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Dormant season vegetation management in broadleaved transplants and direct sown ash (*Fraxinus excelsior* L.) seedlings

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Abstract

In northern temperate climates, broad-spectrum contact acting herbicides could be used in the dormant season to remove established herbaceous weeds, and release trees from competition. Unfortunately, there is little published information on broadleaved tree tolerance. In an experiment on open-grown 2-year-old planting stock, 1.1 kg a.i. ha^{-1} paraquat was found to be generally safe to spray over dormant oak (*Quercus robur*), ash (*Fraxinus excelsior*), sycamore (*Acer pseudoplatanus*), cherry (*Prunus avium*), birch (*Betula pendula*), alder (*Alnus glutinosa*), and sweet chestnut (*Castanea sativa*), provided no immature buds, bark, or leaves were present. Survival of these species was unaffected, although there were occasional reductions in subsequent growth. Poplar (*Populus* sp.) and willow (*Salix* sp.) were severely damaged. Growth and survival of dormant beech (*Fagus sylvatica*) transplants were also apparently unaffected. Previous work has suggested that younger seedlings may respond differently than older, larger transplant stock, particularly where seedlings have grown amongst dense weed cover and are less dormant. Hence in a further experiment on 1-year-old container grown ash seedlings kept outdoors, glyphosate and paraquat were applied at two doses as an overall spray in January and before bud-burst in March. None of the treatments had any apparent adverse effects. In a field experiment, plots of ash seedlings were kept weed-free or grown with a natural population of weeds for one season, then paraquat sprayed at five doses (0.4–2.0 kg a.i. ha^{-1}) in late March over the dormant seedlings. Paraquat had no apparent effect on either plant type. First-year weed competition reduced height increment but not survival, although growth recovered once weeds were removed. Seedlings grown in unweeded conditions flushed earlier than those grown in weed-free conditions, potentially making them more susceptible to early spring frosts. This work suggests applications of up to 1.1 kg a.i. ha^{-1} paraquat may be tolerated by dormant ash seedlings grown in open conditions, and this could be a useful treatment for controlling over-wintering weeds in direct sown woodlands, forest nurseries and in natural regeneration situations, where an overstorey of trees is not present.

Keywords: Herbicides; Weed control; Vegetation management; Dormant season; Direct seeding; Paraquat; Glyphosate; *Quercus robur*; *Fraxinus excelsior*; *Acer pseudoplatanus*; *Prunus avium*; *Betula pendula*; *Alnus glutinosa*; *Castanea sativa*; *Fagus sylvatica*; *Populus* sp.; *Salix* sp

1. Introduction

Competition from weeds for light, water and nutrients in forest nursery seedbeds, and in direct sown, naturally regenerating, or transplanted trees on establishment sites in the UK, leads to reduced tree growth and survival (Davies, 1987; Williamson and Morgan, 1994; Willoughby and Clay, 1996; Harmer et al., 2000). This can be a particular problem when trying to establish trees on lowland sites formerly under arable cropping, where seed banks of weed species are large, and soil moisture deficits are common in the summer. Effective post-emergence residual herbicide programmes have been identified for transplants (Willoughby and Clay, 1996), and are being developed for direct seeded trees (Willoughby et al., 2003, 2004a), to maintain weed-free conditions and maximise survival and growth in the first season after planting or sowing.

Recent direct seeding experiments confirm the importance of weed control to minimise tree seedling death and suppression, in particular in the first growing season following germination when root systems are not well developed (Willoughby et al., 2004b). Clay and Dixon (1997) found with poplar (*Populus* sp.) and willow (*Salix* sp.) cuttings that allowing growth of annual weeds in the year of planting but controlling weeds from that point on, had no effect on survival but tree biomass after 4 years was reduced by 60%. By contrast,

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allowing uncontrolled weed growth for 2 years severely reduced both survival and growth of poplar cuttings. In their work the particular weed species present appeared to affect survival, with a dense cover of creeping thistle (*Cirsium arvense* (L.) Scop.) killing more poplar plants than annual weeds. Löf et al. (2004) also found that weed competition in the year of planting affected seedling or transplant growth more than survival.

However, even if the benefits of first year weed control in direct sown seedlings are accepted, given the limited number of safe potential herbicide treatments (Willoughby et al., 2004a) and the expense of alternatives such as hand weeding (Willoughby et al., 2004c), there may be occasions when vegetation is left inadequately controlled at the end of the tree first growing season. Most pre-emergence herbicides control germinating weeds, and to be effective need to be applied to bare soil in the spring. The effect of these residual herbicides often diminishes before the end of the growing season. Hence recommended herbicide regimes often require an end of season clean up of vegetation that develops late in the growing season (Willoughby et al., 2004a). With seedlings planted at regular spacing and the less regularly located seedlings that arise from direct seeding, natural regeneration and some nursery production systems, the application of directed sprays of broad-spectrum contact herbicides to achieve end of season control of established herbaceous weeds can be difficult to achieve safely.

Promising results have been found when using glyphosate, glufosinate-ammonium and paraquat as overall sprays on dormant tree seedlings in the UK. However, selectivity varies with tree species (Willoughby and Clay, 1996), and only a limited range of perennial weed species will have sufficient live, above ground growth, to be susceptible to treatment with contact acting herbicides when trees are dormant. Robinson (1985) reported that many deciduous shrub and tree species can be safely sprayed with glyphosate when dormant, but results may vary with time of application and dose rate (Clay, 1972; Garnett and Williamson, 1992; Stott et al., 1974; Willoughby, 1996). Glufosinate-ammonium can be sprayed after 1 March in the UK (Whitehead, 2004); overall application in March has been found to be safe on broad-leaved species but very damaging on conifers (Willoughby, 1996). Paraquat has been regarded as safe as an overall spray of dormant fruit trees and bushes providing no green wood or buds are present (Fryer and Makepeace, 1978). However, Harmer et al. (2000) found this treatment applied in December caused tip die back of beech (*Fagus sylvatica* L.) seedlings whereas glyphosate was safe. This damaging effect was thought to be due to greater susceptibility of seedlings grown under a canopy of trees and amongst weed vegetation. Dormant poplar and willow coppice have been sprayed with all three herbicides after cut-back with little damage, although treatment when buds were emerging has caused more injury (Parfitt, 1989; Clay et al., 1990; Clay and Dixon, 1996).

These results suggest that there are a number of potentially useful contact herbicide treatments but reasons for occasional damage need investigation. There is also a need to assess whether seedlings subjected to weed competition in their first year are more susceptible to contact herbicide damage than larger plants grown in weed-free conditions. Three experiments were set up to investigate the effects of paraquat or glyphosate on young, dormant broadleaved trees. In the first experiment, 2-year-old transplants of 10 broadleaved species grown in open conditions in a nursery were treated with paraquat at three doses and three timings in the dormant season. The second experiment examined the effect of two rates of glyphosate or paraquat applied at two dates in the dormant season on smaller, 1-year-old, pot-grown ash (*Fraxinus excelsior* L.) seedlings. In the final experiment, paraquat was applied at five doses to dormant 1-year-old direct-sown ash seedlings in March, established in either unweeded or weed-free conditions to give trees of varying size and vigour.

2. Materials and methods

2.1. Experiment 1

In the autumn of 1997, 2-year-old transplants of oak (*Quercus robur* L.), ash and beech, and 1-year-old undercut transplants of sycamore (*Acer pseudoplatanus* L.), cherry (*Prunus avium* L.), birch (*Betula pendula* Roth), alder (*Alnus glutinosa* (L.) Gaertn.), sweet chestnut (*Castanea sativa* Mill.), and unrooted cuttings of poplar and willow, were planted into a weed-free transplant bed at Headley Research Nursery, UK (51°08′N, 1°51′W), a site which receives an annual average of 804 mm of rainfall and 1798 growing degree days (above 4 °C). Soil type according to Mackney et al. (1983) was a humic–ferric podzol, Shirrell Heath 1 series. A pH of 5.5 was maintained by liming before planting.

Three herbicide treatments and a control were applied at three dates, arranged in two randomised blocks, giving 24 plots in total per species. This gave nine treatment combinations, plus a control, each repeated three times per block. Each species plot consisted of 10 trees at 10 cm spacing, and 10 species plots made up a treatment plot, with a 1.5 m buffer between treatment plots. A base dressing of 200 kg ha^{-1} 0:24:24 ($N:P_2O_5:K_2O$) fertiliser was applied before planting, and three top dressings of 100 kg ha^{-1} 25:0:15 ($N:P_2O_5:K_2O$) fertiliser were applied during the growing season, with 6 mm of irrigation being applied over 2 h if no rainfall occurred within 24 h of the application. Paraquat (Gramoxone 100; 200 g a.i. l^{-1} SL; Syngenta) was applied at one of three rates, 0.6, 1.1 or 2.2 kg a.i. ha^{-1} (recommended application rates for weed control in forestry using paraquat are usually between 0.6 and 1.1 kg a.i. ha^{-1}; Syngenta, 2002). Applications were made on three dates, 26 November 1997, 29 December 1997, and 12 March 1998 using a Cooper Pegler CP3 Knapsack Sprayer fitted with a green nozzle, giving an output of 1200 ml a minute at a pressure of 100 kPa and a volume rate of 200 l ha^{-1}. Treatments were carried out in dry, frost-free conditions. All trees appeared to be dormant at the first two application dates. For the final application in March, a few trees in some species had started to flush—the state of dormancy at this final spray date is given in Table 1.

Table 1
Plant dormancy at onset of March paraquat application—Experiment 1

Species	Dormancy status[a]
Oak	1.8
Ash	1.5
Sycamore	1.7
Beech	2.0
Cherry	3.0
Birch	2.5
Alder	2.8
Sweet chestnut	2.5
Poplar	1.8
Willow	2.0

[a] Dormancy was visually assessed using a three point scale, where 1 = appeared fully dormant, 2 = some buds had started to break, 3 = leaves were visible.

Survival, height and stem diameter at 10 cm above ground level were measured in March and November 1998 for all species except poplar and willow, for which only survival and height increment were measured. Plots were kept weed-free by a carefully directed application in February 1998 of a three-way tank mix of Challenge (150 g l^{-1} glufosinate ammonium; Aventis), Butisan (500 g l^{-1} metazachlor; BASF) and Stomp (400 g l^{-1} pendimethalin; BASF), followed by hand weeding as necessary throughout the growing season. Plots were subject to 6 mm of irrigation immediately before soil moisture tension at 20 cm depth fell to 50 kPa, as indicated by tensiometers, to prevent moisture stress developing in trees.

2.2. Experiment 2

In March 2001 ash seed, pre-treated to break dormancy (Jinks et al., 1995), was sown in pots containing a compost mixture of four parts sterilised loam, two parts peat and one part Cornish grit, with Osmocote slow release fertiliser (5–6 months duration) at 4.5 g l^{-1} and magnesium limestone at 2.7 g l^{-1} added to the compost. In December 2001 the ash seedlings were transplanted singly into 12 cm diameter 1 l pots containing a similar compost mix and allowed to grow on. Plants were grown outside at Long Ashton Research Station, UK (51°25′N, 2°40′W), which receives an annual average of 870 mm of rainfall and 1922 growing degree days (above 4 °C).

Treatments of glyphosate (Roundup Biactive; 360 g a.e. l^{-1} SL; Monsanto) at 0.54 and 1.08 kg a.e ha^{-1} (the recommended application rate of glyphosate for selective weed control in conifers is 0.54 kg a.e. ha^{-1}; Monsanto, 2003), and paraquat (Gramoxone 100) at 0.6 and 1.0 kg a.i. ha^{-1} were applied with a laboratory track sprayer at a pressure of 210 kPa with a volume rate of 206 l ha^{-1}, at two dates, to separate sets of trees. The first treatment was made on 29 January 2002 to dormant trees with no sign of buds bursting, and the second application was on 25 March 2002 when the trees to be treated were still showing no signs of bud activity, but the untreated controls generally had buds bursting with leaves up to 2 cm in length. Plants were kept under cover for 24 h after herbicide application and then set out on capillary matting in eight randomised blocks on an outside hard-standing area. There were 10 treatments (including two untreated controls) giving 80 pots in total. Basal stem diameters and shoot heights were measured in January before treatment and again in July at the end of the experiment, and diameter and height increments calculated. Plant health was visually scored at regular intervals throughout the experiment, using a scale ranging from 0 to 7, where 0 = dead, 4 = 50% reduction in growth compared with the best untreated score of 7.

2.3. Experiment 3

2.3.1. Establishment

The experiment was sited at Failand, near Bristol, UK (51°27′N, 2°41′W), which receives an annual average of 853 mm of rainfall and 1883 growing degree days (above 4 °C), on land that was ploughed and cultivated during February and March 2002. Soil type according to Mackney et al. (1983) was a typical brown earth, Newbiggin Association, and had a pH of 5.8 and an organic matter content of 3.3%. Plots were marked out on 5 April 2002 and ash seeds, pre-treated to break dormancy (Jinks et al., 1995), were sown at a rate of approximately 100 viable seeds per m^2. There were 54 plots in total (6 rows of 9 plots), each plot was 1 m × 3 m, with a 1 m buffer between the rows and the plots within the rows. Throughout April, the experiment was irrigated every 2–3 days with 2–3 cm of water to encourage germination. On 12 April 2002 pendimethalin (Stomp 400SC; 400 g a.i. l^{-1} SC; BASF) was sprayed using an Oxford Precision Sprayer on alternate rows of plots at 1.54 kg a.i. ha^{-1} in a spray volume of 240 l ha^{-1}, to establish the weed-free treatments. Propaquizafop (Falcon; 100 g a.i. l^{-1} EC; Makhteshim Agan) at 0.15 kg a.i. ha^{-1} was sprayed on 24 June to the weed-free plots to kill grass weed species. The weed-free plots were then hand weeded at regular intervals to maintain weed-free conditions throughout 2002. The abundance of the main weed species present on the untreated, unweeded plots was recorded on 13 August 2002 based on a modified Braun–Blanquet cover-abundance score, where 0 = no plants, 1 = rare, 2 = sparse, 3 = frequent, <4% cover, 4 = abundant, 5% cover, 5 = 5–12.5% cover, 6 = 12.5–25%, 7 = 25–50%, 8 = 51–75% and 9 = 76–100% cover (Westhoff and van der Maarel, 1973). On 18 November 2002, the unweeded plots were sprayed with propaquizafop at 0.15 kg a.i. ha^{-1} to kill grass weed species and during January and February 2003 all the plots were hand weeded and any dead vegetation also removed. Hence at the time of application of the experimental herbicide treatments, all plots were weed free. Heights of the ash and their stem diameter 5 cm above ground were measured in early March 2003 and within both the weeded and unweeded treatments, an equal number of the plots with the most numerous seedlings were selected for further experimental study.

2.3.2. Herbicide treatments

There were twelve treatments, which consisted of the two weed treatments during the year of establishment (weed-free and natural weed infestation) and six further herbicide treatments (including an unsprayed control) laid out in four

Table 2
Effect of paraquat applied at three dose rates to oak, ash, sycamore and beech—Experiment 1

Spray date	Herbicide (kg a.i. ha^{-1})	Oak			Ash			Sycamore			Beech		
		Survival (%)*	Height increment (cm)	Diameter increment (mm)	Survival (%)*	Height increment (cm)	Diameter increment (mm)	Survival (%)*	Height increment (cm)	Diameter increment (mm)	Survival (%)*	Height i ncrement (cm)	Diameter increment (mm)
26 November 1997	Paraquat 0.6	100 a	19.2	4.7	100 a	7.7	3.0	100 a	15.4	5.7	100 a	13.9	3.2
26 November 1997	Paraquat 1.1	100 a	9.3	4.3	100 a	8.3	3.6	100 a	14.8	5.2	100 a	14.2	3.9
26 November 1997	Paraquat 2.2	95 a	7.9	3.2	100 a	5.6	3.0	100 a	14.1	4.8	100 a	16.3	3.3
29 December 1997	Paraquat 0.6	100 a	16.4	3.5	100 a	7.2	3.1	100 a	17.9	4.6	100 a	9.5	2.8
29 December 1997	Paraquat 1.1	100 a	11.4	3.8	100 a	8.0	2.4	100 a	12.2	3.8	100 a	12.0	2.9
29 December 1997	Paraquat 2.2	100 a	12.7	4.3	100 a	7.4	3.3	100 a	9.9	4.2	100 a	13.6	2.9
12 March 1998	Paraquat 0.6	100 a	18.2	3.8	100 a	7.4	2.8	100 a	10.8	3.8	100 a	19.4	3.1
12 March 1998	Paraquat 1.1	100 a	19.0	3.9	100 a	8.1	2.8	100 a	8.3	3.5	100 a	11.7	2.7
12 March 1998	Paraquat 2.2	100 a	20.8	5.4	100 a	7.3	3.4	100 a	10.9	5.5	100 a	17.0	4.3
Untreated (all dates)		100 a	18.7	4.21	100 a	8.1	3.01	100 a	9.4	3.63	100 a	14.1	2.74
S.E.D. (d.f. 13), control vs. treated		–	4.47	0.77	–	1.82	0.66	–	6.06	1.12	–	2.18	0.49
LSD (at $p \leq 0.05$)		–	9.65	1.67	–	3.93	1.43	–	13.10	2.41	–	4.70	1.06
p (from ANOVA, rate × date interaction)		–	0.50	0.20	–	0.96	0.71	–	0.94	0.65	–	0.14	0.22

* Within each species, mean survival percentages sharing the same letter are not significantly different at the $p \leq 0.05$ level. S.E.D and LSD values not presented, as analysis took place on linear predictor scale.

randomised blocks, giving 48 plots in total. Treatments of paraquat at 0.4, 0.6, 0.8, 1.0 and 2.0 kg a.i. ha^{-1} were applied on 20 March 2003 using an Oxford Precision Sprayer with a 1 m boom fitted with two 11,003 nozzles at a spray pressure of 126 kPa giving a spray volume of 357 l ha^{-1}. Applications were made in dry, frost-free conditions. All plots were regularly hand weeded throughout the growing season. The number of seedlings in leaf on each plot was counted on 17 April. Tree height and stem diameter at 5 cm were measured in November 2003 at the end of the growing season. Plant health was scored at regular intervals throughout the experiment as previously described.

2.4. Analyses

Survival data for the first experiment were analysed using a generalised linear model with binomial error and logit link function, and the significance of the herbicide treatment tested using a chi-squared test of the deviance, followed by a least significant difference test applied to the linear predictor scale, using Genstat (Genstat 5 Committee, 1993). Species were analysed separately. All other experimental data were subjected to analysis of variance using Genstat, and Fishers least significant test performed (Snedecor and Cochran, 1967).

3. Results

3.1. Experiment 1

The nursery grown oak, ash, sycamore, beech, cherry, birch, alder and sweet chestnut were largely unaffected by any of the treatments (Tables 2–4). There were no significant reductions in survival for these species, although there was an apparent but non-significant reduction in survival of 10% from the high dose of paraquat applied in March to cherry. There were also few effects on growth. However, there were apparent, but non-significant, reductions in height increment of 50% for the middle and higher dose applications to oak in November, of 30% for higher dose applications to ash in November and March, and of 30% for the higher rate application to alder in December. Although some individuals of beech, cherry, alder birch and sweet chestnut had already started to flush by the time of the final application in March (Table 1), no consistent indications of greater damage were noticed in these species, apart from the non-significant reduction in the survival of cherry.

Applications to poplar and willow were more damaging. For poplar, there was a significant date effect, with November applications being the most damaging. All rates from the November application, and the highest rate from the December application caused reductions in survival of up to 50%. Rates of up to 1.1 kg a.i. ha^{-1} did not appear to reduce survival when applied in December or March. Surviving growth appeared to be largely unaffected. With willow, all treatments above 0.6 kg a.i. ha^{-1} produced unacceptable reductions (losses of 20–80%) in survival, with the highest rates producing the most deaths. Only the highest rate applied in March reduced height growth of the surviving stems.

3.2. Experiment 2

There were no significant effects from the herbicide treatments on date of tree flushing, plant health after treatment (data not shown) or on growth (Table 5).

Table 3
Effect of paraquat applied at three dose rates to cherry, birch and alder—Experiment 1

Spray date	Herbicide (kg a.i. ha^{-1})	Cherry			Birch			Alder		
		Survival (%)*	Height increment (cm)	Diameter increment (mm)	Survival (%)*	Height increment (cm)	Diameter increment (mm)	Survival (%)*	Height increment (cm)	Diameter increment (mm)
29 November 1997	Paraquat 0.6	100 a	36.9	5.5	100 a	47.6	6.7	100 a	50.0	9.6
29 November 1997	Paraquat 1.1	100 a	51.0	6.7	100 a	38.3	6.1	100 a	53.5	10.3
29 November 1997	Paraquat 2.2	100 a	61.0	6.3	100 a	55.4	6.2	100 a	48.9	9.7
29 December 1997	Paraquat 0.6	100 a	27.4	3.6	100 a	41.8	4.3	100 a	54.1	9.4
29 December 1997	Paraquat 1.1	100 a	39.4	4.7	100 a	51.1	5.6	100 a	48.9	9.4
29 December 1997	Paraquat 2.2	100 a	54.3	5.7	100 a	55.1	6.9	100 a	35.3	8.5
12 March 1998	Paraquat 0.6	100 a	15.8	3.0	100 a	32.0	4.5	100 a	37.0	7.8
12 March 1998	Paraquat 1.1	100 a	26.6	3.3	95 a	31.3	4.2	100 a	43.2	9.2
12 March 1998	Paraquat 2.2	90 a	31.6	5.0	100 a	44.2	6.7	100 a	45.5	9.5
Untreated (all dates)		100 a	30.4	4.04	100 a	45.1	5.5	100 a	48.0	9.3
S.E.D. (d.f. 13), control vs. treated		–	10.88	1.00	–	13.52	1.10	–	8.37	1.24
LSD (at $p \leq 0.05$)		–	23.50	2.16	–	29.21	2.37	–	18.08	2.69
p (from ANOVA, rate × date interaction)		–	0.98	0.783	–	0.95	0.47	–	0.48	0.82

* Within each species, mean survival percentages sharing the same letter are not significantly different at the $p \leq 0.05$ level. S.E.D and LSD values not presented, as analysis took place on linear predictor scale.

Table 4
Effect of paraquat applied at three dose rates to sweet chestnut, poplar and willow—Experiment 1

Spray date	Herbicide (kg a.i. ha^{-1})	Sweet chestnut			Poplar		Willow	
		Survival (%)*	Height increment (cm)	Diameter increment (mm)	Survival (%)*	Height increment (cm)	Survival (%)*	Height increment (cm)
29 November 1997	Paraquat 0.6	100 a	15.9	6.0	70 bc	100.1	80 a	131.9
29 November 1997	Paraquat 1.1	100 a	13.0	5.1	70 bc	143.3	20 b	142.0
29 November 1997	Paraquat 2.2	100 a	11.8	5.4	45 c	102.0	20 b	177.5
29 December 1997	Paraquat 0.6	100 a	17.6	4.3	90 ab	119.4	75 a	150.8
29 December 1997	Paraquat 1.1	100 a	13.9	4.9	95 ab	129.5	35 b	129.2
29 December 1997	Paraquat 2.2	100 a	15.0	4.7	65 bc	121.2	30 b	144.8
12 March 1998	Paraquat 0.6	100 a	15.3	4.5	95 ab	94.5	70 a	141.8
12 March 1998	Paraquat 1.1	100 a	12.0	4.4	80 abc	158.7	35 b	148.1
12 March 1998	Paraquat 2.2	100 a	21.8	6.5	95 ab	122.1	15 b	48.5
Untreated (all dates)		100 a	13.8	4.5	97 a	128.2	92 a	144.5
S.E.D. (d.f. 13), control vs. treated		–	3.06	0.80	–	27.91	–	19.29
LSD (at $p \leq 0.05$)		–	6.62	1.74	–	60.30	–	42.99
p (from ANOVA, rate × date interaction)			0.24	0.34	–	0.83	–	<0.01

* Within each species, mean survival percentages sharing the same letter are not significantly different at the $p \leq 0.05$ level. S.E.D and LSD values not presented, as analysis took place on linear predictor scale.

3.3. Experiment 3

There was a clear difference in the growth of the ash growing in unweeded conditions compared with the weed-free plots. Weed cover on the unweeded plots in the middle of August 2002 was almost 100% on most plots, obscuring the ash seedlings completely. The main weed species were creeping bent (*Agrostis stolonifera* L.), creeping thistle, common couch grass (*Elytrigia repens* (L.) Nevski), and creeping buttercup (*Ranunculus repens* L.). However, there were no significant correlations between the abundance of these individual species and ash seedling numbers (data not shown). There were no differences between the weed treatments in the number of ash seedlings that established by the end of the first year (data not shown) but those that had been growing in the unweeded conditions were less than half the height of those in the weed-free plots (Table 6). In April 2003, 1 month after applying the paraquat treatments, the majority of the trees that had previously been growing in unweeded conditions were in leaf, whilst virtually none of the trees on previously weed-free plots had flushed (Table 6). However, there were no differences in numbers in leaf between the different paraquat treatments and no differences in health later in the growing season between any of the treatments (data not shown). Measurements at the end of the growing season showed that none of the paraquat treatments had had any adverse effect of the growth of the ash (Table 6). Seedlings on both previously unweeded and weed-free plots made good growth. Overall, although height increment of the

Table 5
The effect of glyphosate and paraquat on growth of 1-year-old pot grown ash seedling—Experiment 2

Herbicide	Dose (kg a.i./a.e. ha^{-1})	Application date	29 January–24 July 2002	
			Diameter increment (mm)	Height increment (cm)
Glyphosate	0.54	January	3.3	14.0
Glyphosate	1.08	January	4.2	15.6
Paraquat	0.60	January	3.4	13.9
Paraquat	1.00	January	4.1	14.2
Untreated		January	2.9	12.0
Glyphosate	0.54	March	4.1	15.5
Glyphosate	1.08	March	4.5	19.1
Paraquat	0.60	March	3.8	10.3
Paraquat	1.00	March	3.6	11.0
Untreated		March	3.3	13.0
S.E.D. (d.f. 71), control vs. treated			0.63	3.42
LSD (at $p \leq 0.05$)			1.26	6.82

Table 6
Effect of paraquat applied on 20 March 2003 on the growth of ash seedlings—Experiment 3

Herbicide (kg a.i. ha^{-1})	March 2003[a]			April 2003	November 2003	March–November 2003	
	Plants per plot	Height (cm)	Diameter (mm)	Seedlings in leaf	Plants per plot	Height increment (cm)	Diameter increment (mm)
Weed-free							
Untreated	28.5	10.9	5.7	0	28.5	54.3	7.6
Paraquat 0.4	23.8	11.3	6.2	0	24.7	54.1	7.7
Paraquat 0.6	22.5	9.2	5.4	0	23.0	43.4	7.1
Paraquat 0.8	20.2	9.3	5.3	0	20.5	48.1	7.4
Paraquat 1.0	24.2	9.4	5.3	0	24.2	52.0	7.3
Paraquat 2.0	24.8	9.7	5.4	0	25.2	43.6	7.4
Unweeded							
Untreated	29.5	4.0	2.1	17.2	31.2	24.3	6.4
Paraquat 0.4	23.0	4.1	2.2	14.0	23.5	38.5	7.7
Paraquat 0.6	24.5	4.4	2.3	11.2	28.7	21.2	6.6
Paraquat 0.8	23.5	3.9	2.1	14.3	26.5	33.8	7.3
Paraquat 1.0	24.2	3.8	2.4	12.3	30.2	35.9	7.5
Paraquat 2.0	27.5	4.0	2.4	15.5	28.7	31.7	7.3
S.E.D (d.f. 33 (15[b]))		–	–	6.57[b]	7.39	9.90	1.12
LSD (at $p \leq 0.05$)		–	–	13.99	15.03	20.15	2.28
Treated means							
Weed-free		9.75	5.5	0	23.5	48.2	7.4
Unweeded		4.06	2.3	13.5	27.5	32.2	7.3
LSD (at $p \leq 0.05$)	–	0.89	0.41	–	11.64	9.01	1.02

[a] March data for individual herbicide treatment plots included to provide an initial baseline only. Mean figures for March data illustrate the effects of previous years weed and weed-free treatments.
[b] Weed-free data not included in analysis.

seedlings in the previously unweeded plots was still much less, there was little difference in basal stem diameter increment (Table 6).

4. Discussion

In the nursery experiments involving transplant stock there were few signs of damage from applications of paraquat to oak, ash, sycamore, beech, cherry, birch, alder and sweet chestnut made at any time during the dormant season. This is an important result as there is little other evidence in the literature of investigations into the tolerance of transplants of these species to dormant-season applications of paraquat. Poplar and willow grown from cuttings appeared much more susceptible, although rates of up to 1.1 kg a.i. ha^{-1} in December and March were moderately tolerated by the poplar. Glufosinate ammonium, glyphosate or amitrole may be safer alternatives for these latter two species (Willoughby, 1996).

Overall applications of glyphosate during the dormant season at doses up to 1.1 kg a.e. ha^{-1} and paraquat at doses up to 2 kg a.i. ha^{-1} had no significant adverse effects on ash seedling growth. In our work on paraquat, and experiments reported here and elsewhere with glyphosate, involving overall sprays on dormant transplants, there have been occasions when these treatments were damaging to some broadleaved species. Where damage occurred with glyphosate applied at doses of 0.54 or 0.72 kg a.e. ha^{-1} weather conditions were reported as mild and damp in the days before and after application (Garnett and Williamson, 1992; Willoughby, 1996), and it is possible that hydration of shoot surfaces in these conditions allowed greater uptake of the herbicide. Conditions of high humidity are also known to increase adsorption of paraquat (Ashton and Crafts, 1981). In the experiments reported here, the weather was fine and dry before and after all applications except the December spray to nursery grown transplants, where rainfall occurred 5 h after spraying. It would seem prudent therefore to determine whether particular climatic conditions are responsible for greater susceptibility of dormant trees to damage from contact herbicides, to give greater confidence in their use.

Based on evidence from these and the other experiments quoted, application of glyphosate or paraquat 1 or 2 weeks before bud burst does not appear to increase chances of damage compared with winter applications; this later application date has the advantage that more weeds have commenced growth so long-term efficacy is greater.

In our experiments, no visual differences in bud or bark condition or response to paraquat were found in ash seedlings previously grown in unweeded or weed-free conditions, although the seedlings on unweeded plots were clearly smaller and closer to breaking dormancy (Table 6). Harmer et al. (2000) considered that damage from December applied paraquat to apparently dormant, naturally regenerated beech seedlings, was linked with the fact that the plants were small, sheltered beneath a near continuous canopy of trees and in a dense mix of bramble (*Rubus fruticosus* L. agg.) and herbaceous weeds, which may have influenced seedling dormancy. However, in the same experiment glyphosate at 0.54 kg a.e. ha^{-1} or triclopyr at 0.96 kg a.i. ha^{-1} caused little damage. The results from our experiment suggest that weed competition up to the point of spraying by itself does not explain an apparently greater susceptibility of small seedlings beneath a canopy of trees, compared to transplants grown in open conditions. Competition for resources from the overstorey trees themselves may be having a greater effect than ground level weed cover. However, it is more likely that differences in seedling tolerance result from the microclimate on the forest floor being more humid, shadier, warmer and less subject to frost than open conditions (Man and Lieffers, 1999; Langvall and Lofvenius, 2002). Environmental differences may also cause a change in the seasonal pattern of dormancy induction and breakage, resulting in differential susceptibility of seedlings to herbicide damage. Environment may also affect the maturation of cortical tissues and in particular the formation of the outer protective layer of closely packed, dead, cork cambium cells. This may result in forest-grown seedlings being less tolerant of applications of paraquat, which can be adsorbed by stomata in leaves and immature live bark, causing damage to those plant structures containing chlorophyll by interrupting active photosynthesis and liberating hydroxyl (OH) radicals (Ashton and Crafts, 1981). However, although survival was not affected, and higher dose rates had no effect, applications of 0.6 and 1.1 kg a.i. ha^{-1} paraquat caused slight reductions in height increment in nursery grown beech transplants in Experiment 1, suggesting that beech as a species may simply be more susceptible to dormant season sprays. More work on the seedlings of different tree species grown beneath a canopy of trees would be required to test such a hypothesis.

The final experiment confirmed the competitive effect of weeds on ash seedling growth and the value of post-sowing residual herbicides for weed control (Willoughby et al., 2004b). Willoughby et al. (2004b) also found numbers of oak and pine (*Pinus sylvestris* L.) seedlings were reduced by more than 50% where weeds were uncontrolled in the year of sowing. In this experiment, weed competition appeared to have little effect on seedling survival, which is consistent with the suggestion of Löf et al. (2004) that weed competition can instead have a greater effect on seedling growth. However, in our experiment, although irrigation ceased once tree seedlings had emerged, it may have had an influence on the competitive effect of weeds with young seedlings.

The results here showed no correlation between tree growth and the abundance of particular weed species, with all weeds and densities appearing to be equally competitive. A similar result was found by Willoughby et al. (2004b), who found few differential effects of different weed or cover crop species on competition with direct-sown trees.

Ash seedlings in the plots kept unweeded in year 1 but weed-free in year 2, grew strongly in the absence of weed competition, which is consistent with results reported by Willoughby et al. (2004b). Recovery after severe suppression in the year of planting has also been shown with transplanted trees (Davison and Bailey, 1980) and poplar and willow planted as cuttings (Clay and Dixon, 1997). Our results suggest that even where growth of direct-sown trees has been suppressed in the year of sowing, effective weed control from the first winter onwards may still make it possible to achieve satisfactory establishment.

The assessment of numbers of trees in leaf on 17 April (Table 6) indicated that small seedlings, previously suppressed by dense weed growth, had flushed earlier than seedlings grown for their first year under weed-free conditions. Murray et al. (1994) found that increasing nutrient supply lengthened the growing season, through later onset of senescence and earlier flushing, implying that nutrient starved trees may flush later. However, although nutrient levels in trees were not assessed in our work, weed competition usually lessens nutrient availability (Davies, 1987). Termination of a period of winter dormancy requires exposure to chilling temperatures followed by exposure to a genetically determined accumulated heat sum (Larcher, 1995). Other work on direct seeded trees (Willoughby, unpublished) found that weed competition with ash seedlings can also result in earlier growth cessation in the autumn. This suggests that the seedlings with weed competition in our experiment may have entered dormancy earlier, received their dormancy breakage period of winter cold sooner, and flushed earlier than equivalent trees grown in weed-free conditions the previous season. In practical terms it seems that in addition to reduced growth and survival, there is a risk of weed competition leading to earlier flushing, which may make tree seedlings more susceptible to potentially damaging early spring frosts (Cannell and Smith, 1984). Care should also be taken to eliminate weed competition from any provenance trials aiming to select for date of flushing using young trees in nurseries.

The work reported here suggests that the normal recommended dose for weed control of 1.1 kg a.i. ha^{-1} paraquat is generally safe to spray over deeply dormant, open grown transplant stock of oak, ash, sycamore, beech, cherry, birch, alder and sweet chestnut, provided no juvenile green buds or bark are present. Survival of these species seems unlikely to be affected, although there may be occasional instances of reductions in subsequent rate of growth. More work on late winter application of contact herbicides is needed to confirm their safety to tree seedlings. However, applications of up to 1 kg a.i. ha^{-1} paraquat appear to be tolerated by deeply dormant ash seedlings grown in open conditions, and this may be a useful treatment for controlling established herbaceous weed vegetation that has live, above ground growth over the winter period, in direct sown woodlands, forest nurseries and in natural regeneration situations.

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References

Ashton, F.M., Crafts, A.S., 1981. Mode of Action of Herbicides. John Wiley and Sons, New York.

Cannell, M.G.R., Smith, R.I., 1984. Spring frost damage on young *Picea sitchensis*. 2. Predicted dates of bud burst and probability of frost damage. Forestry 57 (2), 177–197.

Clay, D.V., 1972. The response of various fruit crops to glyphosate. In: Proceedings of the 11th British Weed Control Conference. pp. 451–457.

Clay, D.V., Lawrie, J., Parfitt, R.I., Stott, K.G., 1990. Evaluation of herbicides for coppice biomass. In: Grassi, G., Gosse, G., Dos Santos, G. (Eds.), Proceedings of the Fifth EC Conference on Biomass for Energy and Industry, vol. 1. Elsevier, London, pp. 134–140.

Clay, D.V., Dixon, F.L., 1996. Weed management in short-rotation energy coppice: selectivity of foliar acting herbicides. Aspects Appl. Biol. —Veg. Manage. For. Amenity Ind. Areas: Managing Multiple Object. 44, 109–116.

Clay, D.V., Dixon, F.L., 1997. Effect of ground-cover vegetation on the growth of poplar and willow short-rotation coppice. Aspects Appl. Biol.: Biomass Energy Crops 49, 53–60.

Davies, R.J., 1987. Trees and Weeds—Weed Control for Successful Tree Establishment. Forestry Commission Handbook 2. HMSO, London.

Davison, J.G., Bailey, J.A., 1980. The effect of weeds on the growth of a range of nursery stock species planted as liners and grown for two seasons. In: Proceedings of the Weed Control in Forestry Conference, Association of Applied Biologists, pp. 13–20.

Fryer, J.D., Makepeace, R.J. (Eds.), 1978. Weed Control Handbook: Recommendations. 8th ed. Blackwell Scientific Publications, Oxford, UK, pp. 131–158.

Garnett, R.P., Williamson, D., 1992. The susceptibility of trees to over the top applications of glyphosate during the winter dormant season. Aspects Appl. Biol.: Veg. Manage. For. Amenity Conserv. Areas 29, 131–135.

Genstat, 1993. GENSTAT 5 Release 3 Reference Manual. GENSTAT 5 Committee/Clarendon Press, Oxford.

Harmer, R., Willoughby, I., Robertson, M., 2000. Use of herbicides to control weeds and promote the natural regeneration of *Fagus sylvatica*. Aspects Appl. Biol. 58, 9–14.

Jinks, R., Jones, J., Gosling, P., 1995. Improving the pre-treatment and germination of broadleaved seed. For. Br. Timber 24 (12), 24–26.

Langvall, O., Lofvenius, M.O., 2002. Effect of shelterwood density on nocturnal near ground temperature, frost injury risk and budburst date of Norway spruce. For. Ecol. Manage. 168 (1–3), 149–161.

Larcher, W., 1995. Physiological Plant Ecology, 3rd ed. Springer-Verlag, Berlin.

Löf, M., Thomsen, A., Madsen, P., 2004. Sowing and transplanting of broadleaves (*Fagus sylvatica* L., *Quercus robur* L., *Prunus avium* L. and *Crataegus monogyna* Jacq.) for afforestation of farmland. For. Ecol. Manage. 188, 113–123.

Mackney, D., Hodgson, J.M., Hollis, J.M., Staines, S.J., 1983. Legend for the 1:250,000 soil map of England and Wales. Soil Survey of England and Wales, Rothamsted, Harpenden.

Man, R., Lieffers, V.J., 1999. Effects of shelterwood and site preparation on microclimate and establishment of white spruce seedlings in a boreal mixedwood forest. For. Chronicle 75 (5), 837–844.

Monsanto, 2003. Roundup pro biactive. In: Product Label, Monsanto UK Limited, The Maris Centre, Hauxton Road, Trumpington, Cambridge.

Murray, M.B., Smith, R.I., Leith, I.D., Fowler, D., Less, H.S.J., Friend, A.D., Jarvis, P.G., 1994. Effects of elevated CO_2, nutrition and climatic warming on bud phenology in Sitka spruce (*Picea sitchensis*) and their impact on the risk of frost damage. Tree Physiol. 14, 691–706.

Parfitt, R.I., 1989. Response of established willow stools at different growth stages to foliar herbicide applications. In: Proceedings of the Brighton Crop Protection Conference: Weeds, vol. 1. pp. 355–360.

Robinson, D.W., 1985. Efficacy of glyphosate in nursery stock and amenity horticulture. In: Grossbard, E., Atkinson, D.J. (Eds.), The Herbicide Glyphosate. Butterworths, London, pp. 339–354.

Snedecor, G.W., Cochran, 1967. Statistical Methods, 6th ed. Iowa State University Press, Iowa.

Stott, K.G., Harper, C.W., Clay, D.V., Rath, N., Uprichard, S.D., Abernethy, W., 1974. The response of blackcurrants, gooseberries and apples to overall or directed applications of glyphosate made between October and March. In: Proceedings of the 12th British Weed Control Conference. pp. 603–611.

Syngenta, 2002. Gramoxone 100. In: Product Label, Syngenta Crop Protection UK Limited, Whittlesford, Cambridge.

Westhoff, V., van der Maarel, E., 1973. The Braun–Blanquet Approach. In: Whittaker, R. (Ed.), Handbook of Vegetation Science. V. Classification and Ordination. The Hague, Junk, pp. 617–726.

Whitehead, R., 2004. The UK Pesticide Guide 2004. CAB International Publishing, Wallingford, UK, 625 pp.

Williamson, D.R., Morgan, J.L., 1994. Nursery weed control. In: Aldhous, J.R., Mason, W.L. (Eds.), Forest Nursery Practice, Forestry Commission Bulletin, 111. HMSO, London, pp. 167–180.

Willoughby, I., 1996. Dormant season application of broad spectrum herbicides in forestry. Aspects Appl. Biol. —Veg. Manage. For. Amenity Ind. Areas: Managing Multiple Object. 44, 55–62.

Willoughby, I., Clay, D., 1996. Herbicides for farm woodland and short rotation coppice. Forestry Commission Field Book, 14. Forestry Commission, London, 60 pp.

Willoughby, I., Clay, D., Dixon, F., 2003. The effect of pre-emergent herbicides on the germination and early growth of broadleaved species used for direct seeding. Forestry 76 (1), 83–94.

Willoughby, I., Jinks, R.L., Gosling, P.G., Kerr, G., 2004a. Creating new woodlands by direct seeding. In: Forestry Commission Practice Guide, Forestry Commission, Edinburgh.

Willoughby, I., Jinks, R.L., Gosling, P.G., Kerr, G., 2004b. Factors affecting the success of direct seeding for lowland afforestation in the UK. Forestry 77 (5), 469–484.

Willoughby, I., Evans, H., Gibbs, J., Pepper, H., Gregory, S., Dewar, J., Nisbet, T., Pratt, J., McKay, H., Siddons, R., Mayle, B., Heritage, S., Ferris, R., Trout, R., 2004c. Reducing Pesticide Use in Forestry. Forestry Commission Practice Guide, 15. Forestry Commission, UK, 141 pp.