *Picea sitchensis*.

Running headline: Multi-trunking decline in *Picea sitchensis*.

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Abstract

Trends in the incidence of multi-trunking at 21 sites in Glenbranter Forest in western Scotland are reported. Monitoring began in 1978 and continued for 30 years except at five sites that were felled. Incidence varied greatly between sites, from 9% up to 67% of trees multi-trunked at age 15-16 yr, but rates declined slowly at nearly all sites after this peak. Decline was partly due to trunk singling and partly to multi-trunked tree death; in GLMM analyses we found that singling showed a highly significant relationship to the girths of the main and second-ranked trunks, respectively positive and negative, and mortality showed a highly significant relationship to the difference between the main-trunk girth and plot mean girth. From observations at older sites monitored to felling we predicted the final incidences of multi-trunking at three sites monitored since planting; for these sites the trees predicted to remain multi-trunked had suffered substantially more leader browsing from deer when young than trees predicted to be finally single-trunked. Sites planted in the 1970s are forecast to have final incidences of multi-trunking from 3 to 40%, with most expected to be in the range 20-30% multi-trunking. Hence appreciable losses in crop value are likely, and measures to combat multi-trunking are discussed.

Keywords: crop losses, deer browsing, multi-trunking, *Picea sitchensis*, trunk mortality

Introduction

Multi-trunking of trees is a phenomenon sometimes reported but little studied. It can arise from sprouts growing out of the bases of felled trees, mainly broad-leaved ones; these may develop into several trunks that may later be harvested as coppice. But multi-trunking can also result from damage to the leading shoot when trees are small, notably in conifers such as larch (*Larix*), pine (*Pinus*) and spruce (*Picea*). First, some buds of the damaged leaders develop into new leaders, or side branches of the damaged leaders flag (= bend or turn) up to become new leaders, then two or more of these leaders may persist as upright trunks.

Multi-trunking frequently occurs in Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and has the potential to substantially reduce the value of final harvested crops. Sitka spruce is now the main species grown commercially in the British Isles (Mason & Perks, 2011), so any large-scale damage to crops is of much concern. Multi-trunking or forking in Sitka spruce has been reported as arising from damage to leaders due to deer browsing (Welch et al., 1992), frost (Rouse 1948), green spruce aphid (Straw et al., 2000), spruce weevil (Alfaro & Omule, 1990) and windsnap (Thompson, 1984). Young trees generally recover by producing several new leaders, some or all of which then become trunks. Later, weaker trunks may flag down as the strongest trunk asserts dominance, and sometimes weaker trunks are too small to survive this competition and die, then soon fall. Also in even-aged stands the main trunks of multi-trunked trees are usually thinner than the trunks of single-trunked trees (Scott et al., 2009), so multi-trunked trees may suffer greater mortality than single-trunked trees due to their smaller bulk and height making them more vulnerable to shading in later forest stages.

Decline in the incidence of multi-trunking as a stand ages is therefore to be expected in plantations, and is the general experience of foresters, which may explain why little attention has yet been given to this form of damage in maturing stands of Sitka spruce. But with deer now widespread in British forests and much leader damage being sustained (Welch et al., 1991), appreciable proportions of multi-trunked trees are likely in future mature crops of Sitka spruce. Hence it is desirable to understand the factors which control or influence trunk singling and mortality in multi-trunked trees, and also to assess whether the incidence of damage on young trees is reflected in the incidence of multi-trunking at felling.

We therefore now relate trends observed over a 30-year period in multi-trunked Sitka spruce trees in Glenbranter Forest, Argyll, Scotland, to site factors, stocking density and tree qualities. Trends for periods of up to 15 years for 34 stands of differing age in Glenbranter have already been described (Welch et al., 1995); we now report the findings of continued monitoring at 21 of these sites. Having more sites reaching felling in the study and a longer time span for our observations gives greater certainty to our assessments of possible crop losses. Our main aim was assessing how persistent is multi-trunking in Sitka spruce, hence the long duration of our frequent monitoring for which we do not know a parallel in this species. A secondary aim was explaining its incidence, relating it not only to site and tree factors, but also to damage when the trees were young, for some sites which we have observed since planting.

Materials and methods

Study area

Glenbranter Forest lies near the west coast of Scotland (56º 07' N, 5º 03' W), and has an altitudinal range from 90 to 410 m. The climate is moderately oceanic (July mean temperature 14.7 ºC, January mean 1.4 ºC) and wet (c. 2200 mm rainfall per year). The soils are relatively fertile, and vary from brown earths to gleys to peaty podsols.

The forest is stocked predominantly with Sitka spruce. Afforestation began at the lower altitudes in the 1920s, and extended to higher ground in the 1950s, 1960s and 1970s. At first, more Norway spruce (*Picea abies* (L.) Karst.) than Sitka spruce was planted, but since the 1950s almost all plantings have been Sitka spruce, with provenance from coastal British Columbia usually Queen Charlotte Island. A major storm in 1967 blew down many maturing stands, which were then soon restocked. Typical crop yield figures are 12-16 m^3 ha^{-1} yr^{-1}.

Methods

Our studies in Glenbranter Forest began in 1978, aimed at assessing the long-term impact of red deer (*Cervus elaphus* L.) and roe deer (*Capreolus capreolus* L.) on the tree crop. We have reported on the incidence and effects of damage by leader browsing (Welch et al., 1991; Scott et al., 2009) and by bark-stripping (Welch et al., 1987; Welch & Scott, 2008). Initially we monitored 40 sites with different-aged crops, these selected randomly from the stock of 1-2 ha units obtained by dividing all forest compartments. Felling has steadily depleted the number of sites monitored, and for the present paper on multi-trunking we report mainly on the 21 sites at which monitoring continued after 1992, although we include all sites in one figure showing the long-term changes in incidence. Except at one site where a few individuals of Lodgepole pine (*Pinus contorta* Douglas ex Loudon) had been planted, all the trees were Sitka spruce.

At each site, six plots were selected using randomly-chosen distances from the sites` SW corner, then marked out and the trees mapped. Because in 1978 we wanted to assess deer usage and expose possible differences between edge and interior of stands, the plots were allocated to three zones defined by distance (<18, 18-60, >60 m) from plantation edge, proportionately to the zones` extents in the site. However, because of felling, windblow, planting, road-building, etc, many plots subsequently changed zone, and this zonal classification is not used in the present analyses. Plot size varied between 15 x 5 m and 18 x 10 m to allow for differences in tree spacing; we aimed to have at least 25 trees in the plots initially, so sites planted between 1950 and 1970 at close spacing had plots of 15 x 5 m or 18 x 5 m, whereas more-recently planted sites with 2 x 2 m spacing had mostly 18 x 10 m plots.

Tree growth was monitored by measuring the girth of all trunks at breast height (1.3 m). Trunks were defined as vertical axes with secondary thickening at least 20 cm long in the 50-150 cm height stratum. So trees with a trunk forking above 130 cm were classed as single-trunked, whilst those with a subsidiary trunk flagging down were considered multi-trunked if this trunk had the required vertical length (>20 cm). For trees at newly planted sites, we recorded height and number of leaders, and progressively changed to assessment of girth and multi-trunking state once heights exceeded 1.5 m; this occurred between 7 and 10 years after planting depending on performance.

The girth measurements took place at 1- or 2-year intervals up to 1995 (1-year at young sites with both height and girth assessment), and every 3 years thereafter. At some young sites extra trees joined the crop by natural regeneration, and were included in the measurements once their height exceeded 0.5 m; they were soon indistinguishable from the planted trees at several restocked sites and considerably increased their stocking. Other trees were lost, by being removed to create rides or extend drains, by windblow, and by dying, which became more frequent as the stands matured and inter-tree competition increased. In a few trees the main trunk and a weaker one coalesced; this prevented girth measurement but the trees were still classed as multi-trunked. For this paper we have chosen a stand age of 15 or 16 years on which to base assessments of the subsequent performance of multi-trunked trees, since at this age the number of multi-trunked trees has peaked, consequent on extra trunks developing in response to browsing and other damage in earlier years. However, a few more trees became multi-trunked after this stand age, and they are included in the multi-trunking percentages of Figure 1 and Tables VII and VIII. To illustrate some relationships, we grouped trees at stand age 15-16 years by their proportionate girth, this being defined as the ratio of the girths of the second-ranked trunk to the main trunk.

The sites experienced little management apart from fertiliser treatment in the early years after planting, and some clearing and deepening of drains. No site was thinned, although thinning was tested at a few stands in Glenbranter during our study. The market value of the thinned trees was poor, and the managers considered thinning increased windblow. In the third year of the study, 1980, we assessed plot wetness (either wet or dry) from the associated plant species.

To identify the factors that control the mortality of multi-trunked trees we fitted generalised linear mixed models (GLMMs (Bolker et al., 2009)) to binary (alive or dead) response data for all available multi-trunked trees at stand age 15-16 years (15-20 years for thicket sites). All models had the binomial dispersion (scale) parameter fixed to unity, and had the design variables of site and plot within site as random effects to avoid pseudo-replication in the event that the true variance components were not zero. Fixed effects were either chosen to demonstrate the effect of particular explanatory variables, whether individually or in combination, or were chosen by stepwise selection, iteratively omitting the least significant fixed effect from the current model until all terms were significant at the 5% level. During the stepwise modelling, selection was carried out firstly using only tree-specific terms based on trunk girths, secondly on addition of altitude (site-level), wetness and stocking density at age 15-16 years (plot-level) to the previously selected model. The significance of altitude was assessed by referencing the Wald statistic to an $F_{1,19}$ distribution, with 19 as denominator degrees of freedom taken from the design, there being 21 sites in all and this being the only site-level effect. The significance of all other effects was assessed by referencing the Wald statistics to X^2_1 distributions, there being over 100 plots and many more trees.

Analyses of the decline in multi-trunking due to trunk singling were conducted in an equivalent fashion to those for the analysis of mortality. We also did separate runs with the two measures of initial girth, for main and second-ranked trunks, replaced by the initial proportionate girth ratio. Additional analyses were conducted for Tables II, III and IV in the form of linear mixed models (LMMs) with random effects site and plot and with response variables and fixed effects chosen to shed light on additional features of the data. All LMMs and GLMMs were fitted using the REML and GLMM commands in Genstat 11.1 (VSN International Ltd).

We finally predicted the incidence of multi-trunking at felling for sites that we have observed since planting in 1978 and 1979. First we calculated the proportions of multi-trunked trees which survived, singled or died at our five thicket sites (TD2, TD4, TB5, TW1 and TC2 (Table I)) from stand age 27-28 years up to last assessments at stand age 42-44 years. This was done for each of nine sub-classes obtained by three-way classifying these trees, both from their proportionate girth and also their difference to plot mean girth. Then, for the three sites observed since planting which had many multi-trunked trees and a full record of damage (EW5, ED6 and ED9 (Table I)), we used the proportions observed at the five thicket sites to predict, for each of the same nine sub-classes, how many multi-trunked trees at 29 years stand age would survive, single or die up to felling age. We similarly calculated survival rates for single-trunked trees at the sites observed since planting from what happened to these trees at the thicket sites, in order to produce final estimates of percentage multi-trunking.

For the three sites observed since planting, we compared single- and multiple-trunked trees in browsing damage, both for actual classes at stand age 29 years and for predicted classes at felling. Individual trees were deemed to be ‘probably finally single-trunked' or 'probably finally multi-trunked' if belonging to a sub-class that at thicket sites had 75% or more of its members finally in these states; other trees were assigned to a 'finally uncertain' category. Then t tests were used to compare the means of classes and sub-classes in the number of occurrences of leader browsing that had been recorded when the trees were young.

Results

Incidence trends, trunk singling and multi-trunked tree mortality

At stand ages 15-20 years there were 856 multi-trunked trees at the 21 sites reported on here, referred to as initially multi-trunked (M_I) trees, with numbers at individual sites ranging from 16 to 85 (Table I). These sites had 2932 trees in total then, hence 29% were multi-trunked. The percentage incidence of multi-trunking varied sharply between sites, from 66.5% at EW4 and EW5 down to 8.8% at TD2 (Figure 1). Incidence tended to be lower at the sites planted before 1970, but was also low (14.5%) at site EHN planted in 1979 and heavily stocked. For the recently planted sites, Figure 1 shows the sharp rise in multi-trunking up to about age 15 years, and then a steady fall after about age 20 years. From Table I, trees becoming single-trunked and multi-trunked trees dying contributed roughly equally to this decline, and both of these events tended to increase after stand age 25-26 years.

The three sites felled at ages typical of present Scottish practice (40-45 yr) (TB5, TW1 and TC2, Table I) had respectively 7.9, 0.8 and 10.7% multi-trunking at the last recording prior to felling. The ten sites planted before 1950 reported in Welch *et al.* (1995) and included in Figure 1, had even less multi-trunking, incidence averaging just 4% (Figure 1). Only at the site planted in 1949 (PB1), did incidence exceed 10%, and then only in the first three years observed, at ages 29 to 31 years. In contrast, the six sites planted in 1973 and 1974 (EW1, EW4, ED4, EC2, EC5 and EC6) had a high incidence of multi-trunking when last assessed at stand age 32-35 years (mean 43%, with range from 22% for ED4 (28 trees) to 60% at EW4 (55 trees)), implying that at them the harvested crops will contain many multi-trunked trees.

The fate of the M_I trees was greatly affected by the initial proportionate girth (PG_I) of their trunks. The percentage of M_I trees that became single-trunked by stand age 27 years was highly significantly related to PG_I (Wald statistic 74.1, $P < 0.001$ in GLMM analysis with no other fixed effects), nearly all such trees having had their weak trunks less than half the girth of the main trunk at age 15-16 years (Table II). Although few multi-trunked trees had died by age 27, the relationship between percentage dead and proportionate girth was already significant (Wald statistic 8.2, $P = 0.004$ in GLMM analysis with no other fixed effects). The evidence for this relationship increased as more trees died after age 27, so for the last assessment (at ages up to 41 years (Table I)) the significance level was $P < 0.001$ (Wald statistic 13.2). During these further years, trunk singling increased markedly for the six classes with girth ratios less than 0.70 at age 15-16 years, so at last assessment the occurrence of single-trunked trees remained very strongly related to initial proportionate girth (Wald statistic 80.9, $P < 0.001$).

The main trunk grew faster than the second-ranked trunk in most M_I trees, as shown by the mean proportionate girth being lower when last assessed than at age 15-16 years (Table II). But trees that became single-trunked no longer contribute to the mean girth ratios, which obscures this trend. This was especially so for the classes with PG_i less than 0.50 and much trunk singling. The M_I trees that survived in the two classes with least ratios (just 6 and 29 trees) had increased final ratios, due to their weak trunks growing relatively well.

Multi-trunked (M_I) trees that became single-trunked at different stand ages had similar initial girth ratios across site groups (Table III). Mean values of the initial ratio exceeded 0.50 for all the groupings of trees that became single-trunked after 30 years age, and only one of the 20 individual trees having trunk singling at age 39-47 years had an initial ratio less than 0.50. All differences between the four age-class overall means were highly significant ($P < 0.001$ in t tests), except for the comparison between the age 31-38 and 39-47 year classes, which had $P < 0.04$ despite the small sample size in the latter class.

The M_I trees that remained multi-trunked experienced negative mean changes in proportionate girth for all site groups (Table IV). The more-recently planted sites had rather smaller mean changes in their girth ratios, as would be expected given the shorter time periods until the last recording. The mean values of PG_I tended to be lower for these more-recently planted sites (Table IV), since they include some trees having small second-ranked trunks likely to later die.

Factors explaining aspects of continued multi-trunking

The mortality of the M_I trees was found by the GLMM analysis to be related very significantly ($P < 0.001$) to the difference between the girth of their main trunk and the plot mean girth (Table V). The relationship was positive, so the smaller the M_I tree compared to the plot mean girth at stand age 15-16 years, the more likely the tree was to die. Mortality was also significantly related to the initial density of trees and to altitude, these relationships being negative and positive respectively.

The singling of M_I trees had tree attributes as the most significant explanatory variables (Table V). The initial girth of the second-ranked (=wk) trunk had the most significant relationship to singling in the final model (Wald Statistic 110.56, $P < 0.001$); this relationship was negative, so the smaller the initial second-ranked trunk the more likely was singling, all else being equal. The final model also found singling was significantly positively related to the initial girth of main trunks, and to initial tree stocking density, and significantly negatively related to the difference between initial main-trunk girth and the corresponding plot mean girth. In separate GLMM runs in which initial girths of the main and second-ranked trunks were replaced by the initial proportionate girth ratios (PG_I), this factor although highly significant (Wald Statistic 112.38, $P < 0.001$) did not account for as much variation in trunk singling as having terms for both the main and second-ranked trunk.

Prediction of final incidence of multi-trunking at sites observed since planting

At thicket sites, the final state of the 111 multi-trunked trees present at stand age 27-28 years was very closely related to their proportionate girth (PG_{27}) then, more so than to their girth-differences classes (Table VI). The majority with PG_{27} less than 0.40 became single-trunked (16 of 21 trees), whereas those with PG_{27} greater than 0.70 mostly remained multi-trunked (30 of 47 trees). The mean proportionate girth of the surviving multi-trunked trees in this last class was still high (0.76) at stand age 42-44 years, implying that even if felling is delayed there would be negligible further reduction in multi-trunking. For girth-difference classes, there was the expected greater mortality of multi-trunked trees initially at least 10 cm smaller in girth than the plot means (16 of 38 trees, Table VI). In the other two classes almost equal numbers of trees remained multi-trunked (33) as became single-trunked (34). For these girth classes, the final mean girth difference (− 2.3 cm) again implies that many surviving multi-trunked trees would remain in this state if felling was delayed.

For the three sites observed since planting used to predict multi-trunking at felling, we present multi-trunked tree numbers at stand age 29 years for the nine sub-classes based on girth difference and proportionate girth, and also for multi-trunked trees with coalesced trunks (Table VII). At EW5 the predicted final percentage multi-trunking remained high (40%) reflecting its high initial value (64%). Just 24 (= 52-28) trees would be lost from this state up to felling compared to 34 multi-trunked trees at each of the sites ED6 and ED9. The sub-class totals reveal that this lower mortality results from relatively more trees at EW5 having initially proportionate girth ratios exceeding 0.70 (21 trees) and greater mean girth than the plot mean (25 trees). Site ED6 has the most trees with low proportionate girth ratios (13), only 2 of which are predicted to still be multi-trunked at felling. Of the 19 trees with coalesced trunks at the three sites, just 2 are predicted from their total girth to die before felling, but as none of this type was present at the thicket sites at age 27-28 years this prediction is not secure.

At these three sites observed since planting, more browsings of leaders had been incurred by the trees that were multi-trunked at age 29 years than by those single-trunked (Table VIII). This difference was significant (t = 3.40, $P < 0.001$) for the combined sites, but not for the individual sites. For the sub-class of multi-trunked trees at age 29 years likely to be still multiple at felling, browsing damage was also significantly greater than for single-trunked trees (t = 3.27, $P < 0.002$) despite the small number of trees (36) in this multiple-at-felling sub-class. And at site ED9 the difference between trees still multi-trunked at felling and single-trunked trees was also significant (t = 2.32, $P < 0.05$); all other comparisons involving sub-class means were insignificant.

Discussion

Multi-trunking has proved to be long persistent in Sitka spruce stands in Glenbranter Forest, as was considered likely in our earlier report on the trees in this condition (Welch et al., 1995). Indeed the final incidence predicted in that paper (10-30% of trees) is probably too low, since at four of our sites last aged 34 or 35 years (EW4, EC2, EC5, EC6 (Table I)) multi-trunking still ranged from 41 to 60% (Figure 1). Also at one of the three sites observed since planting (EW5 Table VII) we predict a final incidence of 40%, though at the other two of these sites the likely incidence at felling is c. 20%.

The sites planted before 1970 with few multi-trunked trees just prior to felling or when last assessed (Table I), did not have high incidences during their 15-30 years age-span, and showed only gradual decline in multi-trunking (Figure 1). Likely reasons for the greater post-1970 incidence of multi-trunking are heavier deer browsing than in earlier years when the trees were young, and secondly tree stocking being less dense for plantings after 1970. Other factors such as greater incidence of frost, insect or wind damage, are thought very unlikely to be responsible, since our regular monitoring found these much less frequent than browsing damage. A positive relationship between leader browsing and multi-trunking was shown in Welch et al. (1992), and negative relationships between tree stocking density and both browsing incidence and multi-trunking were found at the sites observed since planting (Scott et al., 2009).

The main factors determining the fate of multi-trunked trees were their condition at stand age 15-16 years, expressed by the girth of their main trunk relative to their second-ranked trunk, and secondly their relative size compared to neighbouring trees, expressed as difference in girth to plot mean girth (Table V). There was also a highly significant effect of tree density on mortality, this being less at higher densities, which we suggest is due to the growth of all trees, and especially the single-trunked likely dominants, being checked on densely-stocked plots. Tree condition at age 15-16 years was most conveniently expressed by the weaker-to-main-trunk proportionate girth ratio, as in Tables II-IV, but having two separate terms for main and second-ranked trunks in the GLMM analyses explained more of the observed singling than the proportionate girth ratio alone. This relationship to singling was consistent across our study sites, with for instance no plot or site effects shown up in the REML analysis of the proportionate girths recorded immediately prior to singling (Table III).

Little other study on multi-trunking in Sitka spruce has been undertaken, so we cannot say if the incidence now recorded in Glenbranter is typical of other plantations in Britain and Ireland. But because multi-trunking has been regarded as a minor problem in other relevant studies, e.g. on trunk straightness (Macdonald et al., 2009) and an assessment of the value of pruning in conifer plantations (Fitzsimons, 1989), it seems our current incidence is higher than the Scotland average. Perks et al. (2005), after assessing leader damage imposed experimentally, calculated losses of 10-28% in sawlog production due to multi-trunking, but their actual observations on multiple stems ceased when the saplings were just 6 years old. Moreover the forecasting of losses by both Perks et al. (2005) and Gill et al. (2000) made use of the Glenbranter findings. Observations by Bergquist et al. (2003) and Thompson (1984) on response to leader damage similarly ceased when the trees were still young, although Bergquist et al. considered that their study species, Norway spruce (*Picea abies)*, recovered from multi-stemming more rapidly than our Sitka spruce. But these two studies cited above and Perks et al. (2005) did all show that the more frequent was leader damage, the greater the incidence of multiple stems and trunks, or forked stems in the experiment of Thompson (1984).

Other conifer species in which damage to leaders has been considered to result in multi-trunking are *Pinus flexilis* James (Schuster & Mitton, 1991) and *Picea rubens* Sarg. (Reyes & Vasseur, 2003). But the once-only cutting treatment applied in the latter study removed only 20% of the biomass including lateral shoots, and there was no long-term monitoring to relate multiple-leader incidence to subsequent multi-trunking.

Practical measures that foresters could employ to minimise the incidence of multi-trunking and consequent losses are suggested from our findings. Probably closer spacing at planting would be beneficial, although other key attributes such as timber quality and growth rates that are much affected by tree density (Brazier & Mobbs, 1993) would need to be considered. Also pruning the weaker trunks should be investigated and trialled. Perks et al. (2005) discussed singling young trees and its likely cost: £35 to £150 ha^{-1} depending on the prevalence of multi-trunked trees and their age. They considered from preliminary evaluations in western Scotland that singling would be more cost-effective on high-quality sites with shorter rotations, with which we agree. We also believe that the trees to be pruned should be the ones whose multiple trunks are likely to persist to felling, especially those having proportionate girths of second-ranked to main trunk greater than 0.7 at age 15 years. Perks et al. (2005) said that costs after year five were likely to be too great to make pruning financially worthwhile, presumably because of the increasing thickness of the trunks to be cut, but balancing this there would be fewer saplings needing attention if only trees with nearly equal-sized trunks were dealt with; the remaining saplings may well single themselves before felling age.

As yet the managers of Glenbranter Forest have not had to market stands with many multi-trunked trees, since these have not quite reached felling age. Some of them do contain single-trunked trees of sawlog quality, so marketing for pulp is not the only consideration. Perhaps early felling would be the best policy, so the weak trunks contribute some biomass that would be lost on their death, but this would forego a good return from the sawlog trees.

More knowledge on several aspects of multi-trunking is required, but research is seriously hindered by the long time-scale and large datasets needed. Moreover the numbers of trees that develop into classes of multiple-trunked trees based on trunk proportionate girths and differences to plot mean girths are uncertain. But having insufficient trees in a class can weaken the findings on how that class grows and how persistent is its multi-trunking state; the calculations we have done in Tables VI-VIII verge on being undermined by lack of trees in some sub-classes. Another difficult problem for researchers is the coalescing of trunks, which when it reaches breast height prevents meaningful girth measurement, and so rules trees out from increment estimates. We have recorded coalescing in trees as young as 17 years-old, but its frequency seems to increase with age (Scott et al., 2009) and may disproportionately occur on stronger-growing trees.

To conclude, we believe the main priorities for forest management are an assessment of multi-trunking incidences at felling across a range of sites throughout the UK that received substantial deer damage in the early years after planting, and secondly observations for 10-20-year periods in the middle and later stages of the rotation to find how general are the declines in incidence that we have observed in Glenbranter. If declines in thicket and pole stages are small and incidences at felling are appreciable, then studies aimed at understanding the relationships between the frequency and intensity of leader damage and the development of multiple trunks will be essential. Other minor studies are needed to check on any continuing loss from weak trunks after death due to their side branches impacting on main trunks, and to quantify how much loss occurs to sawlog outputs from different main-to-weak-trunk ratios and heights of trunk division.

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Caption to Figure

Figure 1. Trends in % trees multi-trunked at 39 sites of Sitka spruce in Glenbranter Forest. Each line represents one site, and starts c. 8 years after planting and continues till our last assessment. Sites planted before 1964 have start age of >14 years.

Table I. Numbers of initially multi-trunked (M_I) trees at the individual study sites at stand age 15-16 years*, and their subsequent status (M = multi-trunked, S = Single-trunked, Dd = Dead). Includes natural regeneration trees that were > 2.5 m tall at stand age 15-16 years.

Site	Altitude (m)	Year planted	Mean stocking density^{+} ha^{-1}	Number of M_I trees	Numbers of trees at stand age 25-26 yr			Numbers of trees when last assessed			Stand age when last assessed
					M	S	Dd	M	S	Dd	
EW5	380	1979	880	56	54	2	0	52	4	0	29
ED6	380	1979	1500	60	56	4	0	53	6	1	29
ED9	270	1978	1315	69	60	8	0	57	11	1	29
EHN	240	1979	2505	16	10	5	1	5	10	1	28
EW1	170	1974	1232	48	40	7	1	33	12	3	32
EW2	130	1975	1426	31	21	10	0	15	13	3	31
EW4	380	1973	926	62	61	1	0	55	6	1	35
ED4	300	1974	1398	48	38	8	2	28	17	3	32
EC2	370	1973	1324	75	74	1	0	69	6	0	34
EC5	360	1974	1500	85	82	3	0	73	9	3	34
EC6	410	1974	1204	57	55	2	0	49	6	2	34
ED3	200	1968	1787	26	22	2	2	5	7	14	40
EH1	140	1968	2588	33	15	5	13	3	11	19	40
EH5	100	1967	2222	17	10	3	4	1	4	13	41
EH6	100	1967	3539	22	11	9	2	2	13	7	32F
TD2	400	1963	3370	16	15	1	0	9	6	1	43
TC4	210	1961*	3519	18	15	1	2	10	4	4	28F
TD4	380	1959*	3728	55	55	0	0	10	28	17	47
TB5	220	1959*	2722	24	22	1	1	10	7	7	42F
TW1	240	1958*	3204	20	18	2	0	2	11	7	44F
TC2	220	1958*	2630	18	18	0	0	13	3	2	44F

* first assessment at stand age 17 years (TC4), 19 years (TD4, TB5), 20 years (TW1, TC2)

$^{+}$ stocking density at stand age 15-16 years, or 17-20 years at sites TC4-TC2

F stand felled shortly after last assessment

Table II. Subsequent performance of M_I trees classified by proportionate girths of second-ranked trunks to main trunks at age 15-16 years (PG_I). Includes all multi-trunked trees at the fifteen non-thicket sites planted after 1963, with almost all the last assessments involving trees aged between 29 and 35 years of age. M = Multi-trunked, S = Single-trunked, Dd = Dead.

Classes of Proportionate Girth at Age 15-16 yrs	Number of Trees	% trees at age 27 yr			% trees when last assessed			Mean Proportionate Girth M trees when last assessed
		M	S	Dd	M	S	Dd	
0.01-0.19	37	35	65	0	16	84	0	0.27
0.20-0.29	67	58	39	3	43	49	7	0.30
0.30-0.39	74	72	22	7	58	32	9	0.43
0.40-0.49	34	85	12	3	62	26	12	0.44
0.50-0.59	72	92	3	6	74	13	14	0.48
0.60-0.69	83	92	2	6	72	13	14	0.60
0.70-0.79	96	96	1	3	86	4	9	0.71
0.80-0.89	107	95	1	4	82	7	11	0.78
0.90-1.00	135	95	1	4	87	5	7	0.75

Table III. Mean proportionate girths (ratio of second-ranked trunk girth compared to main trunk) at age 15-16 years (15-20 years at thicket sites) for multi-trunked trees which became single-trunked at different ages, for site groups based on planting date. Excludes trees not surviving till last observation and natural regeneration trees < 2.5 m tall at stand age 15-16 years. Means and standard errors were obtained by fitting LMMs to data from trees that became single-trunked in each of the four age spans.

Site groups	Total Trees	Proportionate Girth means for trees becoming Single-trunked at age spans			
		15-22 yrs	23-30 yrs	31-38 yrs	39-47 yrs
EW5, ED6, ED9, EHN	31	0.25	0.42	NA	NA
EW1, EW2, ED4	43	0.19	0.30	0.52	NA
EW4, EC2, EC5, EC6	27	0.22	0.49	0.55	NA
ED3, EH1	18	(0.12)	0.32	0.57	(0.56)
EH5, EH6	17	(0.23)	0.39	0.72	NA
TD2, TD4, TB5	41	(0.21)	0.32	0.64	0.70
TW1, TC2, TC4	18	(0.25)	0.47	0.50	(0.75)

Parentheses show means based on just 1-2 trees
NA indicates no data available

Table IV. Mean changes in proportionate girth, with standard errors obtained by REML analysis, for trees remaining multi-trunked, for groups of site with different planting years. N = 491, this total excluding 42 initially multi-trunked trees whose main trunk coalesced with a weaker trunk.

Site groups	Initial Mean Proportionate Girths	Initial Age (yrs)	Mean Changes in Proportionate Girth	Age when recorded (yrs)
EW5, ED6, ED9, EHN	0.68	15-16	−0.05±0.02	28-29
EW1, EW2, ED4	0.74	15-16	−0.09±0.03	31-32
EW4, EC2, EC5, EC6	0.70	16	−0.07±0.02	34-35
ED3, EH1, EH5	0.74	15-16	−0.06±0.11	40-41
EH6*	0.83	16	−0.10±0.13	32
TD2, TD4, TB5	0.79	15-19	−0.13±0.04	42-47
TW1, TC2	0.71	20	−0.10±0.05	44

* only 2 surviving multi-trunked trees at this site

Table V. Significances of factors (tree qualities at age 15-16 years, or 15-20 years at thicket sites, and site qualities) that explain a) mortality of initially multi-trunked (M_I) trees and b) trunk singling for surviving M_I trees, in binomial GLMM analyses with a logit link function.. Factors in italics were dropped from the model during the stepwise procedure starting with row 1; factors in upright case show significance and coefficients from the final model..

a) mortality of initially multi-trunked trees

Factor	Test	Wald Statistic	*P* value	Coefficient Estimate	St. error
Log plot mean girth	X^2_1	*0.01*	*>0.9*		
Plot wetness	X^2_1	*0.43*	*>0.5*		
Girth weak trunk (cm)	X^2_1	*2.44*	*0.1*		
Girth ratio wk:main trks.	X^2_1	*1.20*	*>0.7*		
Girth main trunk (cm)	X^2_1	*0.97*	*>0.3*		
Altitude (m)	$F_{1,19}$	5.95	=0.025	0.0067	0.0027
Tree density (no ha^{-1})	X^2_1	20.51	<0.001	-0.0010	0.00022
Girth diff. cf. plot mean	X^2_1	66.03	<0.001	0.263	0.032

b) trunk singling in surviving trees

Factor	Test	Wald Statistic	*P* value	Coefficient Estimate	St. error
Girth ratio wk:main trks.	X^2_1	*0.68*	*>0.4*		
Log plot mean girth	X^2_1	*0.72*	*>0.3*		
Plot wetness	X^2_1	5.06	0.02	-0.997	0.443
Altitude (m)	$F_{1,19}$	8.49	0.009	-0.0063	0.00216
Tree density (no ha^{-1})	X^2_1	7.42	0.006	0.0005	0.00019
Girth diff. cf. plot mean	X^2_1	31.78	<0.001	-0.177	0.032
Girth weak trunk (cm)	X^2_1	110.56	<0.001	-0.343	0.033
Girth main trunk (cm)	X^2_1	65.48	<0.001	0.258	0.032

Table VI. Observed numbers of trees at felling age (italics) in three classes (M = Multi-trunked, S = Single-trunked, Dd = Dead) that developed from multi-trunked trees at age 27-28 years at five sites initially thicket (TD2, TD4, TB5, TW1 and TC2), for combinations of proportionate-girth class and girth-difference class. Classes of girth difference of main trunk compared to plot mean are: A = 10-30 cm less, B = 0-9 cm less, C = exceeds. Ratios of table entries were subsequently used to predict the final extent of multi-trunking at three sites monitored since planting (e.g. for proportionate-girth class 0.01-0.39 and girth-difference class C, 2 of 11 trees (ratio = 0.18) are predicted to be alive and ending multi-trunked at felling).

Class of Proportionate Girth at Age 27-28 yrs	Number of M trees at Age 27-28 yrs	Fate at Felling	Number of Trees in Classes of Girth Difference			Final Total Trees	Final % M at stand age 42-44 yrs of initial M trees
			A	B	C		
0.01-0.39	21		2	8	11		
		End M	*0*	*1*	*2*	*3*	*14*
		End S	*1*	*6*	*9*	*16*	
		End Dd	*1*	*1*	*0*	*2*	
0.40-0.69	43		14	15	14		
		End M	*1*	*4*	*6*	*11*	*26*
		End S	*8*	*9*	*8*	*25*	
		End Dd	*5*	*2*	*0*	*7*	
0.70-1.00	47		22	13	12		
		End M	*10*	*10*	*10*	*30*	*64*
		End S	*2*	*1*	*1*	*4*	
		End Dd	*10*	*2*	*1*	*13*	
All trees	111		38	36	37		
		End M	*11*	*15*	*18*	*44*	*40*
		End S	*11*	*16*	*18*	*45*	
		End Dd	*16*	*5*	*1*	*22*	

Table VII. Observed numbers of multi-trunked trees at age 29 years, classified according to the attribute classes in Table VI, at three sites monitored since planting. Also shown are the % trees multi-trunked for sites (italics), calculated from the total trees present at the sites, and the predicted number of M trees at felling (bold), calculated for each proportionate-girth class using the appropriate ratios from Table VI. Equivalent calculations were performed for coalesced trees and single-trunk trees, to predict multi-trunking percentages at felling. Classes of girth difference of main trunk compared to plot mean are as in Table VI: A = 10-30 cm less, B = 0-9 cm less, C = exceeds.

Site	Classes of Proportionate Girth at age 29 yrs	Numbers of M trees in Classes of Girth Difference at age 29 yrs			Total Trees at age 29 yr	Predicted number of M Trees at felling
		A	B	C		
EW5	0.01-0.39	2	1	5	8	**1**
	0.40-0.69	1	2	10	13	**5**
	0.70-1.00	10	5	6	21	**13**
	Coalesced	3	3	4	10	**9**
	Total M trees at site	16	11	25	52	**28**
	% trees M at site				*64%*	***40%***
ED6	0.01-0.39	3	1	9	13	**2**
	0.40-0.69	7	6	10	23	**6**
	0.70-1.00	8	3	2	13	**8**
	Coalesced	2	1	1	4	**3**
	Total M trees at site	20	11	22	53	**19**
	% trees M at site				*42%*	***19%***
ED9	0.01-0.39	1	3	5	9	**1**
	0.40-0.69	8	6	10	24	**6**
	0.70-1.00	12	4	4	20	**12**
	Coalesced	0	1	4	5	**5**
	Total M trees at site	21	14	23	58	**24**
	% trees M at site				*43%*	***22%***

Table VIII. Mean incidences of leader browsing sustained since planting for trees that are single- (S) and multi-trunked (M) at stand age 29 years, and for M trees grouped according to their probable classes at felling. Trees were assigned to probable classes at felling thus: M - those with proportionate girth (weak/main trunk) greater than 0.70 or coalesced and in Girth Difference Classes B and C (Table VII) at stand age 29 years; S - those with proportionate girth under 0.40 and in Girth Difference Class B and C; uncertain - all other class combinations.

Site	Mean number of browsings per tree				
			Probable classes at felling for M trees at age 29 yr		
	S trees at age 29 yr	M trees at age 29 yr	M	uncertain	S
EW5	2.6	3.0	3.4	2.8	2.0
ED6	2.1	2.4	2.7	2.4	2.6
ED9	3.4	4.1	4.2	4.2	3.9

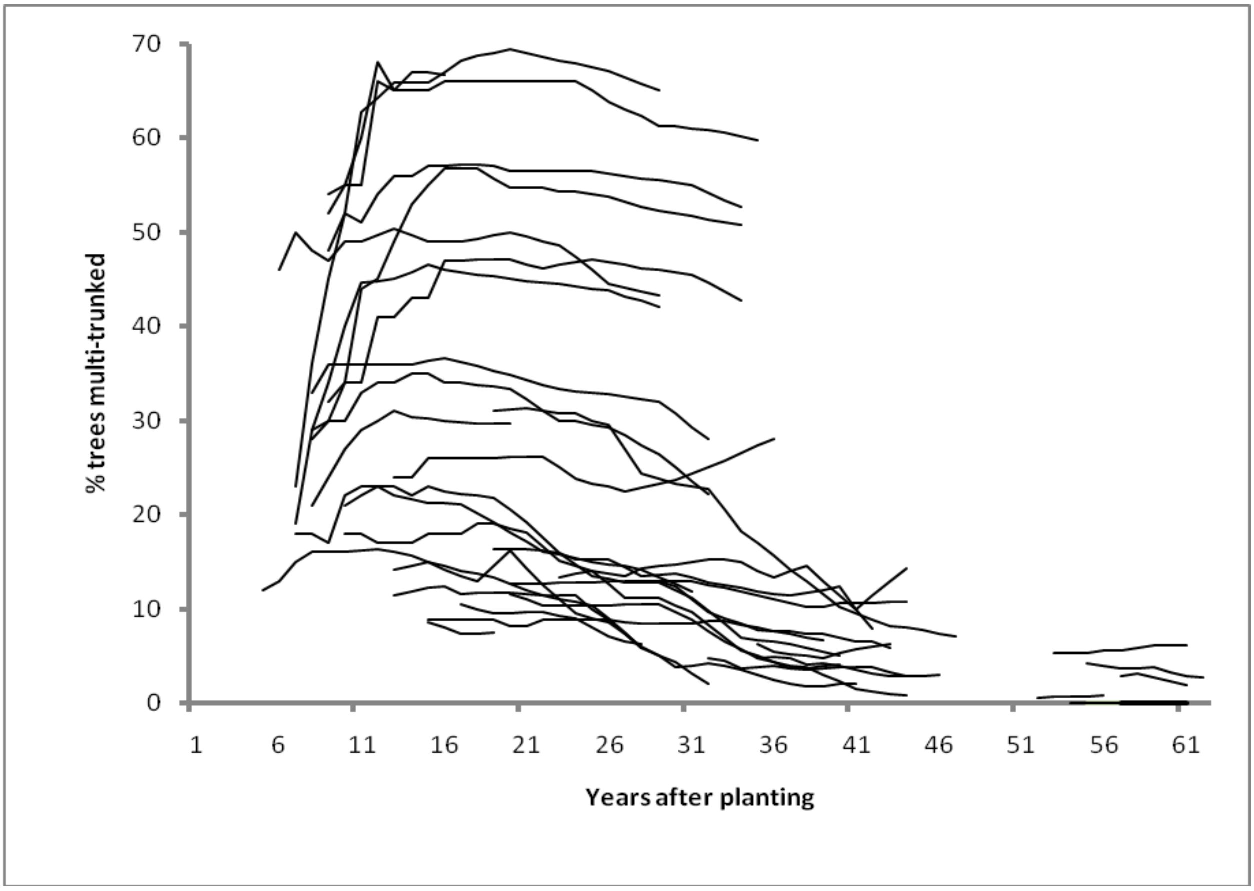

Figure 1. Trends in % trees multi-trunked at 39 sites of Sitka spruce in Glenbranter Forest. Each line represents one site, and starts c. 8 years after planting and continues till last assessment. Sites planted before 1964 have start age of >14 years.